NEUTRON-GAMMA DENSITY (NGD): PRINCIPLES, FIELD TEST RESULTS AND LOG QUALITY CONTROL OF A RADIOISOTOPE-FREE BULK DENSITY MEASUREMENT

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ABSTRACT

Bulk density is among the most critical formation parameters for geoscientists. Traditional acquisition technology employs a radioisotope (137Cs) as a source of gamma rays. With a half-life of 30.17 years, this radioisotopic source continually emits 662-keV gamma rays, posing health, security, and environmental risks, which need to be minimized through rigorous and expensive transportation, storage, handling, and deployment procedures. The well logging industry has been seeking an alternative to the radioisotope-based technology for years; some of these alternatives have focused on finding a way to “make do” without a density measurement. However, the industry-standard technique of comparing neutron and density measurements favors the development of a cleaner and safer way to acquire a true formation bulk density.

Pulsed-neutron generators (PNG) have been successfully used by the well logging industry to acquire a variety of measurements. Electronically controlled pulses of high-energy neutrons can be emitted in precisely timed bursts. The inelastic collision of high-energy neutrons with the nuclei of formation atoms can put them into excited states, which decay through the emission of gamma rays. The characterization of the transport of these gamma rays in the formation can be used to determine the bulk density, in a manner similar to the traditional gamma-gamma density (GGD) measurement. While the principles behind this method are well understood, the practical development of an industry-grade measurement has taken years of careful development and testing.

This paper reviews the principles behind the neutron-gamma density (NGD) measurement and explains its measurement specifications, applications, and quality-control indicators. The new measurement was tested and benchmarked using data from a multifunction logging-while-drilling tool that incorporates the PNG and detectors required for the NGD measurement and a GGD density section. Comparing the results from both density measurements allows a rigorous benchmarking and performance evaluation of the NGD measurement versus the GGD in a diverse range of environments. This is illustrated through field test results detailing the accuracy and precision of the new measurement.

INTRODUCTION

A new multifunction logging-while-drilling service has been introduced, providing a complete suite of measurements, including most notably a radioisotope-free bulk density.

The new service offers the following measurements integrated in a single 26-ft (7.9-m) collar:

- Neutron-gamma density
- Thermal-neutron porosity
- Elemental capture spectroscopy
- Capture cross section, sigma
- 2 MHz and 400 kHz propagation resistivity
- Azimuthal natural gamma ray
- Ultrasonic caliper
- Annular pressure and temperature
- Triaxial shocks and vibration
- Near-bit borehole inclination

![Fig. 1 Sketch of the tool used to make the NGD measurement](image)

This paper reviews the principles behind the neutron-gamma density (NGD) measurement and explains its measurement specifications, applications, and quality-control indicators. The new measurement was tested and benchmarked using data from a multifunction logging-while-drilling tool that incorporates the PNG and detectors required for the NGD measurement and a GGD density section. Comparing the results from both density measurements allows a rigorous benchmarking and performance evaluation of the NGD measurement versus the GGD in a diverse range of environments. This is illustrated through field test results detailing the accuracy and precision of the new measurement.

The top five measurements on the list are collocated (Griffiths, 2010). The nuclear measurements are shown in Figure 1 with their respective position and associated sensors shown in the upper part of the tool sketch. This
means that they are essentially measuring the same formation volume under the same static and dynamic conditions simultaneously. Interpretation is simplified and this assembly allows a more precise, integrated petrophysical evaluation. All measurements are considerably closer to the drill bit than if they were spread out over several tool systems run in tandem. The short distance to the drill bit provides two considerable advantages. Not only is the short distance a crucial advantage when using real-time measurements for geosteering decisions, but the reduced time between drilling and measurement allows a more accurate and relevant determination of the formation properties.

The introduction of the NGD service makes it possible to obtain a bulk density measurement without using a $^{137}$Cs logging source, completing the PNG based measurement suite (Evans et al. 2000, Aitken et al. 2002). This new suite of measurements, being free of radioisotopic logging sources, removes the need for source transportation, handling and abandonment considerations and eliminates the health, security and environmental risks associated with the use of AmBe and $^{137}$Cs logging sources.

Years of data acquisition, analysis and interpretation, allowed the NGD measurement to be fully benchmarked against the traditional GGD measurement, which is the standard reference for equity determination. This was done by using simultaneous density measurements from the multifunction LWD tool (Weller et al. 2005a, 2005b). All of this led to hardware, software, calibration and algorithm improvements that culminated in the introduction of the new sourceless service.

**NGD MEASUREMENT PRINCIPLE**

*Measurement physics*

Figure 2 shows the basic principle of the NGD measurement. It is based on the detection of neutron-induced gamma rays at a long-spacing detector (LSn), which is placed far from the neutron source.

The gamma ray flux at the detector is influenced by neutron transport from the neutron source in the tool to the point of the gamma ray producing neutron interaction in the formation, and by the subsequent transport of the gamma rays from their origin to the gamma ray detector. To eliminate the influence of thermal neutron effects on the answer, only inelastic gamma rays produced by high-energy neutrons are measured. The background count rate from neutron capture gamma rays is subtracted out. The approach is more complex than the GGD measurement since the gamma ray source is not a point source, but rather an extended source as shown in Figure 2.

Neutrons coming from the neutron generator produce gamma rays from materials all around the tool, with most originating in the formation (Figure 3). This, in effect, generates a secondary source of gamma rays that NGD uses to measure formation density. The size and shape of the secondary gamma ray source is relatively constant, changing only slightly with formation porosity, as shown in Figure 4.

![Figure 2](image-url) Using the attenuation of neutron-induced gamma rays to measure the electron density of the formation.

![Figure 3](image-url) Origin of inelastic gamma rays used in the NGD measurement (top view with tool in the borehole and formation around it; results from – MCNP modeling)
The count rate in the detector is largely determined by three effects:

- Attenuation of the fast neutron flux from the source to the point of gamma ray production
- Magnitude of the inelastic gamma ray production cross section at the point of origin
- Gamma ray attenuation from the point of origin to the detector, which is a strong function of the electron density of the formation

The principal influence on detector count rate comes from the attenuation of the fast neutron flux and the attenuation of the gamma rays, not from the inelastic gamma ray production cross section (Figure 5).

The NGD measurement is made possible by compensating for the attenuation of the fast neutrons that generate the inelastic gamma rays (inelastic gamma rays can only be produced by fast neutrons, since the energy threshold for inelastic reactions is high). If the neutron attenuation can be accounted for, then the remaining effect is due to gamma ray attenuation (as in the GGD measurement), since the gamma ray production cross sections have only a small impact on the result.

The attenuation of neutrons from the source to the point of gamma ray production is inferred by using the neutron detectors (\(^{3}\)He tubes) in the tool, which are used to measure neutron porosity. Their count rates provide a measure of the attenuation that the neutrons experience in passing through the formation. This is used in the NGD measurement to compensate for the attenuation of neutrons from the source to the point of gamma ray production in the formation.

The response of a gamma ray detector spaced far from the neutron source versus formation density is shown in Figure 5 (black curve). The dependence of the LSn detector inelastic count rate is not linear (on a log scale) versus density. Instead, it first decreases with increasing density like a traditional GGD measurement, but then
passes through a minimum and begins to increase with a further increase in density. This behavior reflects the fact that there are two types of attenuation in play: neutron attenuation and gamma ray attenuation. The change of neutron attenuation with increasing density (decreasing porosity) increases the LSn detector count rate (blue curve), while the gamma ray attenuation (red curve) decreases the LSn detector count rate with increasing density. The combination of the two effects produces the minimum in the overall LSn detector response (black curve).

Compensation for the neutron transport effects results in a response that depends only on gamma ray attenuation. This is confirmed by plotting the neutron transport-corrected count rate versus the density of the formation as shown in Figure 6.

All neutron attenuation effects having been removed; the remaining response is due to the attenuation of gamma rays from the point of origin in the formation to the detector and should show the same behavior as the GGD and exhibit a logarithmic dependence on density. The results shown in Figure 6 let us conclude that the neutron attenuation effects have been accounted for properly.

Environmental effects

Since the neutron source is not focused, the borehole size and borehole fluid density influence the response. Investigations show that the NGD response is subject to several environmental effects, similar to those of the traditional GGD measurement. The most significant effects are:

- Borehole size and standoff
- Mud weight
- Sigma (macroscopic thermal neutron capture cross section of the formation)

The effect of thermal absorbers is minimized by limiting the analysis to inelastic gamma rays. If thermal capture gamma rays were included, effects of thermal absorbers and in particular of the borehole and formation salinity would become more important.

Determination of the environmental effects is done with experimental data taken in a controlled environment at the Schlumberger Environmental Effect Calibration Facility (EECF). Over 300 measurements have been acquired covering sandstone, limestone and dolomite, different hole sizes, borehole fluids and formation fluids. The database has been expanded through modeling points using an experimentally benchmarked MCNP (MCNPX 2008) simulation, to cover shale and gas. Gaps in experimental data have been filled with results from the benchmarked model covering intermediate porosity formation, salinity and mud characteristics. We have used this method in the past to supplement our experimental data base for other measurements (Gyllensten et al. 2009). For the NGD measurement, over 400 modeling points have been added to the data base.

Benchmarking of the simulation – The first step in the simulation was to benchmark our results with experimental data. Figure 6 includes the comparison between the experimental data (diamonds) and the simulation results (squares) plotted on the long spacing (LSn) count rate spine. The overlay indicates very good agreement between modeling and experiment.

Environmental effects corrections – Borehole effects are due to borehole enlargement, mud weight and borehole salinity.

Since the NGD measurement is defined for an 8 ½-in. reference borehole size, enlargement of the borehole past this size requires the use of a caliper to account for this effect. An ultrasonic caliper measurement is used to correct the apparent density for borehole enlargement in a manner very similar to what is done for the neutron porosity measurement.

Similar to the GGD measurement, the mud weight affects the NGD measurement (see Table 1). The NGD mud weight correction is derived from experimental data and Monte-Carlo modeling.

Unlike GGD, mud salinity and formation sigma affect NGD because the process of computing the inelastic count rate does not completely remove all capture effects and small residual effects due to mud salinity and formation sigma remain. These are removed by using mud salinity values input by the user and sigma values provided by the tool’s sigma measurement.

Table 1 presents the error propagation of the different corrections. The most important sources of error are caliper and mud weight. Algorithm work continues to reduce the caliper dependency of the density response.

Table 1: Environmental effects and error propagation

<table>
<thead>
<tr>
<th>Environmental effects</th>
<th>Input error</th>
<th>NGD error (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caliper</td>
<td>0.254 cm (0.10 in.)</td>
<td>0.010</td>
</tr>
<tr>
<td>Mud weight</td>
<td>0.06 g/cm³ (0.5 lbm/gal)</td>
<td>0.012</td>
</tr>
<tr>
<td>Borehole salinity</td>
<td>50 ppk</td>
<td>0.010</td>
</tr>
<tr>
<td>Formation sigma</td>
<td>20 c.u.</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Tool effects – calibration

Thanks to the real time neutron output determination with the neutron monitor, the effect of source strength variations is removed from the calibration.
Consequently, the calibration is only needed to remove small tool-to-tool variations in detector, neutron source and shielding characteristics and minor differences in tool geometry and material composition.

The calibration is performed in a water tank. An aluminum sleeve is pressed against the tool to simulate a higher “formation” density. Four different measurements are acquired to obtain the calibration coefficients that match the response of each detector to that of the master tool. The redundancy and large dynamic range of the calibration measurements not only improve the accuracy of the calibration, they also provide for enhanced quality control.

Comparison of GGD and NGD specifications

Conventional GGD from the multifunction LWD service and NGD specifications are compared in Table 2. NGD values are given in borehole size up to 9 in. with the tool being run with an 8 ¼-in. stabilizer.

**Table 2: NGD and GGD specifications**

<table>
<thead>
<tr>
<th>Range</th>
<th>Neutron-Gamma Density</th>
<th>Gamma-Gamma Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision$^2$</td>
<td>1.7 to 2.9 g/cm$^3$</td>
<td>1.7 to 3.05 g/cm$^3$</td>
</tr>
<tr>
<td>(ROP, rate of penetration)</td>
<td>at 2.4 g/cm$^3$</td>
<td>at 2.5 g/cm$^3$</td>
</tr>
<tr>
<td></td>
<td>at 61m/h ROP</td>
<td>at 61m/h ROP</td>
</tr>
<tr>
<td>Accuracy: Clean sandstone, limestone, dolomite, Shale</td>
<td>0.018 g/cm$^3$</td>
<td>0.006 g/cm$^3$</td>
</tr>
<tr>
<td></td>
<td>0.015 g/cm$^3$</td>
<td>0.018 g/cm$^3$</td>
</tr>
<tr>
<td></td>
<td>0.045 g/cm$^3$</td>
<td>0.015 g/cm$^3$</td>
</tr>
<tr>
<td>Axial resolution$^3$</td>
<td>89 cm</td>
<td>36 cm</td>
</tr>
<tr>
<td></td>
<td>15 cm (enhanced resolution)</td>
<td></td>
</tr>
<tr>
<td>Depth of investigation (DOI)$^4$</td>
<td>25.4 cm</td>
<td>10.2 cm</td>
</tr>
</tbody>
</table>

The most important difference between NGD and GGD is the depth of investigation (DOI), which is about 2.5 times deeper for NGD compared to GGD, as shown in Figure 7. Therefore, NGD is less sensitive to shallow invasion. This can be particularly important in gas intervals where invasion often plays a significant role.

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1. GGD from multifunction service (Weller et al. 2005a, 2005b)
2. 3 depth level averages
3. Measurement resolution along the tool axis
4. DOI for a fresh water 33 p.u. sandstone formation

**Fig. 7 Comparison of DOI for NGD and GGD (MCNP modeling results) for fresh water invading a 20-p.u. gas-filled (0.2-g/cm$^3$ methane) limestone formation**

The range of the GGD measurement includes anhydrite, whereas the current NGD algorithm is not yet sufficiently accurate to extend the measurement beyond a density of 2.9 g/cm$^3$. No laboratory measurements are available for this environment and the modeling is challenged due to the absence of hydrogen in anhydrite and its high density, which require extremely accurate neutron transport correction.

The NGD measurement is based on an extended source of neutron-induced gamma rays. To enhance the contribution of the gamma ray attenuation, the gamma ray detector is positioned far from the source. This leads to a reduced count rate compared to GGD and a larger statistical uncertainty. The maximum recommended ROP for NGD and for all other neutron measurements is 61 m/h (200 ft/h). Precision can be improved by reducing ROP or by a future increase in the neutron output of the PNG.

The axial resolution indicated in Table 2 is the intrinsic resolution obtained with the LSn detector and does not include any enhanced resolution processing. In thin beds, the difference in axial resolution between NGD and GGD can make level-by-level comparisons of the two measurements more challenging, especially if enhanced resolution processing is used for GGD.

The larger DOI of NGD makes it less sensitive than GGD to tool motion in the borehole and therefore less dependent on well deviation.

Since the NGD measurement in this tool is not focused, its azimuthal sensitivity is poorer than that of GGD, and as a result images are not provided. Also, comparison should be performed with respect to the average GGD...
and not a quadrant measurement or image derived density.

**LOG QUALITY CONTROL**

Error quantification

The total uncertainty of a downhole formation property log value can be divided into the uncertainty in the primary measurement, in the applied corrections, and in the conversion of the measured parameters into the desired formation property. The algorithmic conversion takes into account the tool calibration and downhole conditions such as fluid type and mineralogy.

The uncertainties of the NGD and GGD measurements are listed in the measurement specifications in Table 2.

**Elements of the quality control system**

The quality control pyramid (Figure 8) shows a bottom-up approach to quality control, starting at the general tool system hardware, continuing to the specific sensor functions, the individual sensor measurements, the integrated measurement which may involve multiple individual sensor responses and, at the top of the pyramid, the final integrated answer products that may use multiple measurements. This comprehensive approach to quality control is well suited for the multsensor NGD measurement (Griffiths, 2010).

![Fig. 8 The quality control pyramid](image)

In addition, the diverse measurements provided by the multifunction tool offer a unique opportunity for constructing a unified quality control system. During the extensive worldwide field test, the NGD measurement was evaluated using this comprehensive quality control methodology from tool hardware to the comparison of integrated measurements.

**NGD quality control elements**

Through years of careful evaluation, the NGD log response has been refined and improved along with the corresponding quality control. Some of these quality control indicators are driven by the physics of the NGD measurement; others are specific to the algorithm and the operating environment range.

Hardware Quality Indicators – The base of the NGD quality pyramid is formed by the hardware quality control indicators. NGD is characterized for a nominal borehole size of 8½ in. using an 8¼-in. stabilizer. The sensor and systems hardware must be functioning.

Measurement Quality Indicators – The principal measurement quality indicator is whether the density value is within the range of the neutron-gamma density RHON – specified as 1.7 to 2.9 g/cm³. An intermediate output of the processing, which indicates the impact of standoff, can be used to further qualify the accuracy of the measurement. This output indicates whether standoff contributes to the measurement, and provides a similar quality control as the delta-rho correction for GGD.

Environmental Quality Indicators – This level considers the environmental quality indicators. For NGD important factors are borehole size, deviation, rate of penetration, and formation shaliness.

Borehole size is an input to the NGD measurement. This input is provided by the ultrasonic caliper measurement, allowing correction for the impact of the borehole (mud weight and standoff) on the NGD.

The well deviation is an important factor due to its effect on tool standoff from the formation. In a vertical or near vertical well, it is difficult to control tool movement and consequently predict the data quality of both GGD and NGD due to possible lack of borehole contact.

The ROP impacts the measurement precision as explained earlier.

Fast neutron transport and sigma effects play a significant role in shale. The NGD measurement is generally less accurate in formations containing a large volume fraction of shale. The neutron-density crossover (NDX) computation is a numerical expression of the density-porosity crossover, and may indicate the presence of gas, when it is negative or shale when it is positive. The appropriate matrix end points are applied to compute neutron porosity and density porosity from NGD in various clean lithologies (sandstone, limestone, and dolomite). A cutoff value is used to indicate zones with substantial proportions of shale or gas.

In shale, an accuracy of ±0.045 g/cm³ can be obtained up to an “NDX Value” of 0.2. Above this, the accuracy could be impaired by residual shale effects, especially where the presence of heavy elements is expected. As an example, a clay mineral with a significant impact on
the NGD response is glauconite. Large volumes of shale (NDX > 0.2) may lead to larger uncertainties.

The NGD measurement is environmentally corrected for the macroscopic capture cross section of the formation (sigma). The correction has been successfully validated on log data up to 40 c.u.

**Quality flag definition**

The individual quality control indicators are combined into a measurement quality control flag, which can be “green”, “yellow” or “red”. This log quality control flag was built with a conservative approach. A green flag indicates the measurement accuracy is considered to be within the specified limits (Table 2). A yellow flag indicates the measurement result is likely still within specified accuracy, but further interpretation is required to validate the measurement response.

NGD is typically benchmarked with GGD. However, a direct comparison to GGD may not always be valid. For example, the yellow range includes conditions in which standoff cannot be controlled. This will affect both GGD and NGD measurements to different extents and can cause them to provide different results. NGD is considered to be less sensitive to standoff than GGD because of its deeper DOI. Another example, where a direct comparison cannot be made, is when anhydrite is encountered in the well.

A red quality flag indicates that the measurement is run outside of its specifications.

**Measurement integration**

The multifunction logging-while-drilling service offers the unique possibility of integrating an entire suite of measurements, and to obtain better quality control by making use of neutron porosity (HI), spectroscopy, ultrasonic caliper, sigma and well inclination measurements.

**FIELD TEST RESULTS**

NGD was thoroughly field tested and compared to GGD in a large number of datasets from all over the world. This was made possible through a modified multifunction tool that provided simultaneous acquisition of GGD and NGD data in the same well, from the same bottom-hole-assembly. This simultaneous acquisition of traditional and sourceless density offered an ideal opportunity to characterize the measurement in a wide variety of environments, with negligible difference in external conditions such as time delay and the concomitant potential change in invasion, borehole fluid and/or borehole size.

Through extensive field data analysis during almost a decade, the most representative conditions have been selected in order to quantify the full measurement response. The conditions include, but are not limited to, clean formations of sandstone, limestone, and dolomite; anhydrite as well as shale and heavy shale; gas and light hydrocarbon reservoirs; large borehole sizes; deviated and vertical wells.

These datasets were subject to a detailed comparison between NGD and GGD. The GGD measurement has been qualified and characterized prior to its use as the benchmark. When benchmarking NGD to GGD, the differences and limitations of both measurements must be taken into account. Specifications of NGD and GGD are detailed in Table 2. For the field test, the acceptance criteria were based on a systematic evaluation of parameters of both measurements, to apply an objective, repeatable, and consistent evaluation to all datasets. The analysis is based on a set of numerical and “interpretation” criteria.

Since two independent measurements are compared, the maximum acceptable error is defined as the sum of the individual accuracies (Theys 1991):

- Total error: 0.040 g/cm³
- Total error in shale: 0.060 g/cm³

A straight line $y = f(x) = ax + b$ is fit through the data cloud of each NGD-GGD crossplot. The deviation of this curve fit from perfect agreement ($a = 1$, $b = 0$) is quantified.

Environmental conditions are different in each well. These may include invasion, the presence of gas or light hydrocarbons, and various drilling conditions. All these factors may have an impact on the GGD/NGD comparison. If a large discrepancy can be explained in terms of an evident environmental effect (e.g.: invasion), the test is considered passed.

Reasons for explainable differences are:

- Evidence of invasion and consequent difference in measurement response because of different measurement depths of investigation
- “Sliding” (drilling without rotation of the pipe) resulting in the GGD being unable to provide an average density around the borehole for comparison to the NGD measurement
- Differences in axial resolution

Globally, the field test showed good agreement between NGD and GGD. This section will display some case studies and compare the performance of NGD with traditional GGD.

Figures 9 through 12 display field examples 1 through 4. All examples were obtained in boreholes drilled with an 8 ½-in. bit. The LWD tool was configured with an 8 ¼-in. diameter stabilizer on the GGD section.
Fig. 9 Field example 1: This is a shaly sand example from Egypt. NGD RHON, shown in track 5 in black agrees well with GGD RHOB, shown in red, and is within accuracy limits. The green NGD quality control flag confirms this result.
Fig. 10 Field example 2: This is an example of shaly sand with gas from West Africa. The quality control suggests that the data quality in shale needs a closer look. Data review shows the NGD response is reasonable, and RHON agrees well with RHOB. No discernible invasion is present in gas zones and NGD provides a good gas response.
Fig. 11 Field example 3: This is a limestone example from the Cameron test facility in the US. Two sections of the well are shown. The upper section is flagged yellow because of a major hole enlargement. However, RHON is less affected due to its deeper depth of investigation and hence more reliable than the GGD in this condition. RHON and RHOB agree in the clean limestone interval displayed in the lower panel (x40 to x100 feet).
Fig. 12 Field example 4: This is a second limestone example from the Cameron test facility. Two different sections of the well are shown. The response in this well is good and shows the effects of the different axial resolutions of NGD and GGD.
**Field Example 1**

This shaly sand example from Egypt is shown in Figure 9. The well was drilled using 1.26 g/cm³ (10.5 lbm/gal) water-base mud. The average well inclination is approximately 60°.

- The calipers indicate the borehole is in gauge.
- The density correction on GGD (DRHO) implies no correction is needed, as expected when the borehole is in gauge. The quadrant GGD (ROBB, ROBU, ROBL, ROBR) indicates no major azimuthal effects.
- Sigma (SIFA) is lower than 20 c.u., and therefore in a range in which the sigma correction on NGD is minimal.

The formation is hydrocarbon bearing in the upper section (10 to 40 feet of log) and the resistivity (in track 3) shows signs of invasion in the hydrocarbon bearing interval. NGD and GGD are slightly different because of their different DOI's.

The bottom section of the well (60 to 90 feet of log) is a water-bearing sand, and NGD and GGD are almost identical, (i.e. provide good overlay). NGD is within accuracy limits throughout the well and this is evident from the RHON–RHOB crossplot shown in Figure 13.

![Crossplot of GGD (RHOB) versus NGD (RHON) in the log interval shown in Figure 9. The data are color-coded by their quality flag value. The data align well along the ideal axis and are flagged as “green”. Invasion effects start to occur in the lower density range at ~ 2.3 g/cm³. The spread of the data points around the diagonal is caused by the different axial resolution of the two measurements while crossing different layers at high deviations.](image1.png)

**Field Example 2**

Figure 10 shows a shaly gas sand example from West Africa. The well was drilled with 1.27 g/cm³ (10.6-1bm/gal) oil-base mud. The average well inclination is approximately 70°. The caliper indicates the borehole is in gauge.

The shaly interval in the top 12.2 m (40 ft) of the log is flagged mostly “green” and partially “yellow” based on the formation sigma and the relatively large shale volume. Spectroscopy indicates traces of siderite, and thus heavy elements. The measurement is in agreement with gamma ray and spectroscopy hence the data appear reasonable.

The shaly interval in the bottom 9.14 m (30 ft) of the log, between 36.6 to 45.7 m (120 to 150 feet), is flagged yellow, where the caliper exceeds 22.9 cm (9 in.). Spectroscopy and gamma ray measurements indicate shale, and the density image suggests layering. The large borehole size (greater than 9 in.) and increased shaliness degrade the measurement accuracy.

The NGD quality control signals good response in the gas zones and light hydrocarbon bearing zones (between 40 and 120 feet). Resistivity (in track 3) does not show signs of invasion, and both NGD and GGD are in agreement.

The effectiveness of the log quality control flag is highlighted on a GGD and NGD crossplot color coded with the quality control values (Figure 14). The data flagged yellow indicate increasing measurement uncertainty.

![GGD (RHOB) versus NGD (RHON) in the log interval shown in Figure 10, color coded by their quality control value. Gas-bearing sand flagged green aligns along the diagonal of the crossplot. An increase in shaliness causes NGD to slightly underestimate the true density. In combination with increasing caliper, the uncertainty increases, and the data are flagged as](image2.png)
yellow. The spread of the points is caused by the different axial resolution of the two measurements while crossing different layers at high wellbore deviation.

Field Example 3

Figure 11 shows a limestone example from the Cameron test facility (CTF) in the US. The well was drilled with 1.13 g/cm³ (9.4-lbm/gal) water-base mud. The average well inclination is approximately 25°.

The caliper shows hole enlargement in the upper section of the well at about 10 – 20 feet of log. The NGD quality control flag is yellow, and NGD and GGD are substantially different. The caliper shows that the borehole is in gauge otherwise. The density correction on GGD is within 0.1 and 0.15 g/cm³ over the entire displayed interval. The relatively high DRHO would suggest the borehole is enlarged, in contradiction to the caliper information. This implies uncertainties in GGD. The interval, in which the enlargement occurs shows, if anything, a decrease in the DRHO correction. The washout causes the upper and, to a lesser extent, the left quadrant densities to underestimate formation density. The bottom and right measurements are closer to the expected density, while the average density follows the left quadrant density. This leaves the impression of undercompensation of the average GGD where the hole enlargement occurs. NGD is borehole corrected by the caliper, and because of its deeper DOI is less influenced by variations in the near-borehole environment. The NGD curve tracks the porosity curve BPHI as expected in clean formations. In this example of enlarged hole, NGD appears more reliable than the GGD.

The log quality control flag indicates a reliable NGD response in the bottom section between x40 and x100 feet of log. The comparison of RHOB with RHON shows that GGD and NGD are in agreement in clean limestone. The drilling mode was sliding at x50 feet of log, indicated by a drop of collar rotational speed (CRPM) to zero. Even though sliding can be a cause of an explainable difference between NGD and GGD, this example indicates good agreement. The cross plot in Figure 15 shows that the NGD data flagged green agree well with GGD.

Field Example 4

Figure 12 shows another limestone example from the Cameron test facility located in the US. The well was drilled with 1.14 g/cm³ (9.5-lbm/gal) water-base mud. The well is building from 15° to approximately 45°. Ultrasonic caliper and density caliper indicate the borehole is in gauge.

NGD is within accuracy limits throughout the well and is of good quality. The difference in axial resolution of the two measurements is evident.

The density image indicates layering and a change in formation composition and these layers are reflected in the GGD measurement. Variations of gamma ray, spectroscopy and resistivity measurements confirm this compositional change. However, GGD has sharper axial resolution and hence greater ability to pick up thin layers and the respective compositional change. A good place to observe this effect is in the upper 9 m (30 ft), just below the 20-ft mark, where RHOB is relatively active compared to RHON.

Globally, the NGD response in this well correlates well to GGD as shown in Figure 16.
Neutron-density crossplot

NGD interpretation techniques are identical to those developed for traditional density measurements. A neutron-density crossplot from NGD (Figure 17) is similar to one obtained from GGD (Figure 18), and helps to identify gas and define lithology and porosity (Reichel et al. 2011).

Fig. 17 Multiwell neutron-density crossplot using NGD across the displayed intervals of field examples 1–4.

Fig. 18 Multiwell neutron-density crossplot using GGD across the displayed intervals of field examples 1–4.

CONCLUSIONS

A significant advance in sourceless formation evaluation has been made with the introduction of a PNG-based NGD measurement. Field tests have provided valuable comparisons with the traditional density. Four examples covering various environmental conditions show the strengths of the new measurement and its log response. Combined with a detailed quality control system making use of the multitude of collocated and nearly collocated measurements, it is possible to assess the quality of the new measurement and its limitations.

ACKNOWLEDGMENTS

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>RHON</td>
<td>Neutron-gamma density average [g/cm³]</td>
</tr>
<tr>
<td>RHOB</td>
<td>Compensated gamma-gamma density average [g/cm³]</td>
</tr>
<tr>
<td>ROBB/ ROBL/ ROBR/ ROBU</td>
<td>Compensated gamma-gamma density from bottom/ left/ right/ upper quadrant [g/cm³]</td>
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<tr>
<td>DRHO</td>
<td>Density correction applied to average gamma-gamma density [g/cm³]</td>
</tr>
<tr>
<td>IDRO</td>
<td>Image derived density [g/cm³]</td>
</tr>
<tr>
<td>ROSI</td>
<td>Density image</td>
</tr>
<tr>
<td>UCAV</td>
<td>Ultrasonic caliper [in.]</td>
</tr>
<tr>
<td>DCAV</td>
<td>Density caliper [in.]</td>
</tr>
<tr>
<td>BPHI</td>
<td>Thermal neutron porosity average [ft³/ft³]</td>
</tr>
<tr>
<td>GRMA</td>
<td>Gamma ray average [gAPI]</td>
</tr>
<tr>
<td>SIFA</td>
<td>Formation neutron capture cross section [c.u.]</td>
</tr>
<tr>
<td>A16/22/28/34/40H</td>
<td>Attenuation resistivity [ohm-m]</td>
</tr>
<tr>
<td>P16/22/28/34/40H</td>
<td>Phase shift resistivity [ohm-m]</td>
</tr>
<tr>
<td>DEVI</td>
<td>Deviation [degrees]</td>
</tr>
<tr>
<td>CRPM</td>
<td>Collar revolutions per minute</td>
</tr>
<tr>
<td>LSn</td>
<td>Long spacing detector</td>
</tr>
<tr>
<td>LWD</td>
<td>Logging-While-Drilling</td>
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</tbody>
</table>

REFERENCES


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