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Abstract

Due to the independence of traditional neutron and density measurement instruments, an integrated design was implemented for existing neutron and density instruments to consolidate the neutron-density components and enhance the safety and efficiency of formation information acquisition, with a detailed analysis of gamma influence factors in the integrated design. To thoroughly investigate the impact of the distance between neutron and gamma sources on detector measurements, Monte Carlo simulation was employed to analyze detector counts and energy spectra under various neutron-gamma source separations, with validation conducted across different lithology and density conditions. The research findings demonstrate that, while maintaining constant parameters such as actual instrument source spacing and neutron source intensity, the neutron radiation field has no significant effect on density measurement results when the neutron and gamma sources are separated by 410 mm, with inverted density errors all less than 0.015 g/cm^3. Since similar radioactive sources may exhibit different source intensities that can affect instrument measurement accuracy, the influence of neutron radioactive source intensity was evaluated during the integrated design, and a numerical model relating neutron source intensity to the optimal distance between the two sources was derived, which can facilitate rapid performance evaluation for field instrument testing and provide theoretical guidance for integrated design.

Full Text

Analysis of Gamma Influencing Factors in Integrated Neutron-Density Logging While Drilling

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Abstract

Background: Traditional neutron and density measurement instruments operate independently, which limits the safety and efficiency of geological information acquisition. **Purpose:** This study integrates existing neutron and density instruments through a unified design that merges the neutron and density components, with detailed analysis of gamma influencing factors in this integrated configuration. **Methods:** Monte Carlo simulations were employed to investigate how the distance between neutron and gamma sources affects detector measurements. Detector counts and energy spectra were analyzed at various source distances, with validation performed under different lithology and density conditions. **Results:** Maintaining constant instrument source spacing, neutron source intensity, and other parameters, the neutron radiation field showed no significant impact on density measurements when the neutron and gamma sources were separated by 410 mm, yielding inversion density errors below 0.015 g/cm^3. By varying neutron source intensity, we derived a numerical model relating source strength to optimal inter-source distance, enabling rapid performance evaluation for field instrument testing and providing theoretical guidance for integrated design. **Conclusions:** The distance between sources can be flexibly determined based on neutron source strength, allowing for effective minimization of neutron-induced secondary gamma interference in density measurements.

Keywords: Integrated neutron-density logging while drilling, neutron radiation field, Monte Carlo method

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1. Principle of Gamma Radiation Field Generation

In geological formations, gamma rays released by chemical gamma sources interact with formation materials primarily through photoelectric effect, Compton scattering, and electron-positron pair production. However, since the gamma ray energies used in actual logging operations far exceed 0.1 MeV, we primarily consider photoelectric effect and Compton scattering. The attenuation of gamma photons through the formation and their subsequent detection can be expressed as:

$$\phi_1 = \phi_0 e^{-\mu_n R}$$

where ϕ_1 represents the gamma radiation field, ϕ_0 denotes the gamma radiation field before passing through the formation material, μ_n accounts for Compton scattering and photoelectric effects, and R represents the distance traveled by gamma rays from emission to detection.

Neutron chemical sources utilize radioactive isotopes (such as ^{241}Am-Be or ^{252}Cf) to generate neutron radiation. After emission, neutrons undergo inelastic scattering, elastic scattering, and capture reactions with atomic nuclei of various elements in the borehole environment. Both inelastic scattering gamma rays and capture gamma rays attenuate through absorption in the formation medium before reaching the detector. Consequently, the secondary gamma field distribution can be viewed as a coupling of secondary inelastic scattering gamma field distribution, capture gamma field distribution, and gamma attenuation effects.

According to neutron diffusion theory:

$$S + D\nabla^2\phi - \Sigma_a\phi = 0$$

where Σ_a is the macroscopic capture cross-section of the medium, S represents the number of neutrons absorbed per unit time per unit volume at the neutron source, D is the diffusion coefficient, and Φ is a function of spatial coordinates.

From two-group diffusion theory, we derive the fast neutron flux:

$$\phi_e(r) = \frac{SL_t^2}{4\pi D_t(L_e^2 - L_t^2)}\frac{e^{-r/L_e}}{r}$$

and the thermal neutron flux:

$$\phi_t(r) = \frac{SL_e^2}{4\pi D_t(L_e^2 - L_t^2)}\frac{e^{-r/L_t}}{r}$$

Through the above analysis, the total gamma photon flux within a certain spatial range can be expressed as:

$$\phi_\gamma(R) = \phi_0 e^{-\mu_n R} + \phi_e(r_1)e^{-|R-r_1|\mu_n} + \phi_t(r_2)e^{-|R-r_2|\mu_n}$$

where the first term represents photoelectric effect, Compton scattering, and electron-positron pair production from the primary gamma source, while the subsequent terms account for Compton scattering and photoelectric effects from secondary gamma sources.

Since density calculation using chemical gamma sources employs energy window partitioning methods, and secondary gamma photons from neutron interactions differ from those produced by Compton scattering, they cannot be validated or calculated using the same window method. However, within the radiation field spatial range, these particle populations overlap, and detectors simultaneously collect gamma particles from both sources, causing interference with density measurements. Therefore, the influence of these gamma photons must be eliminated.

Equation (5) demonstrates that secondary gamma production from neutron sources depends on both neutron source strength and detection distance. To investigate and mitigate this effect during instrument design, experimental studies were conducted by adjusting the distance between the two radioactive sources and observing detection phenomena. Through radiation measurements at various distances, we can observe attenuation patterns in space and infer the radiation range of the sources. Radioactive source strength directly affects both radiation range and particle propagation in the medium, with higher source strengths generally producing more extensive radiation fields. This relationship allows experimental adjustment of source strength to effectively investigate radiation effects between sources and targets, providing crucial information for instrument design. In summary, instrument performance evaluation can be achieved by investigating source strength and inter-source distance to obtain optimal parameter settings.

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2. Monte Carlo Model Establishment

The modeled instrument references existing integrated neutron-density tools, preserving original source-detector distances and detector dimensions. Only the distance between neutron and gamma sources was modified in this study. [Figure 1: see original paper] illustrates the instrument structure investigated in this research. Monte Carlo simulations were performed using Geant4 software for model establishment.

The simulation model comprises two main sections: neutron detection and density detection. The density detection section includes a ^{137}Cs source with a 45° emission angle, a far-spaced gamma detector with crystal dimensions of ø21.6 mm × 57.25 mm, and a near-spaced gamma detector with crystal dimensions of ø21.6 mm × 19.2 mm. The neutron detection section includes an AmBe source, a near-spaced He-3 neutron detector measuring ø19.05 mm × 117.5 mm, and two far-spaced He-3 neutron detectors measuring ø19.05 mm × 168.58 mm. Detector source distances are listed in .

All three neutron detectors utilize gas-filled tube detectors, while the two gamma detectors employ NaI crystals. The gamma detectors are shielded by tungsten alloy to block radioactive particles, with beryllium windows allowing gamma particles to enter the detector interior. In the neutron detection section, two far-spaced neutron detectors are placed side-by-side to obtain accurate neutron counts and count ratios.

[Figure 2: see original paper] shows the basic model of the integrated neutron-density tool constructed in Geant4. During simulation, all detector-to-source distances were held constant while the density source position was varied to investigate the impact of neutron-gamma source separation on density measurements. The standard measurement environment consisted of a 6-inch water-filled borehole with limestone lithology and 20% porosity.

The most critical aspect of simulation experiments is configuring the gamma and neutron sources in the instrument. The sources were defined using Geant4's General Particle Source (GPS) class as standard Am-Be and Cs-137 sources. In the main program, GPS class instances were created with parameters including emission energy and position. The Am-Be neutron source strength was set to 8 curies, while the ^{137}Cs gamma source strength was 1.7 curies emitting 0.662 MeV gamma particles. The number of emitted particles was specified in the run.mac file. Given the approximately 4.7:1 source strength ratio in the integrated design, particle count convergence experiments were performed for gamma particles in the standard environment. The Figure of Merit (FOM) factor was introduced to balance simulation runtime and statistical error. As shown in , gamma source emission of 2\$×10^{9}\$ particles provided optimal simulation efficiency. However, for actual engineering simulations matching field measurements, higher precision was desired, so the final simulation used 4\$×10^{9}\$ gamma particles. Based on the source strength ratio, the neutron source emission was set to 1.88\$×10^{10}\$ particles. During simulation in the calibration well environment, sensitive detectors recorded received particle counts, enabling experimental evaluation of the data results to provide reliable guidance for actual design.

Geant4 simulations were performed to model gamma photon distribution from a standalone gamma source and from dual sources. Particle density decreases with distance from the radioactive source. [Figure 3: see original paper] shows that with 1\$×10^{8}\$ particles simulated for the left figure and 1\$×10^{6}\$ particles for the right figure (with 1250 mm source separation), significant overlap and intersection between gamma particles and secondary gamma particles is evident, demonstrating mutual interference between pure density source radiation fields and neutron-induced secondary gamma radiation fields. Notably, if secondary gamma particles are detected by gamma detectors, they may cause counting errors. Gamma particles interact with detector materials to produce secondary particles that propagate and deposit energy in the detector. To accurately record this energy deposition, sensitive detectors log the deposited energy in an energyDeposit variable. When energyDeposit exceeds zero, it indicates gamma particle entry into the NaI detector, incrementing the count value. However, secondary gamma particles from neutron interactions are not genuine formation-reaction gamma particles, causing detector counting errors that directly affect density measurement accuracy. Therefore, the influence of distance between neutron sources and density detectors must be considered.

3. Impact of Neutron-Gamma Source Distance on Density Detection Performance

The integrated instrument combines neutron and gamma sources in a single housing. Based on this integrated design, we investigated density detection performance at various neutron-gamma source distances to determine the optimal separation that eliminates neutron radiation field effects on density detection, examining both detector counts and energy spectra.

3.1. Impact of Source Distance on Gamma Detectors When investigating how source spacing affects density detection performance, radiation field variations must be monitored. Theoretically, changing the source distance alters the energy spectrum shape obtained by gamma detectors. By analyzing these specific changes, we can establish the basis for determining optimal source separation. Experiments compared superimposed radiation spectra (with both neutron and gamma sources present) against pure gamma spectra (without neutron source). [Figure 4: see original paper] reveals that in the 200–410 mm source spacing range, the far-spaced detector spectrum is sensitive to spacing changes, while the near-spaced detector shows negligible influence. At 410 mm separation, the superimposed spectra from both near- and far-spaced gamma detectors essentially coincide with the pure gamma spectrum.

Since formation parameters have nonlinear relationships with detector counts, the Maximum Information Coefficient (MIC) method was used to evaluate nonlinear correlations between formation parameters and counts in each energy channel. Energy windows partitioned based on this approach better reflect instrument characteristics. [Figure 5: see original paper] and show the window divisions according to actual instrument requirements and correlation coefficients. The W1 window serves as the lithology window, while W4 is the density window. The lithology window is typically used for lithology detection, whereas the density window focuses on obtaining formation density. Therefore, we must assess how source spacing affects counts in both lithology and density windows, primarily examining the relationship between superimposed radiation counts and pure gamma source counts.

[Figure 6: see original paper] demonstrates that window counts for both near- and far-spaced gamma detectors gradually decrease with increasing source spacing before stabilizing. Combined with the above analysis, we determined that at 410 mm source spacing, superimposed radiation window counts essentially coincide with pure gamma source window counts.

3.2. Impact of Neutron Source Strength on Source Spacing Source strength measures radioactive intensity. High-strength neutron sources provide higher radiation levels and greater penetration capability, enhancing detector count rates. Conversely, low-strength sources reduce radiation hazards to operators, improving safety and reliability. In neutron-gamma radiation field studies, neutron source strength also affects evaluation of the distance between neutron and gamma sources. In Monte Carlo simulations, neutron source strength was varied while keeping neutron source energy constant, with strengths of 4, 8, 10, and 12 curies implemented by adjusting particle numbers to 0.5\$$\times10^{\{8\},1\times10}\{8\},1.25\times10^{\{8\},and1.5\times10}\{8\}$\$ respectively. Experiments verified how neutron source strength influences the optimal neutron-gamma source distance while ensuring measurement precision across different strengths.

[Figure 7: see original paper] shows that as neutron source strength increases from 4 to 12 curies, the optimal source spacing also increases. At 4 curies, the optimal separation is 350 mm; at 8 curies, 410 mm; at 10 curies, 440 mm; and at 12 curies, 450 mm. At these optimal distances, secondary gamma particles from neutron sources no longer affect density measurements.

The relationship between source strength and radiation range is complex, requiring consideration of multiple factors. Typically, stronger sources produce higher radiation intensities at short distances, but the radiation range decreases rapidly with distance. Whether a curve-fitting relationship exists depends on specific conditions and radiation propagation complexity. In this study environment, experiments and numerical simulations accurately characterized this relationship, yielding the fitted curve shown in [Figure 8: see original paper].

The fitted relationship demonstrates a quadratic function between neutron source strength and inter-source distance. In current instrument designs, this known relationship enables rapid determination of optimal source spacing when neutron source strength is changed, ensuring neutron-induced secondary gamma radiation does not affect density detection.

3.3. Determination of Source Spacing Based on the experimental results and maintaining existing instrument parameters with the inherent neutron source strength of 8 curies, we determined that at a neutron-gamma source separation of 410 mm, neutron radiation impact on density measurements becomes negligible. This allows gamma detectors to accurately capture pure gamma rays without significant neutron radiation interference. Therefore, 410 mm was selected as the optimal source spacing.

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4. Validation

4.1. Different Lithologies Lithology significantly impacts density detection due to varying physical properties that cause different scattering and absorption behaviors, affecting gamma detector counts differently. After determining the source spacing, we further validated its effectiveness across different lithologies. Simulations considered three rock types: limestone (2.697 g/cm^3), sandstone (2.65 g/cm^3), and dolomite (2.86 g/cm^3). As shown in and [Figure 9: see original paper]–[Figure 10: see original paper], relative errors in detector counts and lithology window counts between superimposed and pure gamma fields were all less than 5%, with detector energy spectra achieving complete matching. This demonstrates that the 410 mm source separation meets design requirements across various lithologies, enabling acquisition of pure gamma rays.

4.2. Different Densities After determining the optimal source spacing, results were validated across different formation densities. This was accomplished by varying formation porosity while keeping borehole and instrument parameters constant. Simulations were performed for formations with porosities of 20 p.u., 40 p.u., and 50 p.u., corresponding to densities of 2.3576 g/cm^3, 2.0182 g/cm^3, and 1.8485 g/cm^3 respectively.

and [Figure 11: see original paper] show that relative errors in detector counts and density window counts between superimposed and pure gamma fields remain below 5% across all densities. [Figure 12: see original paper] demonstrates that detector energy spectra at different formation densities essentially overlap, confirming that the 410 mm source separation effectively eliminates neutron-induced secondary gamma field effects, allowing detectors to receive pure gamma radiation.

4.3. Field Validation The field validation phase involved acquiring data from calibration wells and comparing simulated with measured results. Calibration wells are artificially constructed test wells meeting specific formation conditions at experimental facilities. This study selected density standard wells from a calibration well facility ([Figure 13: see original paper]) for experimental measurements. The integrated neutron-density tool was placed in selected calibration wells to collect field data. A one-to-one calibration well environment was constructed in Geant4, ensuring consistency in formation conditions, borehole dimensions, and tool positioning.

Two calibration wells were selected, with partial information provided in . Geant4 simulations were performed at the 410 mm neutron-gamma source distance in the calibration well environment, with both neutron and gamma source data simulated to record detector counts per channel. Since actual calibration involves separate installation of neutron and gamma sources for data acquisition, the measured density data represents pure gamma radiation field data, perfectly matching our research objectives. Comparison between simulated and measured data validated our findings, with spectral matching shown in [Figure 14: see original paper].

The simulation spectra showed strong correlation with measured spectra in the calibration wells, confirming the correctness of the neutron-gamma integrated tool simulation model and its ability to accurately reflect formation information without neutron radiation field influence. To further evaluate simulation accuracy and verify that gamma detectors receive pure gamma rays in the integrated model, density response equations were fitted, with results shown in [Figure 15: see original paper].

The density response equation:

Comparison between simulated and measured responses shows correlation coefficients exceeding 0.9900 for both near- and far-spaced detectors, with curves essentially overlapping, achieving excellent matching. Using these response equations, measured near- and far-spaced detector counts were inverted to obtain formation density values, as presented in .

In the superimposed radiation field, the absolute deviation between inverted apparent density and true formation density was less than 0.015 g/cm^3, meeting error requirements. These results confirm that the current radioactive source configuration eliminates neutron radiation field effects on density measurements.

Conclusions

(1) Based on existing instruments and integrated design requirements, we determined the impact of neutron-gamma source distance on density measurements. With the original neutron source strength of 8 curies, a separation of approximately 410 mm between neutron and gamma sources effectively eliminates secondary gamma field effects.

(2) In calibration wells, simulated and measured detector counts showed relative errors below 5%, achieving good matching results. Density response equation fitting curves essentially overlapped, with inverted formation densities deviating less than 0.015 g/cm^3 from true values.

(3) Considering neutron source strength effects on source distance, the optimal separation increases with source strength: 350 mm at 4 curies, 410 mm at 8 curies, 440 mm at 10 curies, and 450 mm at 12 curies. The relationship between neutron source strength and optimal source spacing follows a quadratic function.

(4) Since this research is based on actual instruments, instrument designs can be adjusted according to these findings, providing guidance for future development.

Author Contributions

Chen Junyan: Literature review, experimental simulation, data processing, and manuscript writing; Fan Jilin: Technical guidance; Zhang Qiong: Technical guidance, review and editing; Yuan Wei: Provision of instrument-related data.

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