

Prompt Fission Neutron Uranium Logging (III): Logging Instrument

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Abstract

The domestically developed prompt fission neutron uranium logging(PFNUL) instrument for uranium exploration represents a significant advancement in China deep uranium mining efforts, though it comes with considerable challenges and complexity. This paper presents the development of a new prompt fission neutron uranium logging instrument(named UNL4) , integrates a domestic D-T neutron generator, two ^3He proportional detectors, a lanthanum bromide (LaBr_3) gamma-ray detector, and digital multi-channel pulse amplitude analyzer. The near ^3He detector is shielded with 1mm of Cadmium (Cd) and 5mm of high-density polyethylene(HDPE), enabling efficient epithermal neutron detection, while the far ^3He detector measures thermal neutron. The LaBr_3 detector is employed for gamma-ray detection, primarily originating from uranium decay. High-speed ADC and FPGA technologies were used to achieve rapid acquisition and transmission of both dual neutron time spectra and gamma spectra. Moreover, this paper proposes a fast signal shaping method, which reduces the dead time effect in ^3He detectors on neutron time spectra. Experiments conducted in standard model boreholes with varying uranium content demonstrated a strong linear relationship between the epithermal-to-thermal neutron ratio (E/T) and uranium content, with a fitting coefficient of $R^2 > 0.999$, confirming the instruments accuracy. The E/T value repeatability, both in short-term (3.16% RSD) and long-term (1.2% RSD) measurements, showed excellent stability. In addition, the instrument demonstrated good performance at neutron logging speeds of 0.3 3 m/min (E/T values) and gamma logging speeds of 1 10 m/min. By conducting measurements in two ore sections of the PU model with lithium contents of 87.1 ppm and 45.6 ppm, the RD is less than about 10% in both logging cases, meeting the requirements for engineering applications. This marks the first successful development of a neutron logging instrument for uranium exploration based on a domestic neutron generator, signifying an

important contribution to uranium resource exploration.

Full Text

Preamble

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The domestically developed prompt fission neutron uranium logging (PFNUL) instrument for uranium exploration represents a significant advancement in China's deep uranium mining efforts, though it comes with considerable challenges and complexity. This paper presents the development of a new prompt fission neutron uranium logging instrument (named UNL4), which integrates a domestic D-T neutron generator, two ³He proportional detectors, a lanthanum bromide (LaBr₃) gamma-ray detector, and a digital multi-channel pulse amplitude analyzer.

The near ³He detector is shielded with 1 mm of cadmium (Cd) and 5 mm of high-density polyethylene (HDPE), enabling efficient epithermal neutron detection, while the far ³He detector measures thermal neutrons. The LaBr₃ detector is employed for gamma-ray detection, primarily originating from uranium decay. High-speed ADC and FPGA technologies were used to achieve rapid acquisition and transmission of both dual neutron time spectra and gamma spectra. Moreover, this paper proposes a fast signal shaping method that reduces the dead time effect in ³He detectors on neutron time spectra. Experiments conducted in standard model boreholes with varying uranium content demonstrated a strong linear relationship between the epithermal-to-thermal neutron ratio (E/T) and uranium content, with a fitting coefficient of $R^2 > 0.999$, confirming the instrument's accuracy. The E/T value repeatability showed excellent stability, both in short-term (3.16% RSD) and long-term (1.2% RSD) measurements. In addition, the instrument demonstrated good performance at neutron logging speeds of 0.3–3 m/min (E/T values) and gamma logging speeds of 1–10 m/min. By conducting measurements in two ore sections of the PU model with uranium contents of 87.1 ppm and 45.6 ppm, the relative deviation (RD) was less than about 10% in both logging cases, meeting the requirements for engineering applications. This marks the first successful development of a neutron logging instrument for uranium exploration based on a domestic neutron generator, signifying an important contribution to uranium resource exploration.

Keywords: Uranium exploration; Neutron logging instrument; Pulsed neutron; Neutron time spectrum detection

Introduction

Nuclear power is one of the most promising methods for efficiently and sustainably producing hydrogen on a large scale without emitting carbon dioxide. Uranium ore, as the primary source of fuel for nuclear energy generation, is crucial for the development of the nuclear power industry. Since the beginning of the 21st century, countries around the world have initiated mineral exploration efforts and developed intelligent technologies and equipment for mineral exploration and development, providing technological support for energy conservation and emission reduction [?].

The uranium logging method based on pulsed neutron technology allows for the direct measurement of uranium (^{235}U) content without the need for core sampling, and it is not affected by the gamma rays from other radioactive nuclides such as thorium and potassium [?]. Since the 1970s, countries including the United States, Canada, Germany, and the former Soviet Union have conducted research and experiments on neutron logging techniques for direct uranium measurement. It is widely recognized that collecting neutron time spectra is an effective method for quantifying uranium [?]. However, it is essential to utilize neutron sources with ultra-short pulse widths and high yields, such as the pulsed neutron uranium logging system ANHK-60 developed by the Russian All-Russian Institute of Automated Design (VNIIA), which employs a D-T neutron generator with a pulse width of 1 μs and a single pulse yield of approximately 10^8 n/pulse, but its operational lifespan is limited to only 150 hours [?, ?].

In recent years, research on neutron logging has primarily focused on methods, theory, and simulation studies, with fewer reports on related instruments [?, ?]. This is largely due to the significant challenges involved in developing uranium logging instruments. One key requirement is the use of compact neutron emitters that produce ultra-short pulses (on the order of microseconds) with high neutron yields. Currently, only a few countries, including Russia, the United States, and France have developed such technology. Examples include Russia's ING-10-20-120 model D-T neutron emitter, France's Genie 16NG, and the U.S. RTNS-II and P383 systems [?]. Another challenge is detecting and collecting the neutron signals generated by these short-pulse, high-yield neutron sources. The widely adopted approach is to use high-efficiency ^3He proportional counters to detect epithermal or thermal neutrons. Epithermal neutron detectors are used to detect prompt neutrons produced by uranium fission, which are essential for uranium quantification [?]. For example, the Russian ANHK-60 logging instrument includes six GM tubes to detect gamma rays from lead and boron, forming a monitoring system for neutron source yield, thus mitigating the impact of source flux fluctuations. The U.S. PFN system is equipped with six miniature ^3He proportional counters to achieve similar functionality [?].

In the past decade, the author team has conducted extensive research in the field of neutron logging for uranium. Through both theoretical and experimental work, they proposed a method based on the ratio of epithermal neutrons (E) to thermal neutrons (T), referred to as “E/T” [?]. This method is not affected by fluctuations in the neutron source yield, allowing for an extended operational lifespan of the neutron source [?]. Therefore, the uranium logging instrument discussed in this paper utilizes two ^3He proportional counters. The first, located closer to the source, is wrapped in cadmium and high-density polyethylene for epithermal neutron detection, while the second, farther from the source, detects thermal neutrons [?]. However, factors such as gas pressure and the material and size of the wrapping layers significantly affect neutron detection efficiency, which is a key topic of this study. Given that the smallest exploration boreholes are only 9 cm in diameter, existing commercial multi-channel analyzers for time and energy spectra do not meet the size requirements for logging instruments, and the large data volumes generated require redesign and customization. This paper proposes using high-speed ADC and FPGA technology to enable rapid acquisition and transmission of dual neutron time spectra, combined with pulse shaping techniques and time spectrum processing algorithms, to meet the specific needs of logging instrumentation [?].

Finally, a series of experiments were conducted using the independently developed prompt fission neutron uranium logging instrument (UNL4) in five standard model boreholes at the Nuclear Industry Airborne Survey and Remote Sensing Center. The calibration results from these model boreholes with varying uranium concentrations demonstrated a strong linear relationship in the uranium content calibration equation, comparable to that obtained using the probe equipped with the Russian neutron tube. The instrument also performed well in both short-term and long-term repeatability tests conducted in the same model boreholes, ensuring accurate calibration of uranium content. A comparison of logging curves at different speeds indicates that the measurement performance is satisfactory at neutron logging speeds ranging from 0.3 to 3 m/min and gamma logging speeds from 1 to 10 m/min. This instrument fills a critical gap in the independent development of neutron logging instruments for uranium exploration in China and holds significant importance for uranium resource exploration and the country’s energy security.

Instruments and Experiments

A. Logging Instrument

The uranium logging instrument developed by our team, as shown in Fig. 1 [Figure 1: see original paper], comprises three main components: (1) neutron source, including a D-T neutron tube and neutron emitter; (2) detection unit, featuring two ^3He neutron detectors and a gamma detector; and (3) electronics unit, consisting of a digital multi-channel pulse amplitude analyzer.

The D-T neutron sources used in the experiments primarily include the Russian

ING-10-20-120 model and the FH-G5DT model from Fan-Hua Testing Technology Co., Ltd., with detailed parameters listed in Table 1. These sources are mainly used for emitting pulsed neutrons. The ^3He neutron detectors, also provided by Fan-Hua Testing Technology Co., Ltd., are referred to as the near ^3He detector and the far ^3He detector, based on their proximity to the neutron source. The near ^3He detector is wrapped in cadmium (Cd) metal and high-density polyethylene and is designed to detect epithermal neutrons, while the far ^3He detector is used for detecting thermal neutrons in the borehole. The gamma detector employed is a lanthanum bromide (LaBr_3) detector, positioned at a greater distance from the neutron source to minimize the effects of gamma rays produced by neutron activation. The primary function of the LaBr_3 detector is to detect the natural gamma radiation emitted by uranium ore, providing an initial estimate of the ore layer's location [?]. The electronics unit consists of time spectrum and energy spectrum acquisition components. It utilizes a fully digital design, incorporating high-speed A/D conversion, FPGA, and DSP technology. This setup enables high-speed sampling of neutron and gamma ray signals and intelligent processing of dual-energy neutron time spectra and gamma energy spectra. The system can operate both independently and in coordinated synchronization, offering enhanced performance. Further details are provided in the following sections.

B. Epithermal and Thermal Neutron Detection

^3He gas detectors are commonly used for thermal neutron detection due to their high efficiency in capturing thermal neutrons. However, during uranium fission reactions in the formation, fast neutrons with energies ranging from 0 to 3 MeV are generated. These fast neutrons are then slowed down within the formation, becoming epithermal neutrons. By detecting the number of epithermal neutrons, it is possible to estimate uranium content. In oil well logging, ^3He gas detectors are often encased in cadmium (Cd) metal and a moderating material, such as high-density polyethylene (HDPE), to detect epithermal neutrons, as shown in Fig. 2 [Figure 2: see original paper]. The Cd metal absorbs thermal neutrons from the borehole, preventing their contribution to the measurement, while the moderating material further slows down epithermal neutrons to thermal neutrons, thus enhancing detection efficiency.

Using the Monte Carlo simulation method, the thickness of the cadmium (Cd) metal and the moderating material (HDPE) for the aforementioned epithermal neutron detector was simulated. The results are shown in Fig. 3 [Figure 3: see original paper]. From Fig. 3a, it is evident that as the thickness of the cadmium (Cd) increases, the shielding efficiency of the epithermal neutron detector for thermal neutrons rises rapidly. When the Cd thickness reaches 1 mm, the shielding efficiency achieves 100%, effectively blocking thermal neutrons. Consequently, the thickness of the Cd metal in the epithermal neutron detector is set to 1 mm. Fig. 3b shows that as the thickness of polyethylene increases, the counts of epithermal neutrons detected by the detector in both uranium-free

(background) and uranium-containing formations also increase. This indicates that the added layer of HDPE not only slows down the source neutrons but also the neutrons produced by uranium fission. Therefore, the counts include both the epithermal neutrons generated by uranium fission and those produced by the D-T neutron generator. Considering the spatial constraints of the detector probe and other factors, the thickness of the HDPE layer is determined to be 5 mm. The final specifications and parameters for the epithermal and thermal neutron detectors are detailed in Table 2 .

Subsequently, the detection sensitivity of the thermal neutron detector and the epithermal neutron detector of different energies (ranging from 0.001 eV to 10 MeV) was calculated using Monte Carlo simulations. The sensitivity results are shown in Fig. 3. As illustrated in Fig. 3c, the thermal neutron detector exhibits high sensitivity within the low-energy neutron range, with sensitivity rapidly decreasing as neutron energy increases. Fig. 3d shows that the designed epithermal neutron detector is more sensitive to epithermal neutrons, while its sensitivity to low-energy and fast neutrons is relatively low. The simulation results confirm that the parameters determined for the epithermal and thermal neutron detectors effectively measure formation thermal neutrons and epithermal neutrons produced by uranium fission.

C. FPGA-Based Digital Circuitry

The dual-energy neutron time spectrum measurement unit designed for the project primarily consists of the following components: dual neutron detectors and their high-voltage driving module, a pre-amplifier circuit, shaping amplifier circuit, polarity conversion circuit, baseline restoration circuit, signal discrimination circuit, pulse counting unit, and data analysis and communication modules. The detailed circuit structure is illustrated in the block diagram shown in Fig. 4 [Figure 4: see original paper].

A digital FPGA chip (the radiation-resistant M2S010 from ACTEL) was selected as the core component to enable pulse counting for both epithermal and thermal neutrons, while also generating the corresponding time spectrum curves. Upon receiving a synchronized measurement signal from the pulsed neutron generator, the FPGA starts counting pulse signals from the epithermal and thermal neutron detectors. The counts for both detectors are accumulated using a fine time-channel width of 2 μ s, thus achieving precise dual-energy neutron time spectrum acquisition. The system simultaneously collects neutron energy and time spectra. By analyzing the shape of the neutron energy spectrum curve, a threshold is set for the countable neutron pulses, which ensures that the time spectrum only includes valid neutron pulses, excluding noise and preventing the loss of effective neutron counts. This method ensures high accuracy in both the neutron energy spectrum and the time spectrum measurements. When traditional logging systems based on analog signals are applied to uranium logging, the presence of numerous analog components such as resistors, capacitors, and operational amplifiers makes them highly susceptible to temperature fluctua-

tions in downhole environments. This leads to significant temperature drift, which increases the complexity of subsequent spectral interpretation. In contrast, using a high-speed digital measurement system with key components such as high-speed A/D converters, FPGA, and DSP mitigates these issues. In this system, radiation pulse signals output by the detector are amplified and directly sampled in full pulse form by a high-speed A/D converter (with a sampling rate of 60 MHz and a precision of 12 bits/1V). This approach captures the entire pulse waveform rather than just the peak value, as done in traditional systems. With the FPGA's internal programmable digital circuits, algorithms like digital filtering and pulse shaping (using a dynamic trapezoidal shaping algorithm with adjustable parameters) are implemented. This allows for peak extraction, identification and separation of pile-up pulses, and generation of the energy spectrum curve. More complex tasks, such as dynamic temperature correction of pulse amplitudes and communication processing, are handled by the DSP. The designed digital measurement system includes a detector, preamplifier circuit, signal conditioning circuit, high-speed A/D converter, FPGA, and DSP. The influence of power noise ripple and other electronic interference on the energy spectrum is controlled to ≤ 5 mV/1V, meaning that for a 1024-channel energy spectrum, noise contributes to no more than 5 channels.

D. Pulse Fast Shaping for Neutron Time Spectrum

In the dual-neutron time spectrum detection system, a key challenge arises due to the high neutron count rate detected by neutron detectors immediately after the neutron pulse is emitted by the neutron source. This can cause significant pulse pile-up, particularly when using standard charge-sensitive preamplifier circuits paired with ^3He proportional counters, which have prolonged tail times on the signal decay. This pile-up effect often leads to saturation in the counting rate. To address this issue, a charge-sensitive preamplifier circuit based on narrow pulse shaping was designed for the neutron detector, significantly improving the pulse throughput of neutron signals. Additionally, the electronics system incorporates full-pulse high-speed sampling technology, where the raw input pulse signals are directly sampled by a high-speed ADC, providing a complete waveform of the radiation pulse. The programmable digital circuits inside the FPGA implement triangular shaping algorithms, enabling the development of a dual-neutron time spectrum measurement system for PFNUL under high count rates. This narrow pulse shaping technique allows the processing of wider detector pulses into narrower pulses, facilitating counting measurement at high pulse throughputs [?]. The shaped pulse width is adjustable, and the experimental results, as shown in Fig. 5a [Figure 5: see original paper], demonstrate a reduction in signal pulse width from 1 μs to 300 ns. This enhancement increases the pulse processing capability of the electronics system from 100k to over 330k, ensuring the validity of the count measurements under high count rate conditions. After being processed by the anti-saturation neutron detection system, the time spectra before and after fast shaping were obtained in the logging model for practical testing, as shown in Fig. 5b [Figure 5: see original

paper].

Additionally, the project conducted research on the time spectrum variation patterns of epithermal and thermal neutrons under high count rates. In the software processing phase, a dead time correction algorithm was incorporated to account for the effects of pulse pile-up. This algorithm converts the observed pile-up count rate into the theoretical pulse count rate, thereby improving the accuracy of uranium quantification during the uranium logging process [?, ?].

Logging Experiments

Using the independently developed PFNUL instrument UNL4, a series of experiments were conducted in five standard model wells at the Nuclear Industry Aerial Survey and Remote Sensing Center. These wells consisted of cylindrical concrete models, identified as Nb4, Nu1, Nu2, and Nu3, with uranium concentrations of 0.000156%, 0.0280%, 0.0684%, and 0.0982%, respectively. The Nb4 model, with a uranium grade far below the detection limit, was defined as a pure sandstone model without uranium. Each cylindrical model measured 1.4 m in diameter and 1.8 m in height. The borehole diameter of the models was 90 mm, and each model was topped with a 0.9 m thick concrete cover and a 0.3 m thick concrete base. Beneath the base, an extended borehole of 2.6 m in depth ensured that the size requirements for saturated uranium models were met. Another logging model, identified as PU, was a single cylindrical concrete structure with dimensions of 1.5 m in diameter and 5.3 m in height, along with an extended layer of 3 m at the bottom. It contains two 90 cm sections with uranium contents of 87.1 ppm and 45.6 ppm, respectively. This setup allowed for continuous measurement of the uranium section when logging within the PU model. Several experiments were carried out in these five model wells, as outlined below, including comparisons between different neutron tubes:

1. **Experiment #1: Neutron Source Comparison** - This experiment compared the performance of a probe with the domestically developed FH-G5DT neutron tube and a probe with the Russian ING-10-20-120 neutron tube in four uranium models, conducting point measurements.
2. **Experiment #2: Scale Factor** - Based on the time spectrum data, the E/T values of both neutron tubes were calculated at different uranium concentrations. A scale factor relating E/T values and uranium concentrations was then derived through fitting.
3. **Experiment #3: Stability Test** - In this experiment, short-term measurements were repeated 10 times for 5 seconds each, and long-term measurements were repeated 9 times for 1 hour each in the same uranium concentration model to assess stability.
4. **Experiment #4: Logging Speed Test** - In the Nu3 model, neutron (E/T values) logging was conducted at speeds of 0.3 m/min, 0.5 m/min, 1 m/min, 1.5 m/min, 2 m/min, and 3 m/min to compare the results at

different logging speeds, and gamma logging was conducted at speeds of 1 m/min, 2 m/min, 4 m/min, 6 m/min, 8 m/min, and 10 m/min.

The Russian ING-10-20-120 neutron tube utilizes a vacuum arc ion source, producing short pulses (1 μ s) with a maximum of 20 emissions per second. In contrast, the FH-G5DT neutron tube, manufactured by Pan Hua Detection Co., employs a Penning ion source, which generates longer pulses (150 μ s) and can emit up to 1000 times per second.

Results and Discussion

A. Comparison of Different Neutron Sources

The time spectrum results obtained from testing different neutron tubes under four uranium ore models are illustrated in Fig. 6 [Figure 6: see original paper]. Fig. 6a presents the results from the assembly of the Russian ING-10-20-120 model neutron tube, while Fig. 6b displays the results from the FH-G5DT model neutron tube. Due to variations in neutron tube manufacturing processes, the pulse widths for the neutron tubes were appropriately set to 10 μ s and 250 μ s during uranium ore measurements. The time spectrum results indicate a significant proliferation of epithermal neutrons with increasing uranium ore content.

From Fig. 6, it can be observed that the FH-G5DT neutron tube experiences a significant decline in the production of epithermal neutrons at approximately 250 μ s, leading to a very low counting rate of epithermal neutrons for times greater than 850 μ s. At this point, statistical fluctuations substantially affect the data, prompting the selection of 250 μ s to 850 μ s as the effective neutron time window. Similarly, the ING-10-20-120 neutron tube shows a significant decrease in epithermal neutron production around 200 μ s, with low counting rates for times exceeding 800 μ s, where statistical fluctuations also play a considerable role. Consequently, the effective neutron time window for this tube is defined as 200 μ s to 800 μ s. Within these time windows, epithermal and thermal neutron counts were calculated at various uranium content levels. The comparative results are illustrated in Fig. 7 [Figure 7: see original paper], which reveals substantial differences in the counting rates of epithermal and thermal neutrons between the two neutron tubes in the same model. These discrepancies are primarily attributed to the different ion sources employed by the two neutron tubes.

B. Scale Factor

Based on the aforementioned conditions, the uranium quantification time windows for the two neutron tubes are 200–800 μ s and 250–850 μ s, respectively. The E/T values were calculated according to the relevant data. Subsequently, a linear fitting of the relationship between the E/T values and uranium content was performed, as shown in Fig. 8 [Figure 8: see original paper]. The calibration

curves for the FH-G5DT and ING-10-20-120 neutron tubes were obtained, with calibration coefficients of 8.57 and 4.24, respectively, and goodness-of-fit values (R^2) of 0.9998 and 0.9996. Both neutron logging instruments demonstrated a strong linear calibration for the standard uranium ore model, with R^2 values exceeding 0.999. The results indicate that the neutron source, a key component of the neutron logging instrument, significantly influences the calibration coefficient. Therefore, it is essential to recalibrate the instrument when the neutron source is changed, using a standard model borehole.

C. Instrument Stability

1. Short-term Stability Measurement The UNL4 instrument conducted ten repeated measurements on the Nu3 model, using the relative standard deviation (RSD) as a metric to assess the instrument's stability, with the calculation formula as shown in Eqs.1 [?, ?]. The results and RSD calculations are illustrated in Fig. 9 Figure 9: see original paper. It can be observed that, across the ten repeated measurements, the counts of thermal neutrons, epithermal neutrons, and the E/T values exhibit good repeatability, with RSD values of 1.11%, 3.23%, and 3.16%, respectively.

$$\text{RSD} = \frac{\sqrt{\frac{\sum(\text{count}_i - \overline{\text{count}})^2}{n-1}}}{\overline{\text{count}}} \times 100\%$$

Where count_i represents the count for each data set, $\overline{\text{count}}$ is the average count from multiple tests, n denotes the number of repeated measurements, and RSD is the result of the relative standard deviation calculation, used to assess the stability of the instrument.

2. Long-term Stability Measurement The UNL4 neutron logging instrument was used to conduct nine 1-hour long-term measurements on the Nu3 model. The data from each hour were normalized, and parameters were selected based on the aforementioned time window. The effective thermal neutrons, epithermal neutrons, and E/T values within the time window were then calculated. Stability was analyzed using the RSD formula, with the specific data and calculation results shown in Fig. 9(e-f). As illustrated in the figures, the long-term stability of the neutron detection system shows that the long-term stability of thermal neutrons within the effective time window is 0.84%, that of epithermal neutrons is 1.49%, and that of the E/T values is 1.2%. These results demonstrate that the logging instrument exhibits excellent stability.

D. Experiments at Different Logging Speeds

The UNL4 neutron logging instrument was used to conduct measurements in the PU model well at the Remote Sensing Center, with neutron logging speeds set to 0.3 m/min, 0.5 m/min, 1.0 m/min, 1.5 m/min, 2 m/min, and 3 m/min, and

gamma logging speeds set to 1 m/min, 2 m/min, 4 m/min, 6 m/min, 8 m/min, and 10 m/min. The neutron logging curves obtained at these six different speeds are shown in Fig. 10 [Figure 10: see original paper]. It can be observed that at logging speeds ranging from 0.3 to 3 m/min, the uranium-bearing sections of the formation (red) can be accurately identified. The quantitative uranium curve (green) demonstrates good consistency with the theoretical curve (red). Table 3 lists the relative errors (RD) of the quantitative values for two uranium-bearing sections at different neutron logging speeds. The calculation formula for RD is shown in Eqs.2, where U_{meas} represents the quantitative mean value of the ore section, and U_{theor} is the theoretical value of uranium content. It can be observed that at logging speeds ranging from 0.3 to 3 m/min, the RD is below about 10%. These findings indicate that the instrument can achieve stable quantification of uranium content at logging speeds of 0.3 to 3 m/min.

$$\text{RD} = \frac{U_{\text{meas}} - U_{\text{theor}}}{U_{\text{theor}}} \times 100\%$$

The direct uranium content scale based on gamma counting was carried out under the gamma logging experiment at different logging speeds, and the results are shown in Fig. 11 [Figure 11: see original paper]. The RD results between the quantitative mean value and theoretical values of the two ore sections are shown in Table 4 ; the RD is below about 10%, with good stability and accuracy.

Instrument Performance Parameters

In summary, after a series of optimizations and related experiments, the instrument has been proven to achieve internationally leading standards for key technical indicators. Detailed performance parameter comparisons are shown in Table 5 . Due to the use of new pulse signal shaping hardware design in this instrument, the neutron signal pulse width has been effectively reduced, increasing the neutron detection efficiency. Coupled with a software dead-time correction algorithm [?], the time spectrum acquisition accuracy has been significantly improved, reducing the impact of dead time on uranium quantification. Additionally, the detector structure inside the probe has been optimized, and a uranium quantification algorithm based on the ratio of thermal neutrons to epithermal neutrons has been proposed [?]. This algorithm effectively reduces the impact of neutron source fluctuations, enabling accurate uranium content quantification. It can be observed that the neutron (E/T values) logging speed of the instrument has reached 3 m/min, the gamma logging speed has reached 10 m/min, and the detection limit is 45.6 ppm. The instrument's operational lifespan exceeds 250 hours, and the neutron pulse width can be adjusted as needed. Compared to three other instruments, this instrument demonstrates a significant performance improvement.

Conclusion

In this study, we developed a new uranium fission prompt neutron logging instrument (UNL4), marking the first use of a domestically produced FH-G5DT neutron emitter, two ^3He proportional detectors, a lanthanum bromide (LaBr_3) gamma-ray detector, and a digital spectrometer. The system employs high-speed ADC and FPGA technology to enable the rapid acquisition and transmission of dual neutron time spectra and gamma energy spectra. Additionally, a fast signal shaping method was proposed, which reduces the dead-time effect in ^3He detectors, thereby significantly improving neutron signal detection efficiency. Monte Carlo simulations were used to optimize the thickness of cadmium (Cd) and HDPE for epithermal neutron detection. The optimal configuration was determined to be a Cd thickness of 1 mm and an HDPE thickness of 5 mm for the near ^3He detector, enabling efficient detection of epithermal neutrons. The far ^3He detector was employed to detect thermal neutrons, while the LaBr_3 detector was used to detect gamma rays emitted by uranium ore itself.

Experimental results from standard borehole models with varying uranium content showed that the ratio of epithermal to thermal neutrons detected by instruments equipped with either the domestic FH-G5DT neutron tube or the Russian ING neutron tube exhibited a strong linear relationship with uranium content, with R^2 values of 0.9998 and 0.9996, respectively. This validated the effectiveness of the newly developed uranium fission prompt neutron logging instrument equipped with the domestic FH-G5DT neutron tube. Short-term testing indicated stability values of 1.11% for the thermal neutron count rate, 3.23% for the epithermal neutron count rate, and 3.16% for the E/T values. Long-term testing indicated stability values of 0.84% for the thermal neutron count rate, 1.49% for the epithermal neutron count rate, and 1.2% for the E/T values, confirming the instrument's high stability. In addition, the instrument demonstrated good performance at neutron logging speeds of 0.3–3 m/min (E/T values) and gamma logging speeds of 1–10 m/min. By conducting measurements in two ore sections of the PU model with uranium contents of 87.1 ppm and 45.6 ppm, the RD was less than about 10% at different neutron logging and gamma logging speeds, and the detection limit reached 45.6 ppm. This instrument fills a critical gap in China's uranium exploration neutron logging equipment and holds significant importance for the advancement of uranium exploration technology.

Contributions Statement

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Hai-Tao Wang, Yan Zhang, Chi Liu, Jian-Qiang Xu, Li-Jiao Zhang, Zhi-Feng Liu, Xiong-Jie Zhang, Rui Chen, Qi Liu, Ren-Bo Wang, and Bin Tang. Hai-Tao Wang and Yan Zhang wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Hai-Tao Wang and Yan Zhang contributed equally to this work and should be considered co-first authors.

Conflict of Interest

The authors declare that they have no competing interests.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are openly available at: <https://doi.org/10.57760/sciencedb.14086>

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