Prompt fission neutron uranium logging (I): Direct uranium quantification method theory

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Abstract

Prompt fission neutron uranium logging (PFNUL) is an advanced method for utilizing pulsed neutron bom- bardment of the ore layer and a fission reaction with uranium (235U) to detect the transient neutrons produced by fission and then directly measure and quantify uranium; however, the stability and lifetime performance of pulsed neutron sources are the key constraints to its rapid promotion. To address these problems, this study proposes a PFNUL technique for acquiring the time spectrum of dual-energy neutrons (epithermal and thermal neutrons) from the upper and lower detection structures and establishes a novel uranium quantification algo- rithm based on the ratio of epithermal and thermal neutron time windows (E/T) via a mathematical-physical modeling derivation. Through simulations on well logging models with different uranium contents, the starting and stopping times of the time window (Δt) for uranium quantification in the dual-energy neutron time spec- trum are determined to be 200 and 800 s, respectively. The minimum radius and height of the model wells are 60 and 120 cm, respectively, and the E/T values in the time window show an excellent linear relationship with the uranium content. The scale factor is KE/T = 1.92 and R2=0.999, which verifies the validity of the E/T uranium quantification algorithm. In addition, experiments were carried out in the Nu series of uranium standard model wells, and the results showed that under different neutron source yields, the E/T-based uranium quantification method reduced the relative standard deviation of the scale factor of the uranium content from 33.41% to 1.09%, compared with a single epithermal neutron quantification method. These results prove that the E/T value uranium quantification method is unaffected by the change in the neutron source yield, effectively improves the accuracy and service life of the logging instrument, and has great scientific and popularization value.

Full Text

Prompt Fission Neutron Uranium Logging (I): Direct Uranium Quantification Method Theory

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Prompt fission neutron uranium logging (PFNUL) is an advanced technique that employs pulsed neutron bombardment of ore layers to induce fission reactions with uranium-235 (^{235}U), enabling direct detection and quantification of uranium through measurement of the resulting transient fission neutrons. However, the stability and operational lifetime of pulsed neutron sources represent critical constraints limiting its widespread adoption. To address these challenges, this study proposes a PFNUL technique that acquires dual-energy neutron time spectra (epithermal and thermal neutrons) using upper and lower detection structures, and establishes a novel uranium quantification algorithm based on the ratio of epithermal to thermal neutron time windows (E/T) through mathematical-physical modeling. Simulations conducted on well logging models with varying uranium contents determined the optimal time window (Δt) for uranium quantification in the dual-energy neutron time spectrum to be 200–800 μs. The minimum model well dimensions were established as 60 cm radius and 120 cm height, with E/T values within this time window demonstrating an excellent linear relationship with uranium content. The scale factor was determined to be K_{E/T} = 1.92 with R^2 = 0.999, validating the E/T uranium quantification algorithm. Experimental validation using the Nu series of uranium standard model wells demonstrated that under varying neutron source yields, the E/T-based quantification method reduced the relative standard deviation of the uranium content scale factor from 33.41% to 1.09% compared to single epithermal neutron quantification. These results confirm that the E/T ratio method is independent of neutron source yield fluctuations, effectively improves logging instrument accuracy and service life, and holds significant scientific and practical value for widespread application.

Keywords: PFNUL; Uranium exploration; Pulsed neutrons; Neutron time spectrum

INTRODUCTION

Nuclear power represents one of the most promising methods for large-scale hydrogen production without carbon dioxide emissions. As the primary fuel

for nuclear power generation, uranium ore is crucial to the development of the nuclear industry [1]. Since the 21st century, nations worldwide have initiated mineral exploration programs and developed intelligent exploration technologies to provide scientific and technological support for energy conservation and emission reduction efforts.

Logging serves as an effective method for uranium exploration. The gamma (total) logging technique originated in petroleum logging during the 1930s and was adapted for uranium logging in the 1960s [2–6]. Gamma logging constitutes an "indirect uranium measurement" approach [7, 8] that detects gamma rays in boreholes to determine radium/radon daughter nuclide activities, from which uranium content is inferred based on activity equivalence relationships. When mineralization environments and geological conditions change, these equivalence relationships are disrupted, breaking the decay equilibrium between uranium and radium/radon and causing deviations in uranium content interpretation. Consequently, China' s uranium mining industry standards require that no fewer than 30% of samples from drill holes must undergo chemical analysis to examine the uranium-radium-radon equilibrium relationship and correct interpretation deviations [9–11]. Therefore, uranium exploration in China primarily relies on core chemical analysis combined with natural gamma logging technology. While natural gamma logging is conceptually simple, its quantitative interpretation accuracy is easily compromised by uranium-radium disequilibrium, radon emanation, and thorium-potassium interference, making it difficult to meet current uranium exploration demands and resulting in long-term shortcomings including high costs, low efficiency, and large quantification errors for uranium resources [12–14]. There exists an urgent need for new nuclear logging theories, technologies, and methods capable of achieving high-precision direct uranium measurement and downhole quantification.

In 1966, Allen and Tittle proposed a novel uranium logging technique called fission neutron logging. To elucidate its principles, they solved single-velocity neutron diffusion equations simulating cylindrical borehole geometry and developed a complete computer program for the analytical numerical problem [15, 16]. In 1972, Czubek analyzed the epithermal neutron time distribution, thermal neutron time distribution from ^{235}U slow fission, and fast neutron time distribution from ^{238}U fast fission, establishing that when background levels are near zero, the formation epithermal neutron count rate is proportional to uranium grade. By modeling a point-like pulsed neutron source in a uniform uranium-bearing spherical formation, Czubek derived the response formula for neutron detectors to epithermal neutron count rates, thereby establishing the methodological foundation for prompt neutron uranium logging [17]. Renken (1976) identified significant variability in epithermal neutron fluxes between formations with and without uranium, concluding that a logging method based on epithermal neutron time decay held great potential. Simulations for various uranium concentrations demonstrated that thermal neutron flux was independent of uranium concentration. In 1977, the Monte Carlo program TIMEX was applied to simulate signal contributions from strata around uranium fission

prompt neutron loggers to epithermal neutron (0.414–454 eV) detectors, revealing that uranium ore at 0.3–0.5 m significantly contributed to detector signals [18, 19]. The work of Allen, Tittle, Czubek, Renken, and others provided the theoretical basis for subsequent pulsed neutron uranium logging development.

Since the 1970s, pulsed neutron-based uranium logging methods capable of directly measuring ^{235}U content without core sampling and without interference from thorium and potassium gamma rays have been studied and experimentally evaluated in the United States, Canada, Germany, and the former Soviet Union [20, 21]. These methods effectively quantify uranium through neutron time spectrum collection but require ultrashort pulse width and high-yield neutron sources. For example, Russia' s ANHK-60 pulsed neutron uranium logging system, developed by the All-Russian Research Institute of Automation (VNIIA), employs a D-T neutron generator with 1 μs pulse width and approximately 10^7 n/s single-pulse yield, yet the generator lifetime is only 150 hours [22]. Consequently, neutron source stability and lifetime are key factors affecting uranium quantification accuracy, as changes or fluctuations in neutron tube flux directly impact logging results [23]. Current approaches to improving neutron tube performance include using new materials, optimizing designs to extend lifetime, and implementing advanced control systems with feedback mechanisms to stabilize source neutron flux and reduce fluctuations through scaling and automatic adjustments [24–26]. For instance, Liu et al. and Guo et al. improved yield stability by optimizing neutron tube ion source pulse power supplies and target film preparation [27, 28], while Chen et al. integrated Kalman filtering with PID algorithms in PLC systems to improve neutron yield stability, achieving stable operation at 1×10^8 n/s with a relative standard deviation of 0.82% [29]. However, these neutron yield control techniques have not resolved the fundamental issue of neutron tube service life, which severely restricts PFNUL popularization and application.

This study proposes a PFNUL technique with upper and lower dual neutron detectors to acquire epithermal (E) and thermal (T) neutron time spectra. Through neutron transport theory exploration, we derive a uranium quantification equation based on the epithermal-to-thermal neutron ratio (E/T). Simulation and experimental measurements determine the optimal extraction parameters for uranium fission neutron information. E/T values within the defined time window exhibit a strong linear relationship with uranium content, and the uranium quantification scale factor based on E/T values remains stable under varying neutron yield conditions. This demonstrates that the method eliminates uranium quantification fluctuations caused by neutron source intensity variations, extends neutron tube service life, reduces neutron uranium logging costs, and holds significant value for PFNUL popularization [30–33].

II. THEORY OF DIRECT URANIUM MEASUREMENT METHODS FOR DUAL ENERGY NEUTRON RATIOS

A. Theory of PFNUL

Figure 1 [Figure 1: see original paper] illustrates the principles of the PFNUL technique. The D-T neutron generator emits fast neutrons (source neutrons) in pulsed mode into the downhole formation. These fast neutrons are moderated through elastic scattering, inelastic scattering, and other nuclear interactions with formation rock, rapidly slowing to epithermal neutrons (E) (epithermal neutron lifetime $\leq t_1$) and thermal neutrons (T) that persist in the formation for extended periods (≤ 5000 μs) through thermal motion. During this period, they undergo radiative capture, fission, and other nuclear interactions with atomic nuclei before ultimate absorption (neutron fading). In a single pulsed neutron measurement cycle, epithermal and thermal neutron time spectra are collected by dedicated detectors. The slowed thermal neutrons readily undergo fission reactions with formation ^{235}U, producing 2–3 uranium fission prompt neutrons that extend the epithermal neutron fading time ($\geq t_1$), as shown in Fig. 1(b). This prolonged Δt portion of epithermal neutrons is positively correlated with uranium content.

B. Uranium quantification by epithermal neutrons

In 1972, Czubek proposed a direct uranium logging method using a 14 MeV pulsed neutron source to continuously irradiate uranium-bearing formations and measure the fission neutron time distribution following the source neutron pulse [17]. Czubek theoretically demonstrated the feasibility of determining uranium content by measuring the prompt fission epithermal neutron time spectrum from ^{235}U thermal neutron fission. Based on neutron energy, time, and space distributions in media under isotropic pulsed neutron point source conditions, Czubek derived the epithermal fission neutron count rate formula within the measurement time window and established that for a detector with fixed performance, epithermal neutron counts depend only on source neutron yield Q when logging system timing parameters, formation uranium content q , formation density , and formation neutron characteristic function f(t , Σ) are constant:

$$\text{Epi.Count} = K_E \cdot Q\rho q_u \cdot f(t_s, \Sigma_a)$$

where Epi.Count represents epithermal neutron counts in the measurement time window, K_E is the system scale factor representing the proportionality coefficient between epithermal neutron counts and uranium content q , Σ is the formation macroscopic thermal neutron absorption cross-section, and t is the average fast neutron slowing time. However, single epithermal neutron time spectra are susceptible to neutron source yield fluctuations.

C. Uranium quantification of the epithermal neutron-thermal neutron ratio (E/T)

Czubek' s 1972 epithermal fission neutron counting model represents an absolute uranium quantification method requiring compensation for parameters including source neutron yield (Q), formation density ( ), and macroscopic thermal neutron absorption cross-section (Σ). In 1978, Givens et al. proposed a relative uranium measurement method adding a thermal neutron detector to logging equipment to measure formation thermal neutron time spectra, quantifying uranium content through the ratio of uranium fission neutron counts to thermal neutron counts [34]. The epithermal fission neutron counts and thermal neutron counts (Ther.Count) from ^{235}U thermal neutron fission within the detector measurement timeframe are given by Eq. (2):

$$\begin{cases} \text{Epi.Count} = \varepsilon_{\text{epi}} N_u \sigma_f^U g(S, \Sigma_a, t_b, t_c) f(\Sigma_a, t_c) \\ \text{Ther.Count} = \varepsilon_{\text{ther}} g(S, \Sigma_a, t_b, t_c) f(\Sigma_a, t_c) \end{cases}$$

where is epithermal neutron detector efficiency, N is formation ^{235}U atomic number density, σ_f^U is the ^{235}U fission cross-section, g(S, Σ , t_b, t_c) is formation thermal neutron flux density at waiting time t_b end, S is source neutron yield, Σ is formation macroscopic thermal neutron absorption cross-section, f(Σ , t_c) is thermal neutron flux at measurement time t_c, and is thermal neutron detector efficiency.

The g(S, Σ , t_b, t_c) term represents the thermal neutron source driving ^{235}U thermal neutron fission, where any factor affecting formation thermal neutron flux influences epithermal fission neutron flux. Formation macroscopic thermal neutron absorption cross-section can affect thermal neutron flux. To correct for formation parameter influences, Givens et al. proposed an epithermal-thermal neutron counting model whose equations share identical thermal neutron correlation terms, enabling elimination of formation influencing factors through ratio methods. The relationship between the epithermal fission neutron-to-thermal neutron count ratio and formation ^{235}U atomic number density is obtained via ratio method, as shown in Eq. (3):

$$\frac{\text{Epi.Count}}{\text{Ther.Count}} = \frac{\varepsilon_{\text{epi}} N_u \sigma_f^U}{\varepsilon_{\text{ther}}}$$

In logging equipment, Givens et al. arranged thermal and epithermal fission neutron detectors with equal source spacing to ensure thermal neutron correlation terms g(S, Σ , t_b, t_c) and f(Σ , t_c) were identical at both detector positions. However, practical engineering constraints make equal source-spacing arrangements unachievable due to spatial limitations. Therefore, we propose using dual neutron detectors with upper and lower structures to acquire epithermal (E) and thermal (T) neutron time spectra separately, as shown in Fig. 1(a), constructing E/T values to eliminate neutron source yield fluctuations.

During a neutron' s lifecycle, thermal neutrons readily fission with ^{235}U in the medium, producing uranium fission prompt neutrons that extend epithermal neutron fading time, as shown in Fig. 1(b). This provides the theoretical basis for uranium fission detection and uranium ore quantification via pulsed neutron logging. According to fission theory, in a homogeneous medium (saturated ore layer) at any time t after all primary pulsed neutrons have slowed to thermal neutrons (denoted as moment t_1), the total existing epithermal neutron population n_E(t) is proportional to the total existing thermal neutron population n_T(t) versus uranium content (or ^{235}U content):

$$\frac{E}{T}(\Delta t) = \frac{N_E(\Delta t)}{N_T(\Delta t)} = K_{E/T} \cdot q_u$$

$$\frac{n_E(t)}{n_T(t)} = \frac{n_E(t_1) \cdot e^{-(t-t_1)/\tau_E}}{n_T(t_1) \cdot e^{-(t-t_1)/\tau_T}} = K_U \cdot q_u$$

Equation (4) shows that after primary neutrons slow to thermal neutrons, total epithermal neutron n_E(t) and thermal neutron n_T(t) populations in homogeneous media decay according to negative exponential laws, making the time spectra during this period decay spectra [35]. Decay rates are described by $1/\tau$_E and $1/\tau$_T (τ_E and τ_T are time constants for epithermal and thermal neutron fading, closely related to formation rock, drilling medium, and neutron nuclear interaction properties). K_U represents the positive coefficient relating the ratio of total epithermal to thermal neutron populations to uranium content q after moment t_1. Determining time window parameters t_1 and t_2 (shown in Fig. 1(b)) is critical, as epithermal neutrons from the neutron source otherwise compromise uranium quantification accuracy.

If a logging probe measures dual neutron time spectra n_E(t) and n_T(t) at a given well axis position, epithermal neutron attenuation over Δt is N_E(Δt), thermal neutron attenuation is N_T(Δt), and their ratio is termed the "Epithermal/Thermal"(E/T) ratio. The detected attenuations originate from upper and lower structural distributions of ^{3}He orthotropic technology tubes:

$$\begin{cases} N_E(\Delta t) = \eta_E \int_{t_1}^{t_2} n_E(t)dt = \eta_E \cdot n_E(t_1)\tau_E(1 - e^{-\Delta t/\tau_E}) \\ N_T(\Delta t) = \eta_T \int_{t_1}^{t_2} n_T(t)dt = \eta_T \cdot n_T(t_1)\tau_T(1 - e^{-\Delta t/\tau_T}) \end{cases}$$

Thus, the E/T ratio is proportional to formation uranium content. In Eqs. (5) and (6), _E is epithermal neutron attenuation detection efficiency (ratio of detected to actual attenuation), _T is thermal neutron detection efficiency, and K_{E/T} is the conversion factor representing the positive coefficient relating E/T to uranium content q . This conversion factor is determined by logging instrument, formation rock, drilling medium, and other covariates. Once the logging instrument, formation rock, and drilling medium are fixed (particularly the instrument), K_{E/T} remains constant.

In these equations, K_{E/T} is the known variable, E/T(Δt) is the measured variable, and q is the unknown to be solved. Therefore, constructing accurate uranium model wells similar to field wells in lithological structure, material composition, and wellbore medium is necessary. The PFNUL instrument is used to calibrate model wells with known uranium content to determine K_{E/T}, which is then applied to field logging data using Eq. (6) to determine field well uranium content q . Consequently, determining appropriate dimensional parameters for uranium model wells is also important in this study.

Equations (5) and (6) incorporate epithermal neutrons, thermal neutrons, and fading time corrections based on their respective negative exponential decay laws, with τ_E and τ_T values obtained from exponential fitting of decay time spectra. Since τ_E and τT *values are relatively stable in homogeneous media, the fading time correction coefficient can be incorporated into* K{E/T}. When t_2 values are large, the tail of the epithermal neutron time spectrum exhibits significant statistical fluctuations (which may include uranium fission delayed neutrons). For pulsed neutron emission frequencies reaching or exceeding 1000 Hz, t_2 must be $\leq$ 1000 μs. Therefore, Δt values between 600 and 1000 μs are recommended.

Figure 2 [Figure 2: see original paper] shows (a) the uranium logging model and (b) epithermal and thermal neutron time spectra with Δt for uranium signature information acquisition, where E_n denotes normalized epithermal neutron time spectrum counts and T_n denotes normalized thermal neutron time spectrum counts.

This method' s advantages include: extracting secondary neutron extinction laws from epithermal neutron time spectra and primary neutron slowing laws from thermal neutron time spectra to select optimal time window parameters; defining the "Epithermal/Thermal" ratio based on dual-neutron time spectra; and constructing a real-time uranium ore quantification algorithm. Thus, "direct uranium measurement" and quantification via prompt fission neutron logging is realized.

III. THEORETICAL VALIDATION OF THE PROPOSED METHOD

A. Time windows (Δt)

This study employed the Monte Carlo method to establish a PFNUL instrument model with epithermal-to-thermal neutron ratio detection and a cylindrical saturated uranium ore model based on actual configurations [36–38], as shown in Fig. 2(a). The probe tube had an outer diameter of 5.5 cm and length of 284 cm. The pulsed neutron source was a 14 MeV D-T source with 10 μs pulse width, and two ^{3}He detectors were arranged in upper and lower structures. The upper ^{3}He detector was wrapped with 1 mm cadmium and 4 mm polyethylene for epithermal neutron (energy range 0.7–1000 eV) time spectrum acquisition,

while the lower ^{3}He detector measured thermal neutrons. Source-to-detector distances were 15.15 cm for the epithermal neutron detector and 43.7 cm for the thermal neutron detector. Formation uranium content was set to 0%, 0.0280%, 0.0684%, and 0.0982%, with simulated time spectra results shown in Fig. 2(b).

Figure 2(b) reveals that thermal neutron time spectra are identical in uranium-bearing and non-uranium-bearing layers, indicating that regardless of uranium presence, formation rocks and drilling conditions produce minimal differences in macroscopic thermal neutron absorption cross-section (nearly identical). At any time ($t \geq t_1$), existing thermal and epithermal neutron populations in formation rocks follow negative exponential decay functions. In the pure sandstone model epithermal neutron time spectrum (0% uranium), no counts appear after 200 μs, indicating all source neutrons have thermalized by this time, establishing the t_1 value in Eqs. (5). For uranium contents of 0.0280%, 0.0684%, and 0.0982%, epithermal neutron counts after 200 μs originate solely from uranium fission reaction fast neutron moderation, with magnitudes proportional to uranium content. After 800 μs, epithermal neutron counts in uranium-bearing layers become less distinguishable, with larger statistical fluctuations potentially including uranium fission delayed neutrons. Therefore, t_1 and t_2 for uranium characterization information acquisition in E/T counts are set to 200 μs and 800 μs, respectively.

B. Standard model wells

Ideal standard model wells should be sufficiently large to exceed the effective detection range, making determination of appropriate height (H in Fig. 2(a)) and radius (R in Fig. 2(a)) critical. Using the Monte Carlo method with the aforementioned neutron logger model, the mineral layer model size was gradually increased while maintaining constant detector performance, source terms, and formation medium. Appropriate standard model well height and diameter were determined based on E/T ratio variations.

Considering that neutron counts measured by uranium fission neutron loggers are affected by both formation uranium content and borehole radius r, formation uranium content was set to 0.0280%, 0.0684%, and 0.0982% while borehole radius was varied as 3, 7, 11, and 16.5 cm. Model height was varied and E/T ratio counts were simulated using Monte Carlo software. Saturated uranium model height was determined based on E/T ratio stability. Under identical conditions, model radius was varied and E/T ratio counts were simulated to determine saturated uranium logging model radius based on E/T ratio stability. Figure 3 shows the simulation results.

Figures 3(a–c) illustrate E/T value variations with model height. Results show that the E/T ratio detected by uranium fission prompt neutron loggers increases with model radius R, but stabilizes when R reaches a certain value, showing no significant change with further height increases. Smaller borehole radii r produce more drastic E/T ratio changes with model radius R variations. When borehole

radius exceeds 7 cm, E/T value changes become relatively insignificant with model height variations. Simulation results indicate that for saturated ore layer radius, R $\geq$ 60 cm.

Figures 3(d–f) show E/T value variations with model radius. Results demonstrate that E/T values detected by PFNUL instruments increase more significantly with model height H when borehole radius is 3 cm. In contrast, E/T value changes become relatively insignificant with model height variations when borehole radius exceeds 3 cm. E/T values show minimal change with increasing model height and are less affected by borehole radius r. After reaching a certain height, E/T values stabilize and become insensitive to borehole radius r. Therefore, simulation results establish that for saturated layer height, H $\geq$ 120 cm.

Post-simulation analysis determined that saturated uranium ore model dimensions of H $\geq$ 120 cm and R $\geq$ 60 cm produce neutron detector measurements equivalent to those from infinite ore layers.

The experimental model employed the Nu series sandstone-type uranium ore standard model wells constructed by the Airborne Survey and Remote Sensing Center of Nuclear Industry (ASRSCNI), as shown in Fig. 4 Figure 4: see original paper. Models Nu-1, Nu-2, and Nu-3 are uranium-bearing models (red) with uranium contents of 0.0281%, 0.0685%, and 0.0983%, respectively. The Nb-4 model, with uranium content far below the cutoff grade, serves as a pure sandstone background count test model (green). Each cylindrical model has a borehole radius r of 9 cm, model radius R of 70 cm, and height of 180 cm, with a 90 cm concrete roof and 30 cm concrete base, plus extension holes to 260 cm depth. These dimensions satisfy saturated model requirements. Figure 4(b) shows the PFNUL instrument containing two ^{3}He tube sets, polyethylene neutron moderating material surrounding the epithermal neutron detector, cadmium metal wrapping around the moderator, detector high-voltage power supply, preamplifier, shaping and screening circuitry, pulse counter for dual neutron detector signals, and time spectrum analysis and cache circuits.

IV. NEUTRON YIELD IMPACT

A. Time spectra of different neutron yields

Due to experimental consumption and tritium depletion, D-T neutron tube yields change with use. To investigate neutron yield effects on uranium quantification accuracy, four experimental sets were conducted with varying D-T neutron source intensities. Based on Experiment I neutron source intensity, relative intensities for remaining experiments were calculated as shown in Table 1 . Four sets of neutron time spectra and epithermal neutron time spectra were measured using the logging instrument in the Nu series sandstone uranium logging model (Fig. 4(a)) at different neutron source intensities.

B. Effect of neutron source strength on epithermal neutron counts and E/T values

According to simulation results, to determine the conversion relationship between E/T ratio and uranium content while minimizing statistical fluctuation effects, simulated time spectra for different uranium contents (pure sandstone, 0.0280%, 0.0684%, and 0.0982%) were analyzed from 200–800 μs to calculate total epithermal and thermal neutron counts. The scale curve for this study' s uranium fission prompt neutron instrument was compared with E/T value curves from experimental raw data, as shown in Fig. 5 [Figure 5: see original paper].

Figure 5 compares simulated and experimental correlations between uranium content and E/T ratio, fitted using Eq. (6). The simulation yielded a conversion coefficient K_{E/T}^{MC} = 1.93 (0.01 %eU/cps) with R^2 = 0.999, while experimental data gave K_{E/T} = 2.07 (0.01 %eU/cps). The simulation-experiment deviation is 7.25%, confirming that simulation results align with PFNUL principles based on epithermal-to-thermal neutron ratios.

C. Variation of the scale factor for different neutron source intensities

Based on experimental data, epithermal neutron counts for different neutron source intensities and uranium contents were calculated within 200–800 μs, and linear relationships between epithermal neutron counts and uranium content were fitted, as shown in Fig. 8 Figure 8: see original paper. The figure clearly shows a good linear relationship between epithermal neutron counts and uranium content, but epithermal neutron counts for the same uranium content vary with neutron source relative intensity. Neutron tube production fluctuations during uranium measurement significantly impact epithermal neutron counting results, directly affecting measurement accuracy. After experimental time spectrum normalization, epithermal and thermal neutron counts from 200–800 μs for different uranium contents across four experimental sets were calculated, and corresponding E/T values were determined. Linear fitting of E/T values versus uranium content produced the relationship curves shown in Fig. 8(b).

Linear fitting results showed that uranium quantification scale factors K_E based on uncorrected epithermal neutron counting were 6896.2, 16110.6, 16381.2, and 13434.1 across the four experiments, with an RSD of 33.41%. In contrast, scale factors K_{E/T} based on E/T values were 2.07, 2.02, 2.03, and 2.05, respectively, with an RSD of only 1.09%. This proves that the dual neutron time spectrum E/T-based uranium quantification method enables accurate uranium analysis with scale factors unaffected by neutron tube yield fluctuations, effectively improving neutron logging instrument service life.

V. CONCLUSION

This research proposes a PFNUL method with upper and lower detection structures based on prompt fission reactions between uranium and neutrons. By extracting secondary neutron fading laws from epithermal neutron time spectra and primary neutron slowing laws from thermal neutron time spectra, we developed a uranium quantification algorithm based on dual neutron time spectrum E/T values, achieving "direct uranium measurement" and quantification via prompt fission neutron logging.

Monte Carlo simulations determined saturated neutron uranium logging model dimensions of $R \geq 60$ cm and $H \geq 120$ cm, with time window (Δt) boundaries of $t_1 = 200$ μs and $t_2 = 800$ μs. Simulation results demonstrated a strong positive relationship between E/T values and uranium content, with a scale factor of 1.93 and $R^2 = 0.999$. Experiments using saturated uranium models verified this relationship and compared results across different neutron source intensities in standard uranium ore models. These results prove that the method maintains E/T value stability under varying neutron source intensities, reducing the uranium content scale factor RSD from 33.41% to 1.09% compared to single epithermal neutron quantification. Thus, the method effectively eliminates neutron source yield fluctuation effects, ensures logging process uranium quantification accuracy, extends neutron tube service life, and reduces neutron uranium logging costs, holding significant value for PFNUL popularization and application.

VI. CONTRIBUTIONS STATEMENT

All authors contributed to study conception and design. Yan Zhang, Chi Liu, Hai-Tao Wang, Xiong-Jie Zhang, Zhi-Feng Liu, Jin-Hui Qu, Ren-Bo Wang, and Bin Tang performed material preparation, data collection, and analysis. Yan Zhang and Chi Liu wrote the manuscript first draft, and all authors commented on previous versions. All authors have read and approved the final manuscript.

VII. CONFLICT OF INTEREST

The authors declare that they have no competing interests.

VIII. DATA AVAILABILITY STATEMENT

The data supporting this study' s findings are openly available in the Science Data Bank at: 10.57760/sciencedb.09149

REFERENCES

[1] H.R. Zhang, Y. Zhang, W.X. Hu et al., Simulation study of uranium content in uranium yellow cake using the active multiplicity method. Nucl. Tech. 47(02), 020202 (2024). doi: 10.11889/j.0253-3219.2024.hjs.47.020202

[2] L.G. Howell, A.Frosch, Gamma-ray Well-Logging. Geophysics. 4(2), 106-114 (1939). doi:10.1190/1.1440486
[3] J.S. Wahl, Gamma-ray logging. Geophysics. 48(11), 1421-1560 (1983). 10.1190/1.1441436
[4] R.A. Broding, B.F. Rummerfield, Simultaneous Gamma Ray and Resistance Logging as Applied to Uranium Exploration. Geophysics. 20(4), 745-961 (1955). 10.1190/1.1438193
[5] P.G. Killeen, Borehole Logging for Uranium by Measurement of Natural γ-Radiation. Int. J. Appl. Radiat. Isot. 34, 231-260 (1983). doi:10.1016/0020-708X(83)90128-X
[6] R.L. Caldwell, Nuclear Logging Methods. Radioisotopes. 17(4), 171-185 (1968). doi: 10.3769/radioisotopes.17.4_{171}
[7] R. Chen, Y.L. Cheng, H.T. Wang et al., A union neutron-gamma logging method for determination of uranium-radium disequilibrium coefficient. Nucl. Technol. Radiat. Prot. 35(2), 103-108 (2020). doi:10.2298/NTRP2002103C
[8] L. Zhang, H.W. Yu, T. Li et al., Improved formation density measurement using controllable D-D neutron source and its lithological correction for porosity prediction. Nucl. Sci. Tech. 33, 3 (2022). doi:10.1007/s41365-022-00988-1
[9] B. Tang, Y.P. Wu, X.J. Zhang et al., Direct uranium quantitative detection in high precision γ-logging by 1.001 MeV ^{234} Pa γ-ray. Nucl. Tech. 35(10), 745-750 (2012).
[10] C. Lin, Y.Q. Chen, Q.W. Zhang et al., Calculation of U, Ra, Th and K contents in uranium ore by multiple linear regression method. Nucl. Tech. 6, 369-371 (1991).
[11] F. Zhang, L.L. Tian, Research Development and Tendency of Controllable Neutron and X-ray Source Well Logging Technology. J. Isot. 32(3), 133-150 (2019). doi: 10.7538/tws.2019.32.03.0133
[12] T. Marchais, B. Pérot, C. Carasco et al., Low-Resolution Gamma Spectrometry of Uranium Ores to Determine U Concentration and U/Rn Imbalance. IEEE Trans. Nucl. Sci. 69(4), 761-767 (2022). doi:10.1109/TNS.2021.3129343
[13] P. Sahu, D.P. Mishra, D. Panigrahi et al., Radon emanation from low-grade uranium ore. J. Environ. Radioact. 126, 104-14 (2013). doi:10.1016/j.jenvrad.2013.07.014
[14] W.M. Yin, H.Z. Liu, B. Tang et al., Determination of Uranium-Radium Equilibrium Coefficient of Uranium Ore Sample Using Characteristic Peaks in γ-ray Spectrum. At. Energy Sci. Technol. 44(7), 769-772 (2010). doi: 10.7538/yzk.2010.44.07.0769
[15] C.W. Tittle, L.S. Allen, Theory of neutron logging; II. Geophysics. 31, 214-224 (1961). doi:10.1190/1.1439737
[16] L.S. Allen, C.W. Tittle, W.R. Mills, Dual-Spaced Neutron Logging for Porosity. Geophysics. (1967). doi:10.1190/1.1439857
[17] J.A. Czubek. Pulsed Neutron Method for Uranium Well Logging. Geophysics. doi:10.1190/1.1440244 32(1), (1970).
[18] J.H. Renken. Determination of the Probing Distance in Pulsed-Neutron Uranium Logging Experiments. Nucl. Sci. Eng. 63(3), 330-335 (1977). doi:10.13182/NSE77-A27044

[19] J.H. Renken. Comparison of predicted signals from the delayed fission neutron and prompt fission neutron uranium logging methods. J. Appl. Phys. 49(2), 6153–6159 (1978). doi:10.1063/1.324538
[20] X.G. Wang, D. Liu, F.Zhang, Development of pulsed neutron uranium logging instrument. Rev. Sci. Instrum. 86(3), 034501 (2015). doi:10.1063/1.4913660
[21] R. Temirkhanova, Application of Prompt Fission Neutron Logging to the Uranium Deposits of Stratified Infiltration Type. 14th Sgem Geoconference on Science and Technologies in Geology, Exploration and Mining (2014). doi:10.5593/SGEM2014%2FB11%2FS5.055
[22] Z.F. Liu, C.L. Ding, R.Y. Wang et al., Current Status and Development Trend Analysis of Neutron Logging in Uranium Mines in China. J. Phys.: Conf. Ser. 1865(2), 022006 (2021). doi:10.1088/1742-6596/1865/2/022006
[23] Z.F. Liu, B. Tang, Z.H. Wei et al., Correction Algorithm of Epithermal Neutron Decay Time Spectrum for Uranium Pulsed Neutron Logging. For. Chem. Rev. . 1368–1376 (2022). www.forestchemicalsreview.com
[24] J.M. Verbeke, K.N. Leung, J.Vujic, Development of a sealed-accelerator-tube neutron generator. Appl. Radiat. Isot. 53(4-5), 801–809 (2000). doi:10.1016/S0969-8043(00)00262-1
[25] L.A. Shope, R.S. Berg, M.L. O' Neal et al., The operation and life of the Zetatron neutron tube in a borehole logging application. Int. J. Appl. Radiat. Isot. 34(1), 269–272 (1983). doi:10.1016/0020-708X(83)90130-8
[26] S.J. Vala, M. Abhangi, Ratnesh Kumar et al., Development and performance of a 14-MeV neutron generator. Nucl. Instrum. Methods Phys. Res., Sect. A. 959, 163495 (2020). doi:10.1016/j.nima.2020.163495
[27] W.B. Liu, M.J. Li, K.Gao et al., Discharge characteristics of a penning ion source for compact neutron generator. Nucl. Instrum. Methods Phys. Res., Sect. A. 768, 120–123 (2014). doi:10.1016/j.nima.2014.09.052
[28] W.T. Guo, S.J. Zhao, S.W. Jing et al., Effect of target film materials on neutron yield of neutron tube with drive-in target. Radiat. Phys. Chem. 182, 109358 (2021). doi:10.1016/j.radphyschem.2021.109358
[29] X.Q. Chen, L. Xiong, H. Xie et al., A high-stability industrial online elemental analysis neutron generator. Nucl. Eng. Technol. 56(4), 1441–1453 (2024). doi:10.1016/j.net.2023.11.048
[30] B. Tang, R.B. Wang, S.M. Zhou et al., Chinese patent 201310408465. 6,13 Sep. 2013.
[31] B. Tang, R.B. Wang, S.M. Zhou et al., Chinese patent 201320592725. 5,2 Apr. 2014.
[32] B. Tang, H.T. Wang, R. Cheng et al., Chinese patent 201810076976. 5,6 Aug. 2018.
[33] B. Tang, R.B. Wang, S.M. Zhou et al., Chinese patent 201310440359. 6,13 Sep. 2013.
[34] W.W. Givens, W.R. Mills Jr., Logging technique for assaying for uranium in earth formations. United States: N. p.,1979. Web. https://www.osti.gov/biblio/5327390
[35] Y. Zhang, C. Liu, S.L. Liu et al., Prompt Fission Neutron Uranium

Logging(II): Dead-time effect of neutron time spectrum. Nucl. Sci. Tech. 36(2), 19 (2025). doi:10.1007/s41365-024-01615-x
[36] Y. Jin, F.L. Chen, X.Y. Chai et al., Development and Application of Nuclear Logging Technique. At. Energy Sci. Technol. 38(S1), 201–201 (2004). doi: 10.7538/yzk.2004.38.S1.0201
[37] X.F. Meng, G.S. Guo, L. Zhang et al., Neutron shielding property test with combination detection method based on moderation sphere detectors. Nucl. Sci. Tech. 39(5), 050201 (2016). doi: 10.11889/j.0253-3219.2016.hjs.39.050201
[38] X.G. Wang, G.B. Wang, G.G. Zhang et al., The Monte Carlo Simulation of Pulsed Neutron-Fission Neutron Uranium Logging Technique. J. Isot. 26(1), 48–52 (2013). doi: 10.7538/tws.2013.26.01.0048
[39] Y. Zhang, B. Tang, W.B. Jia et al., Application of the Monte Carlo Library Least-Squares (MCLLS) approach for chromium quantitative analysis in aqueous solution. Appl. Radiat. Isotopes. 150, 39–42 (2019). doi: 10.1016/j.apradiso.2019.02.018
[40] Y. Zhang, W.B. Jia, R. Gardner et al., Study on the PGNAA measurement of heavy metals in aqueous solution by the Monte Carlo–Library Least-Squares (MCLLS) approach. Appl. Radiat. Isotopes. 132, 13–17 (2018). doi: 10.1016/j.apradiso.2017.10.037

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