A new neutron-gamma density measurement method using mass attenuation coefficient function

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Abstract

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Full Text

A New Neutron-Gamma Density Measurement Method Using Mass Attenuation Coefficient Function

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While traditional gamma-gamma density (GGD) logging technology is widely utilized, its potential environmental risks have prompted the development of more environmentally friendly neutron-gamma density (NGD) logging technology. However, NGD measurements are influenced by both neutron and gamma radiation. In the logging environment, variations in formation composition indicate different elemental compositions, which affect neutron-gamma reaction cross-sections and gamma generation. Compared to traditional gamma sources such as Cs-137, these changes can significantly impact the generation and transport of neutron-induced inelastic gamma rays, posing challenges for accurate measurements. To address this, a novel method is proposed that incorporates the mass attenuation coefficient function to account for the effects of various lithologies and pore contents on gamma-ray attenuation. This approach can achieve more accurate density measurements by clarifying the transport processes of inelastic gamma rays with varying energy and spatial distributions in varied logging environments. The method avoids the complex correction of neutron transport and is verified through Monte Carlo simulations for its applicability across various lithologies and pore contents, showing that the absolute density errors are less than 0.02 g/cm^3 in clean formations and demonstrating good accuracy. The research not only clarifies the NGD mechanism but also provides theoretical guidance for the application of NGD logging methods. Further research will be conducted regarding extreme environmental conditions and tool calibration.

Keywords: Neutron-gamma density, Mass attenuation coefficient, Monte Carlo simulation

INTRODUCTION

In the field of petroleum exploration, traditional gamma-gamma density (GGD) logging technology has played a crucial role for many years [1–5]. However, with growing awareness of environmental protection, the risks of pollution and operational safety associated with GGD technology have become increasingly apparent, posing challenges to its further development. In this context, neutron-gamma density (NGD) logging technology has emerged as a new research focus due to its advantage of environmental protection and controllability [6–10]. GGD relies on the transport of monoenergetic gamma rays from the source to the detectors, while NGD is based on the transport of neutron-induced gamma rays, whose energy exhibits uncertainty. In NGD, the gamma rays detected by the detector are influenced by neutron transport from the neutron source to the point of the gamma ray producing neutron interaction in the formation and by the subsequent transport of the gamma rays from their source to the gamma-ray detector. To eliminate the influence of thermal neutron effects, density measurements are conducted using inelastic gamma rays produced by high-energy neutrons [11, 12]. Once neutrons are emitted, they undergo inelastic scattering reactions with isotopes of crucial elements in the medium in a few microseconds, producing inelastic gamma rays. These gamma rays are less influenced by neutron transport, enabling them to more accurately reflect formation characteristics, making them more suitable for density measurements. However, evaluating inelastic gamma rays can be tricky because it depends on both neutron and gamma physics and undergoes multiple physics processes simultaneously. Hence, the entanglement between neutron and gamma transport increases the complexity of the measurement and its sensitivity to its environment. The generation and attenuation of inelastic gamma rays are directly influenced by environmental factors such as lithology, porosity, and fluid properties. It is critical to understand both neutron and gamma physics pertaining to changing environments in order to develop an accurate method for NGD technology [13–15].

The development of neutron-gamma density (NGD) technology has been actively ongoing for the past few decades. For instance, Odom et al. used inelastic gamma rays for density measurements, which advanced density logging technology based on the neutron-gamma coupled field theory [16, 17]. However, this method is affected by neutron transport, and neutron transport correction needs to be considered in subsequent studies. Jacobson et al. developed a correction technique that employs capture gamma count ratio to obtain a compensated inelastic gamma ratio, achieving the density measurements [18]. Zhang et al. developed a density method by using the inelastic gamma-count ratio and the fast-neutron count to avoid neutron correction [19]. Luycx et al. approximated the initial inelastic gamma flux by fast neutron counts for density measurements [20]. Wang et al. created a correction model utilizing epithermal neutrons and divided the inelastic gamma-ray energy spectrum into high- and low-energy windows to reduce the influence of Pair production [21]. Additionally, Zhang et al. introduced an adaptive method for obtaining inelastic gamma spectra while environment changes and integrated capture correction for density measurement [22]. While these studies have made progress, most researchers focused more on analyzing the neutron transport process and less on the dynamic changes in gamma attenuation process. Inelastic gamma rays generated by neutron-induced reactions exist in formations in a non-monoenergetic distribution, whereas chemical sources like Cs-137 generate monoenergetic gamma in a homogeneous manner. Furthermore, typical neutron-induced gamma rays can reach energies up to 8 MeV [23]. Pair production needs to be considered as it plays a vital role in the neutron-induced gamma transport process. These factors contribute to the complexity of gamma attenuation. Previous neutron-gamma density (NGD) and gamma-gamma density (GGD) provide possibilities for density measurements. However, most previous NGD methods consider mass attenuation coefficient as a constant, which limits accuracy because it is closely related to the formation composition. In our work, we introduce mass attenuation coefficient as a function related to formation lithologies and pore contents in order to accurately depict the intricate interaction mechanisms between radiation and formation, which is essential in obtaining accurate formation density. This can also provide a new approach to complement previous methods.

The manuscript is organized as follows: Section 2 introduces the method and presents the development process. Also, a pulsed neutron density tool is described, which later is employed for concept verification. Section 3 presents the results from different simulated scenarios, demonstrating the method's effectiveness. Finally, conclusions are drawn in Section 4.

II. METHOD

The development of the method is shown in Fig. 1: Box 1 reviews the coupled field theory of neutron-gamma density (NGD) measurement, which is the foundation for the proposed method as it depicts inelastic gamma rays' distribution. Box 2 is key to the method: a function for mass attenuation coefficient is developed, which is then used to derive density. Certain key parameters, such as the hydrogen index cannot be directly expressed in this mathematical form; instead, they are obtained through tool measurement. Box 3 presents analysis of physical parameters using a real NGD tool under development stage. Extensive Monte Carlo simulations are conducted to establish a quantitative relationship between detector responses and formation physical parameters, which is consequently utilized to obtain these key parameters. Finally, density is calculated. Overview of the method is illustrated in Fig. 1.

A. Coupled Field Theory of NGD Measurement

NGD logging technology relies on inelastic gamma rays to measure formation density [24–29]. The distribution of inelastic gamma rays involves two interconnected links of neutron and gamma transport [30–32]. The detailed process is discussed as below:

The pulsed neutron source emits 14 MeV fast neutrons. In a spherical model, according to neutron diffusion theory, the distribution of fast neutrons can be described as follows:

$$\Phi_n(r) = \frac{Q}{4\pi D_n r} \exp\left(-\frac{r}{L_n}\right)$$

where Q is the number of neutrons emitted by the neutron source per second, D_n is the neutron diffusion coefficient, L_n is the fast neutron deceleration length, and r is the distance between the pulsed neutron source and the neutron detector.

The inelastic gamma rays recorded by a detector with a radius R can be described by the following equation [21]:

$$\Phi_{in}(R) = i\Sigma_{in}Q\int_0^{\infty}\frac{1}{4\pi D_n R}\exp\left(-\frac{r}{L_n}\right)\exp(-\rho\mu_m|r-R|)dr$$

where i is the average number of inelastic gamma rays after neutron enters the formation, Σ_{in} is the inelastic scattering cross section, ρ is the formation density, and μ_m is the total mass attenuation coefficient. The inelastic gamma rays within the distance from the source R are recorded [33], and Eq. (2) can be written as:

$$\Phi_{in}(R) = \frac{i\Sigma_{in}Q}{4\pi D_n R}\frac{\exp\left(-\frac{R}{L_n}\right)-\exp(-\rho\mu_m R)}{\rho\mu_m-\frac{1}{L_n}}$$

According to the Lagrange interpolation method, Eq. (3) can be simplified as follows:

$$\Phi_{in}(R) = \frac{i\Sigma_{in}Q}{4\pi D_n R}\exp(-R\xi)$$

where

$$\xi = \frac{1}{L_n}-\alpha\left(\frac{1}{L_n}-\rho\mu_m\right), \quad \alpha\in(0,1)$$

Assuming that the source distances of the near and far gamma detectors are L_1 and L_2 ($L_1 < L_2$), the following equations can be obtained:

$$\begin{cases}\Phi_{in}(L_1) = \frac{i\Sigma_{in}Q}{4\pi D_n L_1}\exp(-L_1\xi_1)\\ \Phi_{in}(L_2) = \frac{i\Sigma_{in}Q}{4\pi D_n L_2}\exp(-L_2\xi_2)\end{cases}$$

where:

$$\begin{cases}\xi_1 = \frac{1}{L_n}-\alpha_1\left(\frac{1}{L_n}-\rho\mu_m\right), & \alpha_1\in(0,1)\\ \xi_2 = \frac{1}{L_n}-\alpha_2\left(\frac{1}{L_n}-\rho\mu_m\right), & \alpha_2\in(0,1)\end{cases}$$

The logarithm of ratio of near and far inelastic gamma counts is as follows:

$$\ln(R_{IN}) = \ln\left(\frac{\Phi_{in}(L_1)}{\Phi_{in}(L_2)}\right) = \ln\left(\frac{L_2}{L_1}\right)+L_1\alpha_1-L_2\alpha_2+L_2-L_1+(L_2\alpha_2-L_1\alpha_1)\rho\mu_m$$

NGD logging technology relies on inelastic gamma rays to measure formation density [24–29]. The distribution of inelastic gamma rays involves two interconnected links of neutron and gamma transport [30–32]. The detailed process is discussed as below:

Suppose $a = L_1\alpha_1 - L_2\alpha_2 + L_2 - L_1$, $b = L_2\alpha_2 - L_1\alpha_1$, Eq. (7) can be reorganized:

$$\ln(R_{IN}) = a + b\rho\mu_m$$

Eq. (8) shows that the response of gamma-ray detector is related to the L_n, ρ, μ_m, and the value of a, b. The fast neutron deceleration length, L_n in typical formations can be characterized by the formation density ρ, the hydrogen index I_H, and the initial energy of fast neutron E_0 [34]:

$$L_n = k\sqrt{\frac{1}{I_H + c}}\sqrt{\ln(E_0)}$$

The key parameter in Eq. (8) is the mass attenuation coefficient μ_m, which directly reflects the attenuation of gamma rays in formations. The section below will focus on analyzing this parameter.

B. NGD Method Development

The attenuation of gamma rays in formations is closely linked to formation density and the mass attenuation coefficient. This attenuation process is primarily influenced by various physics processes, including the Photoelectric effect, Compton effect, and Pair production. Especially for high-energy gamma rays, Compton effect and Pair production are the main factors affecting their attenuation. Thus, the total attenuation coefficient μ_m can be expressed as follows:

$$\mu_m = \mu_{co} + \mu_{pa}$$

where μ_{co} is the mass attenuation coefficient for Compton effect, μ_{pa} is the mass attenuation coefficient for pair production.

According to the principles of Compton effect and Pair production [35, 36], the mass attenuation coefficient of Compton effect and Pair production can be expressed as:

$$\mu_{co} = \frac{2\pi(r_0)^2 N_A}{A}\left\{\frac{1+\eta}{\eta^2}\left[\frac{2(1+\eta)}{1+2\eta} - \frac{\ln(1+2\eta)}{\eta}\right] + \frac{\ln(1+2\eta)}{2\eta} - \frac{1+3\eta}{(1+2\eta)^2}\right\} Z$$

$$\mu_{pa} = \frac{(r_0)^2 N_A}{A} \left(\frac{\ln(2\eta) - 1}{\eta} \right) (Z + 1)$$

where N_A is Avogadro constant, r_0 is the classical electron radius ($r_0 = 2.818 \times 10^{-13}$ cm), $\eta = \frac{E_\gamma}{m_{ec}^2}$, E_γ is the gamma-ray energy, m_e is the electron rest mass ($m_e = 9.110 \times 10^{-31}$ kg), c is the speed of light in a vacuum ($c = 2.998 \times 10^8$ m/s), Z is the atomic number, A is the atomic weight. The total mass attenuation coefficient can be rewritten as:

$$\mu_m = \frac{\pi(r_0)^2 N_A}{A} \left\{ \frac{1+\eta}{\eta^2} \left[\frac{2(1+\eta)}{1+2\eta} - \frac{\ln(1+2\eta)}{\eta} \right] + \frac{\ln(1+2\eta)}{2\eta} - \frac{1+3\eta}{(1+2\eta)^2} \right\} Z + \frac{(r_0)^2 N_A}{A} \left(\frac{\ln(2\eta) - 1}{\eta} \right) (Z+1)$$

Eq. (13) shows the impact of gamma-ray energy E_γ and formation atomic number Z on the mass attenuation coefficient μ_m, highlighting the response sensitivity among these variables. This work emphasizes the variability of the mass attenuation coefficient, which is different from previous studies where the mass attenuation coefficient was typically assumed to be constant. While changes in the mass attenuation coefficient within the average energy range of inelastic gamma rays in formations are small enough to have the effect of gamma energy ignored [37], its close correlation with the formation's composition is emphasized, particularly the effects of lithology and pore content on the macroscopic atomic number (Z). To further prove this point, Fig. 2 is shown which represents the difference in formation's macroscopic atomic numbers when the lithology and porosity content change. These changes in lithology and pore content indicate variations in the constituent elements of the formation, which directly affect the formation macroscopic atomic number (Z), resulting in alterations to the total mass attenuation coefficient. This affects gamma rays' attenuation, thereby complicating gamma-ray transport. So, the mass attenuation coefficient is treated as a function related to the formation lithology (l) and pore content (p). Accurate measurement of density can be achieved by describing the influence of different formation components on the gamma transport process.

[Figure 2: see original paper]

According to the above analysis, treating mass attenuation coefficient as a function pertaining to environmental parameters will better depict gamma-formation reaction sensitivity and thus enable more accurate NGD calculations:

$$\mu_m(l, p) = c + d(Z(l, p) + 1)$$

where

$$c = \frac{\pi(r_0)^2 N_A}{A} \left\{ \frac{1+\eta}{\eta^2} \left[\frac{2(1+\eta)}{1+2\eta} - \frac{\ln(1+2\eta)}{\eta} \right] + \frac{\ln(1+2\eta)}{2\eta} - \frac{1+3\eta}{(1+2\eta)^2} \right\}$$

and

$$d = \frac{(r_0)^2 N_A}{A} \left(\frac{\ln(2\eta) - 1}{\eta} \right)$$

where c and d are constants.

After substituting the mass attenuation coefficient μ_m from Eq. (14) into Eq. (8), the equation can be reformulated as follows:

$$\rho = \frac{e \ln(R_{IN}) + f}{\sqrt{c + d(Z(l,p) + 1)}}$$

This expression is composed of two key parameters: the fast neutron deceleration length L_n and the formation's macroscopic atomic number Z, and L_n is related to the formation density and the hydrogen index. These physical parameters cannot be directly measured; instead, they can be derived through the analysis of detector responses. Consequently, in the next section, we present a real pulse neutron logging tool and construct a high-fidelity Monte Carlo model for the analysis of these physical parameters.

C. Analysis of Physical Parameters Using NGD Tool

Geant4 (Geometry and Tracking 4), an open-source Monte Carlo platform, is used for simulations. The tool model, shown in Fig. 3, has a total length of 2328 mm and a diameter of 188 mm, featuring four neutron detectors and two gamma detectors. To minimize the impact of water in the mud pipe on neutron detection, a boron-containing shield is positioned at the base of the neutron detectors. Additionally, the near gamma detector is used not only for density measurement but also for formation sigma and elemental measurements. To reduce interference from capture gamma rays generated by the tool's interaction with thermal neutrons, a two-layer shielding structure is implemented. A cubic space measuring 6 × 6 × 6 m is designated to simulate formation environment, with a borehole diameter of 215.9 mm, positioning the tool at the center of the borehole. This tool is currently undergoing construction and will be deployed in the field upon completion. Therefore, it is selected to verify the feasibility of the proposed method. Extensive simulations are conducted using a NGD tool model, incorporating various formation lithologies (limestone, sandstone, dolomite) and porosity ranges (0–40 p.u.). These simulations aim to establish the relationship between detector responses and relevant physical parameters in Eq. (17) and therefore will be used for concept validation.

[Figure 3: see original paper]

The specific relationships are as follows:

(a) Hydrogen index (I_H)
The correlation between hydrogen index and detector responses is analyzed using simulation data. Fig. 4(a) presents the correlation coefficients between various detector responses and hydrogen index. These coefficients measure the strength of the linear relationship between the variables, with values closer to 1 indicating a strong correlation. This analysis helps identify the optimal response for representing the hydrogen index. In Fig. 4(a), the features represent various detector counts: FN_1 and FN_2 correspond to near and far fast neutron counts, ETN_1 and ETN_2 to near and far epithermal neutron counts, and CAP_1 and CAP_2 to near and far capture gamma counts. Additionally, RFN, $RETN$, and $RCAP$ represent the respective ratios of fast neutrons, epithermal neutrons, and capture gamma counts. As shown in the figure, the ratio of near to far epithermal neutron counts ($RETN = ETN_1/ETN_2$) exhibits the strongest correlation with the hydrogen index, making $RETN$ the most effective indicator of hydrogen content among all detector responses.

(b) Formation density (ρ)
To accurately represent formation density, correlation analysis is applied to evaluate the relationships between various detector responses and density. In Fig. 4(b), IN_1 and IN_2 represent near and far inelastic gamma counts, while CAP_1 and CAP_2 represent near and far capture gamma counts. R_{IN} is the ratio of near to far inelastic gamma counts, expressed as $R_{IN} = IN_1/IN_2$, and $RCAP$ is the ratio of near to far capture gamma counts. As shown in Fig. 4(b), R_{IN} exhibits the strongest correlation with density, making it the optimal parameter for describing density in Eq. (17). This is also consistent with NGD physics principle [38, 39].

(c) Formation macroscopic atomic number (Z)
The macroscopic atomic number Z, an inherent characteristic of the formation, is closely influenced by lithology and pore contents. By analyzing the detector counts within a specific energy window (0.07 to 0.35 MeV), denoted as N_{lith}, a relationship can be established to represent macroscopic atomic number. As shown in Fig. 4(c), this method allows for the derivation of Z from the detector responses, using counts within the designated energy range to effectively characterize the formation's macroscopic atomic number.

To summarize, density, hydrogen index, and formation macroscopic atomic number Z can be represented using R_{IN}, $RETN$, and N_{lith}, all of which can be obtained from detector counts. Since the root term in the represented equation complicates the acquisition of calibration coefficients, a polynomial fit approach was used to simplify the equation, as shown in Fig. 4(d). After substituting the root term with a second-degree expression, previous Eq. (9) can be rewritten:

$$L_n = \sum_{m=0}^{2} \beta_m (\ln(RETN))^m$$

By substituting the L_n expression into Eq. (17), the density equation can be obtained:

$$\rho = \frac{\ln(R_{IN}) \times \sum_{m=0}^{2} \beta_m (\ln(RETN))^m}{\theta_2 (N_{lith})^2 + \theta_1 N_{lith} + \theta_0}$$

where β_0, β_1, β_2, θ_0, θ_1, θ_2 are the fitting parameters. From Eq. (19), the formation density is determined by three parameters: the ratio of inelastic gamma counts R_{IN}, the ratio of epithermal neutron counts $RETN$, and the count N_{lith}. The coefficients in the above equation are obtained using the Levenberg-Marquardt method.

[Figure 4: see original paper]

III. RESULTS AND DISCUSSIONS

To prove the effectiveness of developing mass attenuation coefficient function, we compare two approaches for treating the mass attenuation coefficient: as a constant versus as a function of formation composition. The results demonstrate that treating it as a function can significantly enhance calculation accuracy, demonstrating the effectiveness of the method. Next, we assess the method's performance across various environments, focusing on two critical factors: formation lithology and pore content. Finally, we present three test cases to validate the method's applicability in complex formations. The absolute errors are used to evaluate the calculated density results, as expressed in Eq. (19). When the absolute errors are less than the threshold of 0.025 g/cm^3, the calculated results are considered accurate [40].

$$\text{Error} = |D_T - D_C|$$

where Error represents the absolute error between calculated density (D_C) and true density of formation (D_T).

A. Comparison of Two Approaches Regarding Mass Attenuation Coefficient

Section 2.2 emphasizes that the proposed method treats the mass attenuation coefficient as a function pertaining to formation lithology and pore content. To evaluate the effectiveness of this method, a comparison is conducted in this section, primarily focusing on two approaches of the mass attenuation coefficient: treating it as a constant (denoted as h) versus treating it as a function. Based on Eq. (8) and the analysis of the relevant physical parameters in Section 2.3, if the mass attenuation coefficient is treated as h, the equation can be obtained:

$$\rho = \frac{\ln(R_{IN}) \times \sum_{m=0}^{2} \beta_m (\ln(RETN))^m}{h}$$

where β_0, β_1, β_2, and h are the fitting parameters. From Eq. (19), the density is determined by two parameters: the ratio of inelastic gamma counts R_{IN} and the ratio of epithermal neutron counts $RETN$.

Limestone with densities ranging from 2.018 g/cm^3 to 2.862 g/cm^3 are designed to compare the two approaches. Fig. 5(a) presents the absolute density errors of both approaches. The results clearly illustrate significant differences: the constant method has a relatively high average absolute error of 0.048 g/cm^3, whereas the error calculated by the proposed method is reduced by about four times compared to the constant method, with an average absolute error of 0.012 g/cm^3. This demonstrates the effectiveness and accuracy of the new method in measuring formation density.

B. Pore Content Impact Analysis

In neutron gamma density (NGD) measurements, neutron transport is sensitive to the presence of pore content. To evaluate the impact of different pore contents on the accuracy of this method, limestone with porosities ranging from 0.9 to 40 p.u. are selected, with pores filled with water, gas, or oil. The density results under different pore contents are shown in Table 1 and Fig. 5(b).

Table 1 and Fig. 5(b) present the density calculation results for varying pore contents. For analysis, seven porosity types are selected, each tested under conditions where the pores are filled with water, oil, and gas. In limestone with pores filled with water, the Hydrogen Index I_H is equivalent to the formation's porosity. The results indicate that the I_H has a minimal impact on density measurements. Regardless of I_H variations, the errors between calculated densities and true densities are less than the threshold of 0.025 g/cm^3, demonstrating that densities calculated by the new method consistently align well with true densities. Additionally, the method can also achieve accurate measurements in high I_H formations. When comparing density calculations for different pore contents, it is observed that when the pores are filled with water or gas, the absolute density errors are relatively small, remaining below 0.015 g/cm^3. However, the errors are relatively large when the pores are filled with oil. Notably, whether the pores are filled with water, oil, or gas, the absolute errors are less than 0.02 g/cm^3. This demonstrates that the method can accurately calculate formation density across various porosities and pore contents.

C. Lithology Impact Analysis

Since different lithologies affect neutron transport and gamma attenuation, 42 models, including limestone, sandstone, dolomite, and one-to-one mixture of any two lithologies, are designed to verify the accuracy of the proposed method. All model pores are filled with water, with porosities ranging from 0.9 to 40 p.u. The densities calculated using the proposed method are compared with true densities used in simulated model construction, which varied between 1.93 g/cm^3 and 2.843 g/cm^3. The density results are shown in Fig. 5(c) and Table 2.

To verify the impact of lithology on density measurement, the study focuses on two types of formations: single lithology (clean formations) and mixed lithology composed of sandstone, limestone, and dolomite. As shown in Fig. 5(c) and Table 2, there are slight differences in density results across various lithologies, and the average absolute error in mixed lithology is slightly larger than that in single lithology, likely due to the complexity of the formation's composition. Whether it is a single lithology or a mixed lithology, the calculated densities closely align with the true densities, and the absolute density errors are less than 0.02 g/cm^3. Overall, the average absolute error in the test database is 0.009 g/cm^3, confirming the accuracy of the proposed method under different lithologies.

D. Multi-Parameter Impact Analysis

The above results quantitatively analyze the impact of lithology and pore content on the accuracy of the density measurement. To further evaluate the proposed method, three cases (Case 1, Case 2, and Case 3) are designed, representing three lithologies (limestone, sandstone, dolomite) and three pore contents (water, oil, gas), while considering mud components (such as chlorite). Specifically, Case 1 simulates a water-filled limestone with 20% chlorite, Case 2 simulates an oil-filled sandstone with 10% chlorite, and Case 3 simulates dolomite containing gas, which has a relatively high chlorite content of 40%. In all cases, the borehole size is 8.5 inches, with a porosity range set from 0 to 25 p.u., and formation densities between 2.211 g/cm^3 and 2.712 g/cm^3. The results are illustrated in Fig. 6.

From Fig. 6, the inelastic gamma ratio and epithermal neutron ratio vary across formations with different lithologies and pore contents, highlighting the impact of formation composition on neutron transport and gamma attenuation. In particular, Case 1 and Case 2 exhibit smaller measurement errors, demonstrating higher accuracy. In contrast, Case 3 exhibits relatively higher measurement errors, possibly due to its more complex formation composition characterized by elevated mud content and gas-filled pores. Nevertheless, the absolute density errors in all three cases remain below 0.02 g/cm^3, demonstrating the accuracy and reliability of the proposed method for measuring formation density.

[Figure 5: see original paper]

E. Tool Calibration Discussion

Due to the fact that only very few commercial tools are available worldwide, NGD tool experimental validation is briefly discussed in this work using Schlumberger's work as a reference where a NGD calibration process is introduced [40]. A step-by-step process summarized is as below:

Step 1: Prepare for Calibration. Use a large, water-filled calibration tank. Ensure access to the aluminum sleeve and the ability to control the fluid in the mud channel (either air or water).

Step 2: Perform Multiple Distinct Measurements. Take measurements under designated configurations to span a wide dynamic range: With aluminum sleeve and water in the mud channel; With aluminum sleeve and air in the mud channel; Without aluminum sleeve and water in the mud channel; Without aluminum sleeve and air in the mud channel.

Step 3: Fit a Linear Model and evaluate fit quality. Apply a best linear fit to calibration data points. Calculate the χ^2 to assess the goodness of fit.

Step 4: Repeatability Check. Repeat the entire calibration process multiple times without altering the tool or setup. Check for consistency in the calibration gain, especially for critical parameters.

Step 5: Analyze and Compare. Compare the calibration gains across the repeated runs to ensure reliability of the calibration process.

By employing multiple configurations, this approach effectively establishes a set of measurement boundary conditions. This design enhances the dynamic range of detector count rates and improves calibration accuracy. The calibration process considers the unique characteristics of NGD tools and can be extended to future NGD tools. Further research along with calibration and field data acquisition are planned to validate the practical utility of the presented method once a new version of NGD tool is ready.

[Figure 6: see original paper]

IV. CONCLUSIONS

1. A new mass attenuation coefficient function of formation lithology and pore content is introduced. Based on neutron-induced gamma attenuation process study, mass attenuation coefficient is shown varying pertaining to formation parameters; therefore, this work proposes to consider it as a function to better evaluate the effects of environmental variables regarding gamma attenuation.

2. A new density measurement method is developed by employing the concept of mass attenuation coefficient function that evaluates the effects of formation composition on gamma attenuation. The method relies on

inelastic gamma rays for density measurement while incorporating epithermal neutrons to correct neutron transport, for example, fast neutron influences on spatial distribution and intensity of inelastic gamma rays. By integrating information from both neutrons and gamma rays, this method can evaluate interaction mechanisms between radiation and formation more accurately and therefore helps obtain more precise density measurement.

3. An elaborate NGD tool model is built and employed to verify the performance of the new method. The proposed method is evaluated using a total of 63 sets of simulated models of varying lithologies and pore contents. The results show that the absolute errors of density calculated by the method are below 0.02 g/cm^3 for all cases. Specifically, the method obtains the same level of accuracy in mixed cases, proving its effectiveness. This can offer theoretical support for the design of new NGD tools.

The method faces challenges in terms of extreme environmental conditions and tool calibration. For example, under logging-while-drilling downhole conditions such as high temperature (150°C) and high pressure (2000 psi), the performance of the tool's detectors and electronics may be affected, while changes in the physical properties of borehole fluids can also occur, thus impacting measurement accuracy. Additionally, the method relies on significant amounts of calibration coefficients, which requires high-level calibration standards in tool-specific environments. To improve the applicability of the method, further in-depth research will be conducted.

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NOMENCLATURE

- μ_m: Total mass attenuation coefficient
- μ_{co}: Mass attenuation coefficient for Compton effect
- μ_{pa}: Mass attenuation coefficient for Pair production
- $\Phi_n(r)$: Fast neutron distribution
- $\Phi_{in}(R)$: The inelastic gamma-rays distribution
- ρ: Formation density
- E_0: Initial energy of fast neutron
- E_γ: Gamma-ray energy
- ETN_1: Near epithermal neutron count
- ETN_2: Far epithermal neutron count
- GGD: Gamma-gamma density
- i: The average number of inelastic gamma rays after neutron enters the formation
- I_H: Hydrogen index

- IN_1: Near inelastic gamma count
- IN_2: Far inelastic gamma count
- l: Formation lithology
- L_n: Fast neutron deceleration length
- L_1: The distance of near gamma detector
- L_2: The distance of far gamma detector
- m_e: The electron rest mass
- N_A: Avogadro's constant
- NGD: Neutron-gamma density
- p: Pore content
- Q: The number of neutrons emitted per second
- r: The distance between source and detector
- r_0: The classical electron radius
- $RCAP$: Ratio of near to far capture gamma counts
- Σ_{in}: Inelastic scattering cross-section
- $RETN$: Ratio of near to far epithermal neutron counts
- A: The atomic weight
- RFN: Ratio of near to far fast neutron counts
- c: The speed of light in a vacuum
- R_{IN}: Ratio of the near to far inelastic gamma counts
- CAP_1: Near captured gamma count
- Σ: Formation macroscopic capture cross-section
- CAP_2: Far captured gamma count
- Z: Atomic number
- D_n: Neutron diffusion coefficient
- D_C: Calculated density
- D_T: True density of the simulated formation

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Note: Figure translations are in progress. See original paper for figures.