Application of Four Neutron Logging in Formation Evaluation

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Abstract. In the middle and late stages of oilfield development, after various measurements, especially in low porosity and low salinity reservoirs, it is more difficult to evaluate oil and water layers, and the existing logging methods can not meet the production needs. In order to solve the above problems, four-neutron logging is introduced. The technology uses AmBe neutron source to collect the information of neutron-neutron and neutron-gamma dual physical processes through four detectors, which reduces the dependence on open hole information. The mud content is calculated by using activated aluminium element. When calculating porosity and identificating fluid, the method of dual physical process measurement is used. So the influence of the borehole environment and fluid properties are eliminated. It can also magnify the fluid response information, so as to accurately evaluate the physical properties and remaining oil distribution after casing. And in the meantime, it is sensitive to the gas-bearing response of reservoirs. Field application proves that the four neutron logging is effective in formation evaluation.

Keywords: Four neutron logging · AmBe neutron source · Formation evaluation · Dual physical process

1 Introduction

Stratigraphic evaluation, especially oil and water layer evaluation, has always been a crucial issue in the process of exploration and development of oil and gas fields. The proportion of waterflooding development in China's oilfields is very large. At present, many oilfields have entered the stage of high water cut or extra high water cut production. In order to maintain the stability of production, it is imperative to strengthen the evaluation of remaining oil. In fact, the key problem of remaining oil evaluation is formation evaluation, or the identification of oil and water layers, which has become a key and difficult point in oilfield development.

Logging technology is an important method of formation evaluation. Because formation water resistivity is not easy to determine after water injection development and the effect of conventional logging technology is limited, saturation logging technology

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has been widely used in formation evaluation field. Many saturation logging tools have been developed, such as neutron lifetime logging tool [1], carbon-oxygen ratio testing tool [2], reservoir monitor (RMT) [3], reservoir property. Energy Monitor (RPM) [4], Reservoir Saturation Logging (RST) [5], Pulse Neutron Attenuation Spectrum Logging (PND) [6], Pulse Neutron-Neutron (PNN) [7], Pulse Neutron Saturation Logging (PSSL) [8], Thermal Neutron Imaging (TNIS) [9, 10]. The above-mentioned methods have achieved good results in some blocks, but in some reservoirs with low porosity, low salinity or both, they can not meet the needs of residual oil monitoring. In addition, shale content and porosity are very important parameters in the interpretation of saturation logging data, which have a great impact on the interpretation conclusion; and the above-mentioned saturation logging methods can not meet the needs of conventional measurement. Well data depend heavily. Conventional logging data are often used to calculate shale content and porosity in data interpretation. Sometimes, conventional logging data is not accurate enough to calculate shale content and porosity, and even causes large errors, which directly leads to misjudgement of interpretation conclusions of saturation logging. Four neutron logging technology collects the information of neutron-neutron and neutron-gamma dual physical processes by four detectors, reduces the dependence on open hole information, calculates shale content by using activated aluminium element, eliminates the influence of borehole environment and fluid properties, enlarges fluid response information, and accurately calculates porosity and fluid identification by combining the measurement method of dual physical processes. The physical properties and remaining oil distribution of post-casing formation are evaluated, and the reservoir gas-bearing response is sensitive. Four-neutron logging technology provides new means for tapping potential of old wells, reservoir evaluation after casing and dynamic monitoring of oilfield development (residual oil evaluation).

2 A Brief Introduction to Four Neutron Logging

2.1 Measurement Principle

An important difference between four-neutron logging and other saturation logging methods is the use of chemical sources (americium beryllium neutron sources). The advantages of using chemical sources are relatively stable and long working time. Two neutron detectors and two gamma detectors are used to emit fast neutrons to the formation. Four detectors are used to obtain short-distance gamma counting rate (SNG), long-distance gamma counting rate (LNG), short-distance neutron counting rate (SNN) and long-distance neutron counting rate (LNN). The parameters of formation porosity, oil saturation and shale content are calculated by using the information detected in the neutron-neutron and neutron-gamma dual physical processes. Four-neutron logging can be measured by cable, steel wire, while drilling, crawler and coiled tubing. Data acquisition method is flexible, real-time mode and storage mode can be used. These advantages are conducive to expanding the application scope of four-neutron logging.

(1) Neutron-neutron process

Fast neutrons emitted from neutron sources collide with elements in the formation, and their energy gradually decreases, and then they become thermal neutrons until they are captured. This process is called fast neutron heating process, in which hydrogen plays a major role. Thermal neutrons are captured by other atoms in the stratum. High capture cross section will reduce the number of thermal neutrons. The main elements that play a role in this stage are chlorine and boron.

(2) Neutron-gamma process

The reaction between fast neutrons and atoms in the stratum will emit gamma rays, mainly from the collision between fast neutrons and nuclei, the capture of thermal neutrons and the ionization of electric field. At the same time, photoelectric effect and Compton effect will occur in the stratum. Gamma counting will decrease. This process is closely related to stratum density. Gamma rays pass through high density. The counting rate of substances decreases.

2.2 Technical Advantages

(1) Combining the information of neutron-neutron and neutron-gamma dual physical processes, we can provide a comprehensive set of post-set petrophysical interpretations, such as lithology, physical properties, oil-bearing properties, etc.
(2) Reducing the dependence on open hole information, wide formation adaptability, good application effect in low, high salinity or low porosity conditions;
(3) Deep detection depth is less affected by borehole irregularity and invasion.
(4) Real-time measurement or storage measurement, simple construction;

For comparison with other saturation logging tools, see Table 1.

Table 1. Comparison of several saturation logging tools

Company	Weatherford	Schlumberger	Baker Atlas	Halliburton	Hunter	Hotwell	Roke
Commercial name	PND-S	RST	RPM	RMT	RAS	PNN	Quad neutron
OD(In)	1.687	1.687	1.687	2.125	1.687	1.687	1.687
Log speed Σ (Ft/Hr)	1200	1800	900	1800	No spec	420	1500
Log speed C/O (Ft/Hr)	360 (Cato)	100	120	300	No spec	Na	Na
#Detectors	2	2	3	2	3	2	4
Neutron detector type	Na	Na	Na	Na	Na	2he3	2he3
Gamma detector type	2nai	2gso	3nai	2bgo	2nai, 1lacl	Na	2nai
Neutron source type	DT neutron generator						Am241be Chemical
Mean neutron energy	14.4 mev						4.5 mev
Depth of investigation(in)	12	10	12	6 Inelastic 12 Capture	No spec	No spec	18 To 36
Vertical resolution (in)	12	15	15	30	No spec	No spec	12
Memory Capable	No C/O	No	No C/O	No	Yes	No	Yes

3 Data Processing and Interpretation

3.1 Interpretation Model

(1) Mud content

Shale content is a very important parameter in log data processing and interpretation. Four neutron logging has two methods for calculating shale content. One is to calculate shale content with traditional GR curve, the other is to calculate shale content with QC (Quad Clay) curve. The calculation of shale content by QC curve is mainly based on two foundations. Firstly, according to the definition of petrophysics, clay is a mineral (kaolinite, montmorillonite, illite, etc.), while shale is a kind of clastic accumulation, clay and shale are interacted, and their contents are directly related. At the same time, the representative element of clay is aluminium (Al), regardless of illite, montmorillonite, illite, etc. Kaolinite contains aluminium, so aluminium, as an indicator element of clay, generates a large number of gamma rays after activation. Combining neutron-neutron and neutron-gamma measurements, the QC clay curve is obtained for calculating the shale content. The comparison of the effect of calculating shale content with GR and QC curves is shown in Fig. 1.

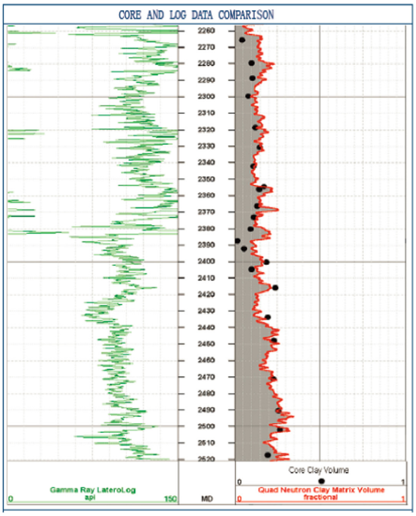

Fig. 1. Comparison of calculating shale content with GR and QC curves

The green color curve on the left side of Fig. 1 is GR curve. It is worth noting that the GR value of 2260–2380 m is higher than that of 2440–2500 m. If the shale content is calculated by GR, the result is that the shale content of 2260–2380 m is higher than that of 2440–2500 m, while the shale content of 2260–2380 m is lower than that of 2440–2500 m, so it is not feasible to calculate the shale content by GR. It is shown that the shale content of 2260–2380 m is lower than that of 2440–2500 m, which is consistent with core analysis. It can be shown that it is incorrect to calculate shale content by GR curve in this case, and reliable to calculate shale content by QC curve of four-neutron logging.

(2) Total porosity
Four neutron logging uses a neutron source of americium and beryllium and combines the principle of electric balance. Four detectors include two thermal neutron detectors and two gamma detectors. Thermal neutron detector detects the counting rate of thermal neutrons; gamma detector detects the total counting rate of collisions, captured gamma rays and ionized gamma rays. Combining the two methods to calculate the total porosity, the influence of irregular borehole tools on the porosity calculation is eliminated, and it is not affected by the skeleton and fluid type. Figure 2 is schematic diagram for calculating total porosity.

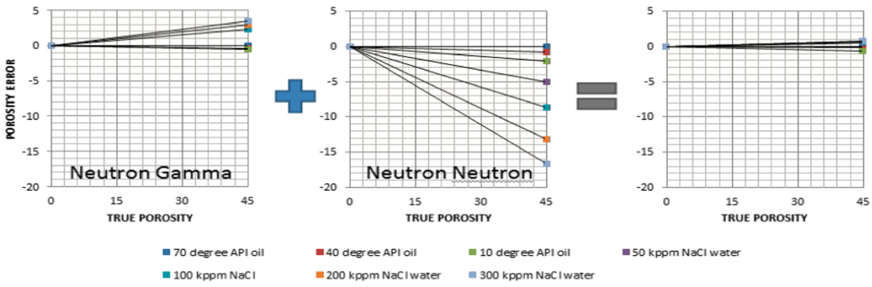

Fig. 2. Schematic diagram for calculating total porosity

(3) Effective porosity
Total porosity (QTP) is effectively porous (QEP) after shale correction.

$$QEP = QTP - Vsh * Hish \quad (1)$$

Vsh: mud content, HIV: mud hydrogen index.

(4) Fluid Recognition Curve (QL)
The purpose of applying fluid identification curve QL is to amplify fluid response information by combining neutron-neutron and neutron-gamma measurements, identify pore fluid types by combining with QTP, identify fluid properties and calculate saturation. Essentially, the size of envelope of QL and QTP is used to determine the oil content.

$$QL = A * Ln(\frac{LNN * LNG}{SNN * SNG}) + B \quad (2)$$

Among them, A and B values are determined by coincidence with the translation of the QTP. The size of envelopes of QL and QTP is affected not only by pore fluid, but also by dense intercalation. Therefore, density correction is necessary for QL curves.

(5) Oil saturation
When QL and QTP coincide in pure water and mudstone formation, the oil saturation of formation can be calculated according to the size of 100% water cut and 100% oil separation and the difference between them in actual measurement. The formula is as follows:

$$S_O = F\frac{QTP - QL}{\phi_{water} - \phi_{oil}} \tag{3}$$

F is the formation factor the relationship between graph QTP and QL is shown in Fig. 3.

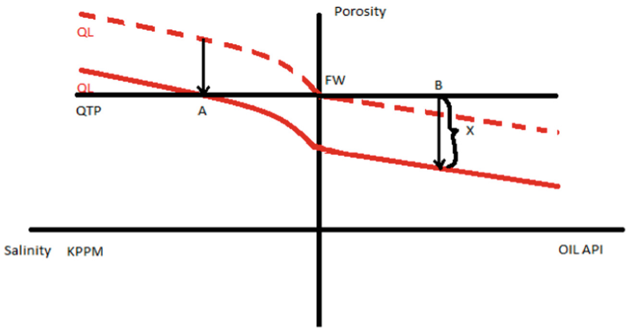

Fig. 3. The relationship between graph QTP and QL

(6) Relative Density (CE)
Both theoretical analysis and experiments show that the neutron and gamma counting rates increase with the increase of density, but the effect of density change on the gamma counting rate is greater than that on the neutron counting rate. The relative density CE is calculated by long-distance neutron counting LNN and long-distance gamma counting LNG. The main applications are: in reservoir section, fluid indicates high density material correction; identifying dense inter-beds to get more accurate lithologic profile; calculating CEP by CE, identifying gas reservoirs by combining CE, CEP and QTP.

3.2 Interpretation Process

(1) Quality check of original curve and curve proofreading. Four neutron logging also measures a GR curve, which can be used to complete depth calibration with open hole GR curve and collar curve CCL.
(2) Determining lithology. For example, the basic lithology of the interpretation area should be grasped as sandstone, limestone or other lithology. QC clay curve and CE relative density curve are important basis.

(3) Standardization of curves. Essentially, by gains and shifts, some curves overlap or separate at certain intervals. For example, four counting rate curves (SNG, LNG, SNN, LNN) are adjusted by gain and migration to match the span of QTP and make them overlap in mudstone or pure water layers; QL fluid curve and DDN overlap in mudstone and pure water layers; DDN-CEP neutron porosity and density porosity are separated in gas layers; and QTP and QL are separated in oil-bearing layers.
(4) Calculating oil and gas saturation. Oil saturation is mainly determined by the separation size between QTP and QL. CE density porosity and QTP coincidence are used as gas identification.
(5) Comprehensive evaluation. The interpretation of four neutron logging data should also refer to open hole evaluation, production data, geological research and other comprehensive interpretation.

4 Application Examples

Four neutron logging has been providing technical services abroad since 2000. Domestic application began in 2016. Up to now, about 200 wells have been applied, covering North China Oilfield, Liaohe Oilfield, Changqing Oilfield, Jilin Oilfield, Dagang Oilfield, Zhongyuan Oilfield, etc. Four-neutron logging plays an important role in lithology evaluation, physical property evaluation and oil-bearing evaluation of formation after casing, thus realizing comprehensive petrophysical interpretation of reservoir after production. It plays an important role in tapping potential of old wells, reservoir evaluation after casing and residual oil evaluation. Two examples are given to illustrate the application of four-neutron logging in residual oil evaluation.

4.1 Well A

The completion logging time of this well is January 2008. In 2008, Units No. 95, No. 96, No. 76–No. 80 were produced, and the initial daily oil production is 20 tons. In October 2010, the original production interval was plugged, and Units No. 63–No. 66 were perforated. The daily oil production is 25.9 tons. In 2015, the water cut of this well rose rapidly to about 85%. Four-neutron logging was carried out in December 2016 in order to understand the distribution and physical properties of remaining oil in each unit and to provide basis for formulating measures. The Fig. 4 is the result of four-neutron log interpretation in Well A. It can be seen from the graph that the envelope area of coincidence of QL and QTP curves in Units No. 63, 76, 78 and 80 is larger and the calculated oil saturation is higher, while the envelope area of coincidence of QL and QTP curves in Units 64, 65 and 66 is smaller and the calculated oil saturation is lower. The result of well interpretation is that Units No. 64–66 produced at present are in strong flooded state, which leads to high water content, while Unts No. 76 and 80 are in weak flooded state, and Unit No. 78 are in medium flooded state, which still has certain production potential. Based on four-neutron logging interpretation and other data, It is decided that plugging Units No. 64–66 and producing Units No. 76–80.

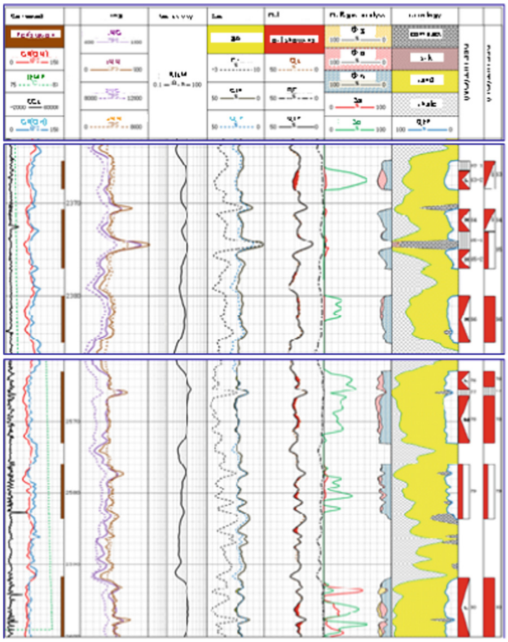

Fig. 4. Four neutron logging interpretation result diagram of well A

Well A has been shut down before the four-neutron test because of its extremely high water cut. After taking measures in March 2017, the daily oil production is 10.7 t, the daily water production is 0.3 m^3, and the water cut is 2.7%. The purpose of decreasing water and increasing oil is achieved. Production practice proves that the four-neutron log interpretation is correct. The production situation before and after the four-neutron test in Well A is shown in Table 2.

Table 2. Production comparison of well A before and after four neutron test

Date	Daily liquid production (t)	Daily oil production (t)	Water content (%)	Remarks
May 2016	21.5	0.31	98.6	
Sep 2016	18.7	0.32	98.3	
Dec 2016	24.2	0.1	99.6	
Jan 2017				Four neutron logging operation
Mar 2017	13.13	10.98	16.4	
Apr 2017	11.0	10.7	2.7	
Jul 2017	10.0	9.8	2.0	

4.2 Well B

The completion time of the well is October 2015. Before the four neutron logging, the production situation is 2.75 t of oil per day, 19.63 m^3 of water per day, 87.7% of water cut, high water cut and unclear oil potential. In order to understand the present situation of remaining oil in each unit, four-neutron logging was carried out in July 2017, measuring interval is 2154 to 2244 m. The Fig. 5 is the result of four-neutron log interpretation in Well B. It is obvious from the graph that the envelope area of QL and QTP curves of 2186 to 2191 m interval (i.e. units No. 41 and 42) is large after coincidence. According to the four-neutron log interpretation principle, the coincidence of QL and QTP can be used as oil-bearing indication, and the calculated oil saturation is high. Therefore, it is considered that there are more remaining oil in 2186 to 2191 m interval.

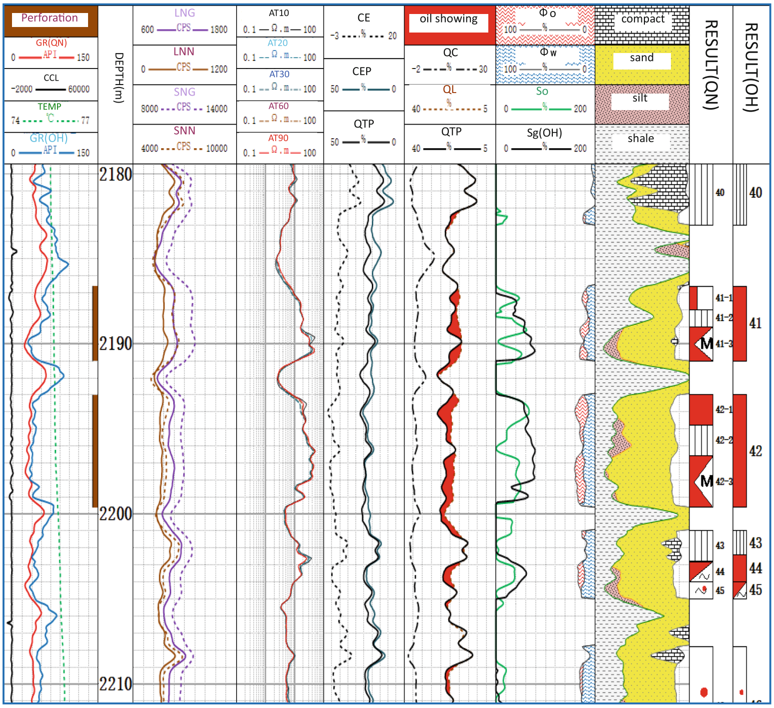

Fig. 5. Four neutron logging interpretation map of well B

According to the interpretation conclusion of the four-neutron log in Well B and other data, measures were taken in August 2017 to transform the 2186.6 to 2191.0 m interval with carbon dioxide huff and puff. After the measures, the daily oil production was 18.73 t, the daily water production was 1.07 m^3, and the water cut was 5.4%. The purpose of increasing oil and decreasing water was achieved. It proved that the interpretation of the four-neutron log was correct. The production situation before and after the four-neutron test in Well B is shown in Table 3.

Table 3. Production comparison of well B before and after four neutron test

Date	Daily liquid production (t)	Daily oil production (t)	Water content (%)	Remarks
Jun 2017	20.4	2.4	88.2	
Jul 2017	22.4	2.75	87.7	
Aug 2017				Construction
Sep 2017	19.8	18.73	5.4	
Oct 2017	2.9	1.67	42.4	
Nov 2017	10.54	3.77	64.2	
Dec 2017	13.32	2.63	80.3	

5 Conclusion

(1) Four-neutron logging combines neutron-neutron and neutron-gamma physical processes to provide comprehensive interpretation and evaluation of stratigraphic lithology. It is more reliable to calculate the shale content by using aluminium as the indicator element of shale. When calculating oil saturation, combining two physical processes can amplify the fluid response information and help to distinguish the nature and content of the fluid.

(2) Four-neutron logging can independently provide lithological, physical and oil-bearing data, reduce the dependence on open-hole logging information, and has wide formation adaptability.

(3) Four-neutron logging has achieved good results in residual oil (water-flooded zone) evaluation, open-hole well data improvement and low-porosity (tight) reservoir evaluation.

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