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Abstract

Logging-While-Drilling (LWD) pulsed neutron porosity logging represents a key technology for advancing logging techniques, supporting unconventional oil and gas exploration, and enabling sourceless logging operations. However, achieving accurate porosity measurement under these novel logging conditions and in complex geological environments has become a critical challenge. This study employs theoretical analysis to derive lithology correction and sensitivity enhancement formulas based on the slowing-down length ratio under identical instrument structures. A slowing-down length formula with excellent fitting performance was obtained through reasonable approximations. The relationships between the slowing-down length ratio and density were investigated under different lithologies and neutron source conditions. Monte Carlo (MCNP) modeling was utilized to establish various formation models to support theoretical analysis and verification. Finally, the correction efficacy was validated by comparing original data, lithology-corrected results, and sensitivity-enhanced results. The findings demonstrate that the slowing-down length ratio is unaffected by the Hydrogen Index (HI). Under different lithologies, the ratio is inversely proportional to density, while under different chemical and pulsed source conditions, it is directly proportional to density. Using the slowing-down length ratio for lithology correction significantly improves porosity calculation accuracy, with errors not exceeding 1 p.u. Applying the ratio for sensitivity enhancement can elevate the thermal neutron count ratio response to the level of a chemical source, greatly expanding the dynamic range and improving porosity sensitivity. This enables more accurate formation evaluation and promotes the transition to sourceless, integrated logging technologies.

Key Words: LWD pulsed source logging; neutron porosity logging; sensitivity enhancement; slowing-down length ratio; lithology correction

1. Introduction

Neutron porosity logging is one of the most common and important logging methods for measuring formation porosity. With the development of modern science and technology, neutron porosity logging has undergone several transformative periods, which can be divided into the chemical source period, the pulsed neutron period, and the LWD pulsed neutron period. Neutron porosity logging during the chemical source period possesses natural advantages in porosity calculation accuracy due to lower neutron energy [?]. However, environmental protection requirements for green development, along with challenges in handling radioactive waste from chemical sources and operational safety risks, have driven the transition from chemical to pulsed source logging [?, ?]. Two alternatives exist for replacing chemical sources with pulsed neutrons: Deuterium-Deuterium (D-D) neutron generators [?] and Deuterium-Tritium (D-T) neutron generators [?, ?]. Over the past 15 years of logging technology development, D-T sources, with their neutron yield of up to 10^8 n/s, have gradually become the core component of controllable neutron source logging tools [?, ?].

This source strength allows the downhole nuclear detection system to obtain count rates exceeding 10^4 cps, thereby greatly reducing errors caused by statistical fluctuations and achieving good results in various applications [?]. With the advent of the pulsed neutron logging-while-drilling era, the mud channel inside the logging tool makes the borehole environment more complex, and higher accuracy is required for measuring formation porosity [?]. Researchers have gradually initiated studies on LWD pulsed neutron porosity logging [?, ?]. During the period when pulsed neutrons were used to manufacture logging instruments, traditional neutron porosity logging transitioned to pulsed neutron porosity logging. While this change made radioactive logging more environmentally friendly, it also introduced problems of decreased porosity measurement accuracy and significant lithology effects [?]. To solve these problems, researchers have proposed many methods. Some have taken a different approach by converting the thermal neutron count ratio to thermal neutron cross-section to improve the accuracy of neutron porosity logging. Since the thermal neutron cross-section is related to formation density and capture cross-section, this reduces interference in porosity measurement and greatly improves accuracy [?]. This method was later improved by adding the fast neutron cross-section, giving it higher accuracy in gas-bearing formations [?, ?].

However, this method requires too much data, the correction process is complex, and its transition from theory to practice still needs gradual improvement. Another approach is based on deriving density correction formulas through the relationship between neutron slowing-down length, formation density, and hydrogen index, combined with numerical simulation analysis, thereby reducing the influence of density [?, ?]. With further development, it was found that the essential reason affecting the count rate is the inelastic scattering during the neutron slowing-down process. By combining simulation and measured data, an inelastic scattering correction method was obtained, making the results consistent with chemical source logging data [?, ?]. However, the apparent porosity calculated by Yu et al. after lithology correction still had significant errors compared to the porosity calculated under Am-Be source conditions. Meanwhile, Zhou et al. only validated their method for limestone formations and did not show the porosity calculation results for other lithologies.

This paper investigates the impact of high-energy neutron inelastic scattering on porosity measurement accuracy. We found that a correction method based on the slowing-down length ratio can be used for both lithology correction and sensitivity enhancement, while also reducing the amount of data required for the correction. Finally, we present a porosity correction formula applicable to sandstone, limestone, and dolomite. Validation confirms that this formula not only improves the accuracy of porosity calculations but also virtually eliminates the influence of lithology.

The paper is organized as follows: Chapter 2 (Theory) outlines the core idea of the correction formula. Chapter 3 (Material and methods) describes the MCNP numerical modeling and the detailed derivation of the slowing-down length ratio correction formula. Chapter 4 (Results and Discussion) presents the porosity calculation results before and after correction for dolomite, limestone, and sandstone. Chapter 5 (Conclusion) summarizes the main achievements of this work.

2. Theory

Traditional neutron porosity logging is based on an Americium-Beryllium (Am-Be) chemical source, which emits fast neutrons with an average energy of 4.5 MeV [**?**, **?**]. These neutrons interact with formation atoms and gradually slow down to thermal energy. A dual-detector system measures the thermal neutron count rates, and a porosity evaluation model is established based on the near-to-far detector count ratio. The physical basis is that, at 4.5 MeV incident energy, the neutron slowing-down length, which governs the count rate ratio, is primarily controlled by the formation's Hydrogen Index (HI). When the pore space is filled with oil or water, the HI and porosity (ϕ) have a linear relationship:

$$\mathrm{HI} = k \cdot \phi$$

where k is the fluid hydrogen density coefficient ($k = 1$ for water). This relationship forms the theoretical basis for using the thermal neutron count ratio to characterize porosity.

However, it must be clarified that the mapping between the thermal neutron count ratio and HI is an idealized approximation. In reality, the thermal neutron count ratio is mainly affected by two physical quantities, acting through three mechanisms:

1. **HI**: Hydrogen (H) elements, due to their extremely high elastic scattering cross-section and average logarithmic energy decrement per collision, significantly reduce the slowing-down length, thereby increasing the near-to-far thermal neutron count ratio.

2. **Density (Atomic Density)**: Density affects the material's atomic density, which in turn affects the reaction cross-section and slowing-down length. This has a positive impact on the thermal neutron count ratio.
3. **Density (Inelastic Scattering)**: Density also affects the inelastic scattering cross-section. Generally, higher density means more medium-mass nuclei, a larger inelastic scattering cross-section, a smaller slowing-down length, and a larger thermal neutron count ratio.

Although all three mechanisms positively correlate with the thermal neutron count ratio, an increase in HI (porosity) implies a decrease in density. Therefore, when porosity increases, mechanism 1 causes the ratio to increase, while mechanisms 2 and 3 cause it to decrease.

Under traditional chemical source (Am-Be, 4.5 MeV) conditions, the effects of mechanisms 2 and 3 are minimal and can be ignored. But when the neutron source is upgraded to a 14.1 MeV pulsed neutron generator (PNG), the high-energy neutrons cause a sharp increase in the previously negligible inelastic scattering cross-section, making the effects of mechanisms 2 and 3 significant. Simultaneously, the high-energy neutrons inherently lead to a larger slowing-down length, which reduces the thermal neutron count ratio and compresses its dynamic response range to porosity [**?**, **?**]. Numerical simulations show that under pulsed source conditions, the near-linear relationship between the thermal neutron count ratio and porosity becomes highly non-linear, and its dynamic response range is significantly compressed (Figure 1 [Figure 1: see original paper]). Focusing on the 0–40 p.u. porosity range, the dynamic range of the chemical source logging response is approximately 366, which is twice that of the pulsed source (180).

Figure 1. Logging response of different neutron sources (Formation: Limestone, Porosity: 1-100 p.u.).

Based on the numerical simulation results for limestone, the apparent limestone porosity calculation formula, derived by fitting the thermal neutron count ratio, is:

$$\phi_{\text{app}} = 2.416 \ln\left(\frac{R}{0.414}\right)$$

Theoretical analysis indicates that the decrease in bulk density (ρ_b) as porosity increases leads to a reduction in the sensitivity of the thermal neutron count ratio to porosity. The apparent limestone porosity formula (Eq. 2) introduces lithology effects, leading to errors in porosity interpretation. This necessitates the establishment of models for lithology correction and porosity sensitivity enhancement.

3. Material and Methods

3.1. Monte Carlo Modeling

This study utilized the Monte Carlo N-Particle transport code (MCNP5) [**?**] to perform three-dimensional numerical simulations for two neutron sources: Am-Be chemical source, average neutron energy $E_n = 4.5$ MeV; Pulsed neutron generator (PNG), monoenergetic neutrons $E_n = 14.0$ MeV. The experimental model is shown in Figure 2 [Figure 2: see original paper] and includes a neutron generator, a near epithermal neutron detector, a near thermal neutron detector, a near gamma detector, two far thermal neutron detectors, and a far gamma detector. The source-to-detector spacings for the near and far thermal neutron detectors are 11.3 in (28.702 cm) and 27.3 in (69.342 cm), respectively. The gamma detectors are used to calculate the formation bulk density. All simulations maintained consistent borehole structure, instrument structure, and formation thickness. Different combinations of rock matrix, porosity, and pore fluid were set according to simulation needs. The number of simulated particles was 10^7, ensuring a relative error of less than 0.03 for the near thermal detector and less than 0.02 for the far thermal detector.

Figure 2. LWD pulsed source instrument model.

Model 1: Rock matrix: Limestone. Porosity: 0-100 p.u. (step 10 p.u.). Fluid: Pure water. Sources: PNG and Am-Be (Table 1). This model is used to show the effect of high-energy incident neutrons on the count ratio vs. porosity relationship. (100 p.u. porosity does not exist in reality but is used to illustrate the effect).

Model 2: Rock matrix: Sandstone (SiO_2), Limestone ($CaCO_3$), and Dolomite ($CaMg(CO_3)_2$). Porosity: Two sets, 0-40 p.u. (step 5 p.u.) for formula fitting, and 2-37 p.u. (step 5 p.u.) for formula validation. Fluid: Water. Sources: PNG and Am-Be (Table 2). This range is close to the actual formation porosity.

Model 3: Rock matrix: Limestone. Source: PNG. Fluid: Water. This model isolates the effects of HI and density: Constant density (2.5 g/cm³), varying HI (0-0.40, step 0.05). Constant HI (0.1), varying density (2.0-2.8 g/cm³, step 0.1 g/cm³). This model is used to investigate the independent effects of density and HI on slowing-down length (Table 3).

Table 1. Model for Dynamic Range Response of Different Neutron Sources.

Source	Fluid	Lithology	Porosity (p.u.)	Density (g/cm³)
Am-Be	Water	Limestone	0-100, step 10	2.71-1, step 0.171

Table 2. Investigation and Validation Model for Lithology and Sensitivity Corrections.

Source	Fluid	Lithology	Porosity (p.u.)	Density (g/cm^3)
Am-Be	Water	Limestone	0-40, step 5	2.71-2.026, step 0.0855
		Sandstone	0-40, step 5	2.65-1.99, step 0.0825
		Dolomite	0-40, step 5	2.87-2.122, step 0.0935
PNG	Water	Limestone	2-37, step 5	2.6758-2.0773, step 0.0855
		Sandstone	2-37, step 5	2.617-2.0395, step 0.0825
		Dolomite	2-37, step 5	2.8326-2.1781, step 0.0935

Table 3. Investigation Model for Independent Effects of Hydrogen Index and Density on Slowing-Down Length.

Source	Fluid	Lithology	HI	Density (g/cm^3)
PNG	Water	Limestone	0-0.4, step 0.05	2.5
			0.1	2.0-2.8, step 0.1

3.2. Lithology Correction Based on Slowing-Down Length Ratio

The physical basis of neutron porosity logging is the application of the neutron flux spatial distribution. To analyze how high-energy neutrons affect PNG porosity calculation accuracy, we must start with the spatial distribution equation:

$$D\nabla^2\phi(\mathbf{r}) - \Sigma_t\phi(\mathbf{r}) = 0$$

where D is the diffusion coefficient, ∇^2 is the Laplacian operator, $\phi(\mathbf{r})$ is the neutron flux, and Σ_t is the macroscopic neutron absorption cross-section. Applying the group diffusion method to solve the neutron diffusion equation, dividing it into a fast group (epithermal) and a slow group (thermal), the solution for the slow group—the thermal neutron flux spatial distribution—is [**?**]:

$$\phi_t(r) = \frac{D_t}{4\pi L_t^2 r}\exp\left(-\frac{r}{L_t}\right)\exp\left(-\frac{r^2}{L_f^2}\right)$$

where $\phi_t(r)$ is the thermal neutron flux; L_t is the thermal neutron diffusion length; L_f is the neutron slowing-down length; r is the source-to-detector distance; and D_t is the thermal neutron diffusion coefficient. Since the thermal neutron diffusion length is much smaller than the fast neutron slowing-down length, the ratio of thermal neutron counts at the near and far detectors can be expressed as:

$$R = \frac{N_1}{N_2} = \frac{r_2}{r_1}\exp\left(\frac{r_2^2 - r_1^2}{L_f^2}\right)$$

where r_1 and r_2 are the source-to-detector distances for the near and far detectors, respectively.

Under identical porosity conditions, different lithologies result in different slowing-down lengths (L_f) and thus different thermal neutron count ratios. This is the lithology effect. To eliminate this effect, we can artificially correct the count ratio of any lithology (R) to what it would be in the standard lithology (limestone, L_{lf}), yielding a corrected ratio (R_{cor}):

$$R_{\text{cor}} = \frac{r_2}{r_1} \exp\left(\frac{r_2^2 - r_1^2}{L_{lf}^2}\right)$$

Using Equation (6) as the target equation, we can derive the correction. We relate R_{cor} and R through L_f and L_{lf}. First, perform an equivalent transformation on the exponent:

$$\frac{r_2^2 - r_1^2}{L_{lf}^2} = \frac{r_2^2 - r_1^2}{L_f^2} \cdot \frac{L_f^2}{L_{lf}^2}$$

Substitute (7) into (6):

$$R_{\text{cor}} = \frac{r_2}{r_1} \exp\left(\frac{r_2^2 - r_1^2}{L_f^2} \cdot \frac{L_f^2}{L_{lf}^2}\right)$$

Through algebraic transformation:

$$R_{\text{cor}} = \left[\frac{r_2}{r_1} \exp\left(\frac{r_2^2 - r_1^2}{L_f^2}\right)\right]^{\frac{L_f^2}{L_{lf}^2}} \cdot \left(\frac{r_2}{r_1}\right)^{1-\frac{L_f^2}{L_{lf}^2}}$$

The term preceding the multiplication sign in Equation (9) corresponds exactly to the uncorrected ratio R from Equation (5). Simplifying gives:

$$R_{\text{cor}} = R^{\frac{L_f^2}{L_{lf}^2}} \cdot \left(\frac{r_2}{r_1}\right)^{1-\frac{L_f^2}{L_{lf}^2}}$$

Applying a transformation to the exponent of Equation (10):

$$R_{\text{cor}} = R \cdot R^{\frac{L_f^2}{L_{lf}^2}-1} \cdot \left(\frac{r_2}{r_1}\right)^{1-\frac{L_f^2}{L_{lf}^2}}$$

Expanding the -1 in the exponent of Equation (11) and canceling the first R leads to the final correction formula for the thermal neutron count ratio based on the ratio of the slowing-down lengths:

$$R_{\text{cor}} = R \cdot \left(\frac{R}{\frac{r_2}{r_1}} \right)^{\frac{L_f^2}{L_{lf}^2} - 1}$$

This formula (Equation 12) is the final thermal neutron count ratio correction formula based on the slowing-down length ratio. It is universally applicable for correcting ratio differences caused by lithology, neutron source, or other factors, as long as the instrument structure is the same.

The slowing-down length (L_f) can be calculated from the thermal neutron count ratio R obtained in the MCNP simulation, using the inverse of Equation (5):

$$L_f = \sqrt{\frac{r_2^2 - r_1^2}{\ln\left(R \cdot \frac{r_1}{r_2}\right)}}$$

One could simulate limestone at different porosities, calculate L_f using (13), and then fit L_f against density (ρ_b). However, it was found that polynomial fitting was not effective. As shown in Figure 3 [Figure 3: see original paper], the error is only acceptable when the polynomial degree reaches 4 or 5.

Therefore, it is necessary to explore the physical relationship between slowing-down length and density to derive a more accurate fitting equation. As discussed in Section 2, density affects L_f in two ways. **Indirect influence**: An increase in porosity (and thus HI) decreases L_f. This same porosity increase also causes a decrease in density. This creates an apparent positive trend between L_f and ρ_b (as ρ_b decreases, L_f also decreases). **Direct influence**: An increase in density directly increases the atomic density and the number of medium-mass nuclei. This increases both elastic and inelastic scattering probabilities, decreasing the slowing-down length. This is an inverse relationship.

Figure 3. Polynomial fitting of the slowing-down length.

To distinguish these effects, MCNP Model 3 was used. The results (Figure 4 [Figure 4: see original paper]) show that the direct influence of density ρ_b on L_f is essentially linear. The indirect influence (plotted against the density that corresponds to the HI) is closer to the inverse of a quadratic function.

Figure 4. Direct and indirect effects of density on slowing-down length.

Based on this, the relationship between density and slowing-down length is given as:

$$L_f = \frac{a_1\rho_b + b_1}{a_2\rho_b^2 + b_2\rho_b + c_2}$$

where a_1, b_1, a_2, b_2, c_2 are constants. The numerator $(a_1\rho_b + b_1)$ represents the direct influence (linear, density-driven, lithology-dependent). The denominator represents the indirect influence (HI-driven, lithology-independent).

Using Equation (14) to fit L_f (for limestone) against the densities of limestone, sandstone, and dolomite (at equivalent porosities) shows excellent fitting results for both PNG (L_f) and Am-Be (L_{Am}) sources (Figure 5 [Figure 5: see original paper]). This proves that the slowing-down length of a standard lithology (like limestone) can be accurately fitted using the densities of other lithologies, only requiring different fitting coefficients.

Figure 5. Fitting of (a) PNG and (b) Am-Be limestone slowing-down lengths using densities of different lithologies.

Now, returning to the correction formula (12), the exponential term is the ratio of slowing-down lengths, L_f/L_{lf}. When we substitute Equation (14) for both L_f (formation) and L_{lf} (limestone), the HI-dependent denominator cancels out, as it is the same for both at equivalent porosity. The ratio becomes a function of the numerators (the direct density/lithology effect):

$$\frac{L_f}{L_{lf}} = \frac{\alpha_1\rho_b + \beta_1}{\alpha_2\rho_b + \beta_2}$$

where ρ_b is the density of the formation (L_f); α_1, α_2, β_1, β_2 are constants. Figure 6 Figure 6: see original paper shows the slowing-down length ratio L_f/L_{lf} (for dolomite and sandstone) plotted against density. When the matrix density is higher than limestone (dolomite), the ratio is < 1. When it is lower (sandstone), the ratio is > 1. This is because higher density increases inelastic scattering, reducing L_f. As density decreases (porosity increases), all ratios converge to 1 (the value for 100% water).

Figure 6. (a) Slowing-down length ratio vs. density; (b) Transformed slowing-down length ratio vs. density.

The curves in Figure 6(a) are not simple and are difficult to fit. However, they have similar shapes. By transforming the curves (shifting them vertically by -1, reflecting the dolomite curve, and shifting horizontally), they can be merged into a single curve, as shown in Figure 6(b).

This transformed curve is much simpler to fit and satisfies:

$$\left|\frac{L_f}{L_{lf}} - 1\right| = \alpha_3(\rho_b - 1)^n$$

where α_3 is a lithology-dependent coefficient (0 for sandstone, 0.27 for dolomite in this simulation). This transformation simplifies the fitting process.

The final lithology correction formula is:

$$R_{\text{cor}} = R \cdot \left(\frac{R}{\frac{r_2}{r_1}} \right)^{\left(\frac{2.416(0.414\rho_b - 1)}{2.416(0.414\rho_b - 1)} \right)^n - 1}$$

where 2.416 and 0.414 are constants determined by the instrument's source-detector spacing.

The value of n is defined as follows: n is odd if the matrix density of the target rock is greater than that of limestone; n is even if the matrix density is less.

3.3. Sensitivity Enhancement Based on Slowing-Down Length Ratio

During the transition from chemical sources to pulsed sources, the involvement of inelastic scattering intensifies the lithology effect and concurrently reduces the sensitivity of porosity calculations. In traditional neutron porosity logging, the calibration is typically achieved by fitting the limestone porosity against the thermal neutron count ratio in standard test pits, as shown in Equation (2). As illustrated in Figure 1, the dynamic range of the thermal neutron count ratio from pulsed sources is significantly narrower, which further diminishes the sensitivity of porosity calculations.

In contrast to pulsed neutron sources, the thermal neutron count ratio for an Am-Be source is given by:

$$R_{Am} = \frac{r_2}{r_1} \exp\left(\frac{r_2^2 - r_1^2}{L_{Am}^2} \right)$$

Where R_{Am} is the thermal neutron count ratio under Am-Be source conditions, obtained from either MCNP simulations or physical measurements; L_{Am} represents the slowing-down length for neutrons under Am-Be source conditions.

We can use the same correction logic (Equation 12) to correct the PNG ratio (R) to the Am-Be ratio (R_{Am}) level.

$$R_{\text{enh}} = R \cdot \left(\frac{R}{\frac{r_2}{r_1}} \right)^{\frac{L_{PNG}^2}{L_{Am}^2} - 1}$$

This formula can be applied to data that has already been lithology-corrected (all values are for limestone) or applied to raw data, treating each lithology separately.

Using MCNP Model 2, we calculate L_{PNG} and L_{Am} for all three lithologies and plot their ratio (L_{PNG}/L_{Am}) against density (Figure 7 [Figure 7: see original paper]).

Figure 7. Slowing-down length ratio (PNG/Am-Be) vs. density.

Observing Figure 7, the ratio L_{PNG}/L_{Am} shows a strong linear relationship with bulk density ρ_b for each lithology. This is likely because the increase in L_f from PNG vs. Am-Be is dominated by inelastic scattering, and its density dependence is primarily linear (as seen in Figure 4).

The linear fit for each lithology can be determined. For example, using a two-point formula, we observe that at 0 p.u. (matrix density, ρ_{ma}), the ratio is near 1, and at 40 p.u. (density ρ_{40}), the ratio is near 1.153. This gives the linear equations:

$$\frac{L_{PNG}}{L_{Am}} = A\rho_b + B$$

Validation using the density of pure water (1 g/cm³) shows the three lines intersect at $x = 1$ with a relative error of only 2.9% compared to the MCNP simulated water point. This confirms that the linear relationship is a robust approximation.

The final formula for sensitivity enhancement is:

$$R_{\text{enh}} = R \cdot \left(\frac{R}{\frac{r_2}{r_1}} \right)^{(A\rho_b+B)^2-1}$$

where A and B are the linear coefficients (e.g., -0.2236 and 1.6062 for limestone).

4. Results and Discussion

MCNP Model 2 was used to simulate the LWD pulsed source response in dolomite, limestone, and sandstone. The raw thermal neutron count ratios are plotted in Figure 8 [Figure 8: see original paper] (top). The apparent limestone porosity was calculated using the standard limestone calibration (Equation 2), shown in Figure 8 (middle), and the error is plotted in Figure 8 (bottom).

Figure 8. PNG thermal neutron ratio response, apparent porosity, and error.

Three phenomena are observed in Figure 8:

1. **Low Dynamic Range**: The count ratio increases with porosity, but the dynamic range is small (max 204 for dolomite). This phenomenon occurs because the pulsed source emits higher-energy neutrons, which exhibit

a larger inelastic scattering cross-section. When porosity increases, formation density decreases, leading to a longer inelastic scattering slowing-down length. This increased length counteracts the hydrogen index (HI) effect, thereby attenuating the increase in the count ratio and resulting in a narrower dynamic response range.

2. **Lithology Effect**: At the same porosity, Dolomite > Limestone > Sandstone. This is because at constant HI, the count ratio is dominated by the inelastic slowing-down length. Dolomite has the highest matrix density, thus the largest inelastic scattering cross-section, the shortest L_f, and the highest count ratio.
3. **Error Trend**: The apparent porosity error is positive for dolomite and negative for sandstone, and the absolute error increases with porosity. This is because, as porosity increases, the difference in L_f (inelastic) between lithologies becomes more pronounced, increasing the error.

Next, the lithology correction formula (Equation 17) was applied to the raw sandstone and dolomite data. The corrected count ratios, the resulting apparent porosities (calculated using the limestone formula (Equation 2), and the errors are shown in Figure 9 [Figure 9: see original paper]. Both the fitting data (left) and the validation data (right) are presented.

Figure 9. Lithology-corrected thermal neutron ratio, apparent porosity, and error for original (left) and validation (right) data.

As shown in Figure 9, after correction, the thermal neutron count ratios and apparent porosities for dolomite and sandstone almost perfectly coincide with the limestone data. The calculation error for both datasets is less than 1 p.u. The maximum error for the original data is 0.68 p.u., and for the validation data is 0.97 p.u.

Figure 10 [Figure 10: see original paper] shows the relative error. Controlling relative error at low porosity is difficult. However, the results show that for porosity > 5 p.u., the relative error is controlled within 5%. For porosity < 5 p.u., it remains within 10%. This is a significant breakthrough.

Figure 10. Relative error of lithology correction.

Next, the sensitivity enhancement (Equation 22) was applied to the MCNP data (both fitting and validation sets). This correction aims to elevate the PNG dynamic range to the Am-Be source level. The corrected PNG data is plotted alongside the reference Am-Be source data in Figure 11 [Figure 11: see original paper].

Figure 11. Sensitivity-enhanced thermal neutron ratio, apparent porosity, and error for original (a) and validation (b) data.

From Figure 11(a), the sensitivity-enhanced PNG data (dark points) and the calculated apparent porosities are in excellent agreement with the Am-Be chemical source values (light points). The validation data in Figure 11(b) shows similarly good results. The porosity calculation error is kept within 5 p.u., which is smaller than the original uncorrected error in Figure 8.

To further quantify the sensitivity enhancement, the sensitivity (ε) of the count ratio (R) to porosity (ϕ) was calculated using:

$$\varepsilon = \frac{dR}{d\phi}$$

The sensitivity before and after correction is plotted in Figure 12 [Figure 12: see original paper], alongside the Am-Be source sensitivity.

Figure 12. Sensitivity (R vs. ϕ) before and after correction.

As Figure 12 shows, the sensitivity of the corrected data is significantly improved, especially at high porosity, and it perfectly matches the Am-Be source sensitivity. Before correction, the sensitivity increases and then decreases, indicating the negative influence of density becomes dominant at high porosity. After correction, sensitivity consistently increases with porosity, showing the density effect has been managed, and the ratio is now primarily determined by HI, as intended.

Finally, the apparent porosity errors for all five datasets (PNG Raw, Cor1 Raw, Cor1 Validation, Cor2 Raw, Cor2 Validation) are summarized in the box plot in Figure 13 [Figure 13: see original paper] and Table 4 .

Figure 13. Box plot of apparent porosity errors for the five datasets.

Table 4. Error analysis for the five data sets.

Data Set	MBE (p.u.)	Std Dev (s) (p.u.)
PNG Raw	-	-
$\phi_{\text{cor1\_raw}}$	-	-
$\phi_{\text{cor1\_va}}$	-	-
$\phi_{\text{cor2\_raw}}$	-	-
$\phi_{\text{cor2\_va}}$	-	-

Figure 13 and Table 4 clearly show that the error range (whiskers) and interquartile range (box) of the lithology-corrected data (Cor1) are dramatically smaller and more concentrated around zero. This confirms the effectiveness of the lithology correction, achieving an error (MBE) of less than 1 p.u. The sensitivity enhancement (Cor2) also improves the error statistics compared to the raw PNG data, making it suitable for comparing new pulsed logs with old chemical source logs.

5. Conclusion

1. Based on neutron diffusion theory, a correction formula based on the slowing-down length ratio was derived. This formula applies to different lithologies and neutron sources, given an identical instrument structure.
2. MCNP simulation verification revealed that the slowing-down length ratio under different lithologies (L_f/L_{lf}) is almost unaffected by the Hydrogen Index (HI) and shows a distinct inverse relationship with density.
3. MCNP verification showed that the slowing-down length ratio under different neutron sources (L_{PNG}/L_{Am}) is also unaffected by HI and exhibits a linear relationship with density.
4. Based on conclusions 1 and 2, a lithology correction formula (Equation 18) was derived. It effectively corrects for lithology, reducing the porosity calculation error to within 1 p.u., and controlling relative error within 5% for porosities above 5 p.u.
5. Based on conclusions 1 and 3, a sensitivity enhancement formula (Equation 22) was derived, successfully elevating the pulsed source thermal neutron count ratio to the chemical source level. This allows for excellent matching between new pulsed source logs and legacy chemical source data.

Limitations and Future Work: Although this method has been shown to effectively eliminate the influence of common lithologies (sandstone, limestone, dolomite), it has not been verified in complex lithologies such as shaly sand, where clay remains a key factor affecting porosity measurements. This requires further study.

In addition to formation environmental effects, borehole environmental effects (e.g., borehole size, mud density, mud salinity, tool eccentricity) must also be considered. The optimal approach would be to first perform environmental corrections to obtain the thermal neutron count ratio under standard borehole conditions, and then apply the slowing-down length ratio correction. This would achieve the highest possible accuracy in porosity calculation.

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