Current Status and Development Trend Analysis of Neutron Logging in Uranium Mines in China

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Abstract. Neutron logging is a method of measuring uranium fission neutrons by bombarding uranium in ore beds with neutrons emitted by neutron sources or neutron generators. The pulsed neutron logging technology of uranium ore has been popularized and applied in the United States, Russia, Australia and other countries. The key technology is almost monopolized by these countries, but the technology is prohibited in China. In the field of uranium logging, natural gamma logging has always been used in China for uranium quantification, which is characterized by large error, low efficiency, high cost and technical and economic bottlenecks. Due to the fact that the research and application of pulsed neutron log in the field of petroleum exploration and production is relatively mature in China, it is urgent to develop relevant logging instruments and uranium quantitative interpretation methods as independent intellectual property rights. This will lead to a change in the backward appearance of uranium logging. This paper analyzes the research status and development trend of neutron logging in uranium at home and abroad.

Keywords: Neutron Logging, Neutron Logging Technology Of Uranium Ore, Uranium Quantitative Interpretation Methods.

1. Principle of neutron logging in uranium ore

Pulsed neutron logging is a nuclear logging method based on the interaction between pulsed neutron and formation [1, 2]. Fast neutrons are generated by a downhole neutron generator placed in the borehole. Fast neutrons are produced by a downhole neutron generator placed in a borehole. After entering the wellbore and formation, inelastic scattering, elastic scattering, radiation capture, neutron activation, nuclear fission reaction and so on occur with the nucleus of the substance contained. Neutron decay time spectrum information in formation is recorded by neutron detector, and relevant parameters of borehole and formation are evaluated by extracting neutron decay time spectrum information. In uranium logging (take 235U as an example), the cross section of fast neutron is very...
small relative to that of thermal neutron (0.15%). The nuclear fission caused by fast neutron is mainly used for delayed measurement, while the fission reaction after the fast neutron slows down to thermal neutron can be used for instantaneous neutron logging. The inelastic scattering gamma curve of fast neutron is shown in Figure.1.

Figure 1. System design scheme.

Uranium ore pulsed neutron log (or uranium fission prompt neutron logging) is used to induce nuclear fission of 235U formation by pulsed neutron, then instantaneous neutrons are produced. And then they slow down to epithermal and thermal neutrons. By detecting the formation of the neutron (thermal and epithermal, with energy range, at 0.002eV to 0.025eV is thermal energy and power in 0.3eV to 0.5eV is epithermal) decay time spectrum [3], thus realize the quantitative interpretation method of uranium. In China, this method is still in its infancy, and the prototype of pulsed neutron logging tool has been developed successfully [4]. The instantaneous fission neutron energy spectrum of 235U is shown in Figure.2. The instantaneous fission neutron energy spectrum at the detector under formation conditions is shown in Figure.3.

Figure 2. Instantaneous fission neutron energy spectrum at $^{235}$U.
2. Development status of neutron logging in uranium ore abroad

About 99% of the natural gamma rays come from uranium, thorium, and potassium elements in the earth's crust, so the search for uranium deposits is almost impossible without natural gamma (total or energy spectrum) logging [5]. In the 1930s, Dresser Atlas research Center developed the first batch of gamma logging tools, which were mainly used in oil logging. In the 1960s, the United States, Soviet Union and other Western countries successively developed relevant methods and technologies for uranium exploration and quantification using gamma logging [6].

In the early 1970s, the polish scholar J.A.Czubek first proposed: when there is fast neutron irradiation of uranium formation rock, strata will slow fast into the nucleus of thermal. Thermal easy to make the 235U fission occurs, and release 2–3 secondary prompt neutron. When the instantaneous neutron reaches the epithermal neutron energy zone, measuring the epithermal regularly. The number (rate) of epithermal neutrons is proportional to the uranium content in the formation rock [7]. In the mid-1970s, many American scholars studied the method of uranium fission instantaneous neutron logging, systematically discussed the expression and developed the technology of Czubek model. According to different formation and material structure, neutron detector performance, neutron source emission yield and other conditions. The theoretical calculation was carried out by using the Monte Carlo simulation technology. It was found that the uranium content obtained according to the response of the epithermal neutron detector was far lower than the actual uranium content. In the 1970 s to 80 s, the U.S. department of energy (doe) for the financing of Sandia national laboratories W.W.Givens, H.M.Bivens, G.W.Smith, D.H.Jensen, W.R.Mills, D.R.Humphreyes scholars carried out such as uranium fission neutron logging method research [8], including uranium fission prompt neutron logging, delayed neutron logging two aspects, and focuses on pulsed neutron induced instant (delayed) of uranium fission neutron logging basic principle, detection technology and influence factors [9-12].

Last century after the end of the 1970s, due to the impact of the three Mile Island nuclear reactor accident in the United States. The research of uranium fission instantaneous neutron logging method, as well as the further improvement and industrialization of the logging tool were gradually discontinued and put on hold for more than 20 years. Since the turn of the 21st century, Sandia National Laboratory's patents on uranium fission instantaneous neutron logging have gradually expired and been published. On this basis, GeoInstruments commercialized it and reconstructed a standard model well with a quantitative scale of uranium, realizing the commercialization of uranium fission instantaneous neutron logging tool. In 2010, Australian Uranium Exploration Company (ASX: UXA), which is owned by Geo Instruments, took full responsibility for producing the uranium fission instantaneous neutron logging tool (which provides logging services only). At present, this tool is still the world's only commercially available nuclear logging system that can "directly measure uranium" and quantify uranium deposits. In recent years, Russia in automation research institute also rolled out

Figure 3. Instantaneous fission neutron energy spectrum is generated at the detector under formation conditions.
across the country based on uranium fission of prompt neutron probe АИНК-60 type of pulsed neutron logging tool, its technical level and basic quite early levels in Sandia LABS, but when measuring uranium ore grade is 0.01%, the relative error is 20%.

3. Domestic development status of neutron logging in uranium ore

In the early 1960s, China started the research of small portable controllable neutron generator, whose main application is in the field of logging. In the 1990s, a number of serialized products have been formed, the representative of which are MZ series and MZT series of Xi’an Petroleum Exploration Instrument General Plant [13] (as shown in Figure 4). Among them, MZ30 series of neutron tubes can work for 150h at 150°C and $1.5 \times 10^8$ n/s yield, the output of DSD series neutron tubes in Northeast Normal University is more than $1 \times 10^8$ n/s, and the service life exceeds 500h. In 2007, the Institute of Electronic Engineering of CaEE began to study the neutron tube with a yield of $10^9$ n/s to $10^{10}$ n/s, a life span of over 300h, and a maximum stable working time of not less than 16h per day. At present, some progress has also been made. Xi’an AoHua Electronic Instrument Co., Ltd. also launched the SNG series of neutron tubes in 2015 [14] (as shown in Figure 5), which can work for 300h at $1.5 \times 10^8$ n/s yield. In the 1990s, China Institute of Atomic Energy and Beijing Xin Cheng Technology Group started to develop neutron tubes, and successfully developed neutron tubes with high yield and high stability [15, 16]. However, the above-mentioned neutron generator tube diameter is relatively large, which is mainly used in the field of neutron activation analysis in petroleum exploration and industrial manufacturing. The main object of detection is thermal neutron or secondary gamma rays generated by neutron activation. It is not suitable for uranium ore logging with small pore size and ultra-thermal neutron detection object.

Figure 4. Pictures of MZ and MZT series neutron tubes.

Figure 5. SNG series neutron tube.
Because the key components and core technology of uranium fission instantaneous pulse neutron logging technology are controlled and blocked by developed countries in Europe and America, it has become a "jam" project of uranium exploration, mining and smelting technology progress in China. To break the monopoly and blockade of developed countries in Europe and America, Aerial Survey and Remote Sensing Center of nuclear Industry and East China University Of Technology research team under the strong support of the superior departments concerned, began to develop the fission neutron logging model standard device in 2000, and established the corresponding measurement standard for the first time, which played a leading role in the measurement; Uranium fission instantaneous neutron logging tool was first introduced in 2009, namely Russia in automation research institute introduced across the country АИHK-60 type pulse neutron logging tool, carried out the fission neutron logging tool calibration technology research. It mainly includes: Tang Bin, Zhang Feng, Zhang Jiyun and others discussed, studied and summarized relevant theories [15, 17-18]. Wang Xingguang et al. simulated PNFN response under different uranium content and formation porosity conditions by using Monte Carlo, and analyzed the relationship between instantaneous fission epithermal neutron and delayed fission thermal neutron and formation uranium content and porosity [19, 20]. Zhang Kunming et al. determined the decay time spectrum of fission epithermal neutrons using Monte Carlo simulation to determine the uranium content in uranium yellow cake [21]. Zheng Zhenfeng preliminarily studied the key technology of dual-neutron detection in pulse neutron uranium mine logging [22]. Wang Zhi studied the influence of different source distances of pulsed neutron logging tool in uranium mine on detection data and the correction method [23]. Most of the above research results from East China University Of Technology professor Shang Bin led the team, the team with the support of relevant state ministries and achieved initial success [24-26], lasted more than four years hard research, developed China's first neutron log uranium measurement and control system. This system uses multiple detector technology, and the uranium is measured directly.

4. Development direction of neutron logging in Uranium mines in China
Due to the limitations of neutron detector efficiency and neutron generator yield, at present the lower limit of neutron logging tool detection at home and abroad is basically 0.01% uranium content, and the logging speed is (0.3~0.6) m/min, so the detection efficiency is very low. In order to solving the problem of insufficient detection lower limit of fission neutron measurement technology in uranium exploration, mining and metallurgy, N-γ logging tool based on 3He gas detector needs to be developed and research on N-γ logging technology. It is expected to analyze the equilibrium coefficient of uranium radium through the statistic data of neutron and gamma logging in ore body or ore section, and solve the defects existing in gamma logging and neutron logging alone. Lower detection limit, improve detection efficiency, so that logging tool measurement characteristics meet the needs of uranium exploration, mining and metallurgy production.

The lower detection limit of neutron logging tool is directly related to the neutron yield and detector detection efficiency of neutron generator and is limited by the measurement principle of gas detector. Under the current technical conditions, it is difficult to improve the detection efficiency of 3He detector significantly. To lower the detection limit below 0.01%, it is necessary to further increase the neutron generator yield to improve the SNR at low uranium content. In order to meet the needs of uranium exploration, mining and metallurgy, the neutron generator with high yield can meet the practical requirements. It is necessary to further improve the product performance and quality reliability of the neutron tube by optimizing the material selection, processing, tube body, assembly, vacuum exhaust and tritium filling process of the structural components of the neutron generator. In addition, the design and optimization of target high-voltage power supply are completed by adopting appropriate high-voltage generator circuit, optimizing transformer and high-voltage insulation components, and the anode pulse power supply with steep front/back edge of pulse is studied to supply power to the ion source of neutron tube, so as to realize the stability and reliability of the high and middle sub-yield of neutron generator. To realize the localization of key components of N-γ logging tool and solve the bottleneck of "jam neck" technology.
The total logging tool used for uranium exploration, mining and metallurgy in China is mainly the gamma logging tool. Which has the advantages of high sensitivity, fast logging speed, high detection efficiency and low cost. However, for the in-situ leachable sandstone-type uranium deposit with serious damage to the uranium radium balance and great changes, it is difficult to accurately evaluate the uranium radium balance and radon balance. The evaluation of uranium reserves based on logging results depends entirely on the results of core sampling analysis in drilling. As a result, the exploration, mining and smelting technology of this type of uranium ore has been suffering from the insurmountable disadvantages such as low efficiency of core drilling, high cost of core sampling and long period of chemical analysis. In order to solve the technical problem, it is proposed to develop a built-in digital natural gamma spectrometer with good energy resolution, high detection efficiency and fast response speed by using the optimized combination of advanced LaBr3 scintillation crystal and photomultiplier tube. First, it is to measure natural energy spectrum, instead of the total amount of natural and natural energy spectrum; At the same time, it can be used to save the neutron tube consumption required by pulsed neutron logging (high cost, about 200,000-300,000 per tube). The other is to combine with neutron logging method to calculate the balance coefficient of ore layer (section) and increase the neutron velocity of uranium ore.

5. Conclusions
The pulsed neutron log has the advantages of high speed, high efficiency, accuracy and reliability. At present, the pulsed neutron log uranium content interpretation technology in China is still in its early stage of development, and some technologies and processes are still far behind those in foreign countries. The main development trends are as follows: (1) Continue to study the basic theories and methods of pulsed neutron log; (2) Forming a quantitative interpretation technology of pulse neutron logging uranium with independent intellectual property rights, looking for a breakthrough point for research and development of pulse neutron logging technology, producing related instruments, and breaking the monopoly of developed countries; (3) Strive to solve the correction problem of various factors affecting the interpretation of the detection data, conduct the finalization of the instrument exploration tube, improve the work efficiency and reduce the cost of transformation, and improve the interpretation accuracy of uranium content. In a word, the above hot research issues are also the focus and hot topic of foreign research. Due to the technical blockade imposed by foreign countries on this technology, it is also a difficult problem for China's current research in the field of uranium exploration.

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