The progress of technology and application of isotopic neutron-source well logging in China

Zhang Feng, Yuan Chao, Wang Xinguang, Huang Longji
(Gollege of Geo-Resources and Information, China University of Petroleum, Qingdao, Shandong 266555, China)

Abstract: Isotopic neutron-source logging plays a great role in oil field exploration and development. Several isotopic neutron logging methods which detect gamma ray and neutron are summarized. It's introduced that the isotopic neutron logging tool import, independently develop, numerical simulate, data process and apply in China. Therefore, the prospect of neutron logging technology in future was pointed out.
Key words: isotopic neutron source; neutron logging; petroleum

1 Introduction

Isotopic neutron-source well logging is a nuclear well logging technology to study lithology, porosity and prospect useful mineral reserves, which based on the characteristic of interaction of neutron generated (radiated) by isotopic neutron-source and kinds of nuclides in the formation. After appeared abroad, this technology was traced, introduced and absorbed in our country immediately. Till now, relevant fundamental research and equipment development is processing steadily. This technology is widely used in the field of prospecting oil-gas reservoir and other mineral reserves.

Isotopic neutron-source well logging (Fig. 1), is a nuclear well logging method by using the action of elastic scattering, capture and activation happened when formation interacts with neutron radiated from isotopic neutron-source to form a radiation field of neutron and induced gamma ray, to collect and process epithermal neutron, thermal neutron and gamma ray intensity, and gamma-spectrum data, serving for mineral reserve exploration and development. This kind of nuclear well logging mainly includes neutron-neutron logging, neutron-gamma logging and neutron-neutron-gamma logging. The neutron-neutron logging includes epithermal neutron porosity logging and compensated thermal neutron porosity logging, whereas the compensated neutron porosity logging which is the most general logging method includes wire-line logging and LWD (logging while drilling). The neutron-gamma logging includes neutron gamma ray intensity logging, neutron activation logging and neutron gamma spectroscopy logging. The neutron-neutron-gamma logging includes chlorine spectrum logging and neutron gamma spectrum logging in wide energy domain.

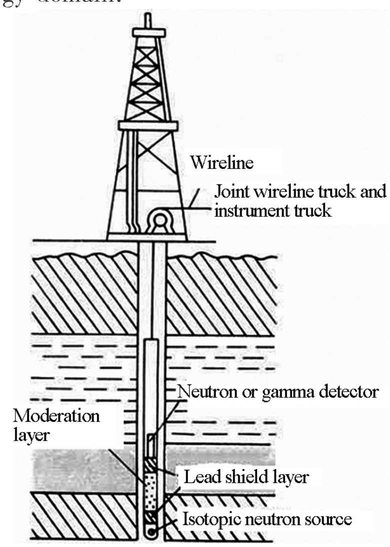

Fig. 1 Neutron logging

1.1 Isotopic neutron-source [1]

Isotopic neutron-sources used in logging includes two types, one kind of them emits neutrons based on nuclear reaction, in the other kind of neutron source, neutrons come from spontaneous fission of some nucleus. The most common source in nuclear logging is the ^{241}Am-Be neutron source, which is fitted for compensated thermal neutron porosity logging, and ^{252}Cf spontaneous fission neutron source is mainly used in neutron activation logging.

1.2 Neutron-neutron logging

1.2.1 Formation hydrogen-index and "neutron logging porosity"

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In nuclear logging, hydrogen-index is defined as the ratio of the number of hydrogen nucleus in rocks, minerals or formation to the number of hydrogen nucleus in water of the same volume, so hydrogen index of fresh water equals 1. When formation matrix minerals don't contain hydrogen and porosity is fully filled with water, hydrogen index equals porosity. The rock's moderating power to fast neutron mainly depends on its hydrogen index, because hydrogen is the most powerful neutron moderator.

Most rocks' matrix minerals don't contain hydrogen, and hydrogen mainly exits in the form of water or hydrocarbon, which include crystal water in minerals, bound water in shale or borehole wall, and moveable oil, gas and water in porosity. Actually, the porosity measured by neutron-logging is just hydrogen index, so called "neutron porosity", and different a little from the real porosity which means the ratio of pore volume to rock volume.

1.2.2 Epithermal neutron porosity logging (sidewall neutron porosity logging)

Isotopic neutron-source (^{241}Am-Be source or Pu-Be source) and neutron detector sensitive to epithermal neutron are installed on the sidewall slider.

Two measures are taken for recording epithermal neutron by detector: a. In order to absorb thermal neutron, thermal neutron absorbents (Cd) are put outside of the detector as shielding layer; b. moderators, that is high hydrogen-content materials such as plastics, paraffin and so on, are placed between shielding layer and detector in order to convert the epithermal neutron through shielding layer to thermal neutron immediately. The neutron flux of high porosity formation is relatively low at the range of long space, and the space is limited between 30 cm and 45 cm generally. The neutron moderation length L_s reflects the scale of porosity. The shorter the L_s is, the lower the count rate of epithermal neutron is, and the larger porosity is. Collect the count rate of epithermal neutron and convert it to porosity for different lithology.

1.2.3 Thermal neutron porosity logging (compensated neutron porosity logging)

The count rate of epithermal neutron porosity logging with one detector is relatively low and also it is largely affected by borehole environment, therefore produced the compensated neutron logging with two spacing which can do borehole compensation. The flux distribution of thermal neutron is relevant to not only slowdown of fast neutron but also the diffusion and absorption of thermal neutron. Since the moderation length of fast neutron is approximately as big as twice diffusion length of thermal neutron, the effect of slow-down and absorption to the flux of thermal neutron at different positions is different. Isotopic neutron-source radiates neutrons into the formation, and thermal neutron is recorded by two thermal neutron detectors (neutron scintillation detector or He-3 tube) at the space of r_1 and r_2 separately. The ratio of thermal neutron fluxes is mainly relevant to the slowing-down length of fast neutron, so the ratio can reflect the scale of porosity, then porosity can be determined by recording the ratio of thermal neutron fluxes at the two positions.

1.3 Neutron-gamma logging

1.3.1 Neutron gamma ray intensity logging

Having elastic scattering and other process with nuclei in rocks, fast neutrons become thermal neutrons. At the same time of capturing thermal neutron by nuclei, generated capture gamma rays. The intensity of neutron-capture gamma rays generated in formation is closely related to the density of thermal neutron, whereas the yield and energy of gamma rays depend on the species and contents of nuclides in formation. Measuring intensity of neutron capture gamma ray in borehole is called neutron gamma intensity logging, which can be called neutron-gamma logging for short. It can be used to identify lithology and distinguish porous and tight layers qualitatively.

1.3.2 Neutron activation logging

The fast neutrons generated by ^{241}Am-Be or ^{252}Cf neutron source slow down to be thermal neutrons in the formation. Nucleuses in formation such as ^{28}Si, ^{27}Al, ^{40}Ca and so on absorb thermal neutrons, generated some radioactive nuclides with certain half-life, respectively. Corresponding characteristic gamma rays emit while these radioactive nuclide decay. The content of elements in formation can be determined by recording the intensity of characteristic gamma rays using gamma detector. This is called thermal neutron activation logging.

1.3.3 Neutron gamma spectroscopy logging (Element capture spectral logging-ECS)[2]

ECS uses a 16 Ci ^{241}Am-Be neutron source, and a large BGO crystal detector is used to record inelastic scattering and capture gamma rays. The relative content of formation elements such as Si, Ca, Fe, S, Ti, Gd and so on can be directly obtained by stripping spectra analysis. And the formation minerals' content can be qualitatively calculated by oxide close model, clustering factor analysis and energy spectral lithology interpretation.

1.4 Neutron-neutron-gamma logging technology

1.4.1 Chlorine spectrum logging[3,4]

Chlorine spectrum logging can search hydrocarbon reservoir directly and monitor reservoir behavior in cased borehole. The logging tool contains an ^{241}Am-Be neutron source, a He-3 tube and a NaI or BGO detector. A logging curve of capture gamma-ray count rate recorded in an energy-window ranging 3.5 ~ 6.5 MeV by NaI detector, is defined as chlorine curve, this count rate is proportional to the chlorine content in formation. At the same time, a curve of thermal neutron intensity determined by He-3 tube is defined as neutron curve, and neutron intensity is inversely proportional to the chlorine content in formation. The kind of formation-fluid can be determined by comparing the two curves, and based on this, oil and water reservoirs can be distinguished.

1.4.2 Neutron gamma spectrum logging with wide energy domain

In fact, Neutron gamma spectrum logging with wide gamma-ray energy domain ranging from 0.03 MeV to 9 MeV is a combination of capture gamma spectrum logging and neutron-neutron logging. The logging tool is made of a ^{238}Pu-Be neutron source and two scintillation crystal detectors, wrapped in a boron coat. The gamma ray total-spectrum can be recorded and divided in two parts, as shown in Fig. 2. The upper part of the Fig. 2, is the part of lower energy-spectrum, showing two peaks, the left one is used to determine formation density as gamma-gamma logging; and the right one is used to measure boron-gamma countrate, which can substitute for thermal neutron countrate, as neutron-neutron logging; The lower halve of Fig. 2, is the part of higher energy spectrum, showing neutron-gamma energy-spectrum, as the neutron-gamma spectrum logging. Analyzing the energy spectra can find out content of elements such as H, C, Ca, Si, B, Gd, Cl and Fe, to identify lithology elaborately, divide sand-shale profile, carbonate profile, coal bed (Brea bed) and other sophisticated profiles, evaluate porosity, determine the contact surface of oil/water or gas/water, and calculate oil saturation of interest layers accurately.

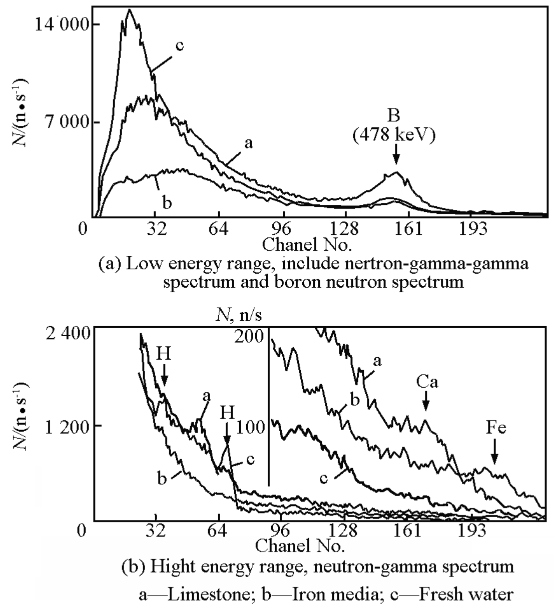

Fig. 2 Spectroscopy of Russia wide energy-domain neutron gamma spectrum logging

2 The development of isotopic neutron source well logging in China

The development of isotopic neutron source well logging technology in China includes the following stages: a. Soviet Union НГК-51 and НГК-55 neutron-gamma logging instruments were introduced in 1950s, which opened the history of neutron well logging in China. FC581 radioactive logging equipment was batch produced in 1959, which had the function of natural gamma logging and neutron-gamma logging. Neutron-gamma and natural gamma are combined to be an efficient nuclear logging series to identify lithology, distinguish clay stone, tight layers and reservoirs, and find gas zones. b. In 1960s until the earlier days of 1970s, nuclear logging kept developing fairly well. The radioactivity scintillation logging tool was completed test and passed examination in 1965, and was batch produced. Also the other exploration of logging instrument caught up with the development abroad. Technologies of compensated neutron logging and compensated density logging had greatly developed abroad in later days of 1970s, but exchanges with outside world were entirely cut off in our country and the gap of nuclear logging technology became great. c. Since the end of 1970s, nuclear logging equipments and technologies were introduced from America in series, it took about ten years to introduce, study, use, absorb and manufacture the new equipments. d. Since then, technical exchanges with outside world opened entirely. The nuclear technologies in Russia recovered and developed except America. The technical exchanges among America, Russia and China were smooth. Chinese technical experts group had already formed and started the period of "full exchanges and independent R&D".

2.1 The development of isotopic neutron source well logging

Most technologies of neutron logging were firstly developed abroad. Since the end of 1970s, nuclear logging equipments were introduced unitized from abroad and then we experienced the process of introduction, tracing, absorption, imitation and independent R&D. Here take compensated neutron porosity logging for example to illustrate.

2.1.1 The situation of introduction

In July 1977, from America DRESSER Company the former Ministry of Oil introduced 3600 series logging equipment which includes 2420 compensated neutron and sidewall neutron log tools. ^{241}Am-Be neutron source was used in compensated neutron logging, and the two detectors were LiI-crystal scintillation neutron-detectors , the spacing of the two detectors were 53 cm and 32 cm, respectively. The ratio of the count rate of long-space detector to the short-space one was used to calculate formation porosity.

Since 1980s, well logging companies of major oil fields purchased numerous American equipments successively. For example, Shengli well logging company began to introduce 3700 series equipments from DRESSER ATLAS COMPANY in December 1987, including 2435 compensated neutron logging tool. The later introduced nuclear equipment, 2436XA compensated neutron logging tool, was used to measure formation porosity in open or cased hole. It includes a 18 Ci ^{241}Am-Be neutron source and two He-3 tubes. Outside diameter of the tool is 89 mm, logging speed is 6 m/min and the range of measurement was 0 ~ 70 apparent limestone porosity. EXCELL 1000 logging system was introduced from HALLBURTON in December 1992, with DSNT-A type dual spaced neutron logging tool. ECLIPS5700 image logging equipment was introduced from WETERN ATLAS COMPANY in April 1997, with 2466 compensated neutron logging tool. The introduction of those foreign nuclear logging tools played an important role in filling the vacancy of domestic logging service in oil fields, improving the related operating efficiency, accelerating the process for Chinese technicians to understand, trace and absorb technologies abroad, and to develop relevant technical equipments.

2.1.2 The situation of domestic research

The neutron-neutron logging tool developed by Beijing Research Institute of Petroleum science was tested in Sichuan in 1958, but it failed. The FC651 scintillation radioactivity tool (includes natural gamma and neutron-gamma log) developed by Xi'an Petroleum Instrument Factory passed field test in 1965, and 160 sets of tools of this category were produced until 1974. In 1982, Ji Changsong et al. in Beijing nuclear tool factory successfully developed a kind of multi-wire Li-glass scintillator used in neutron-neutron petroleum logging, which had main characteristics of high neutron sensitivity, good resolution of thermal neutron peak, big peak-to-valley ratio and valley width, and having the better ability of examining and distinguishing to γ radiation[5]. FBZ801 Compensated Neutron Tool produced by Xi'an Petroleum Instrument Factory passed the examination, and 185 sets (included its derivation) had been produced until 2003. In 1985, Ji Chang-song et al. developed successfully neutron scintillator pair-ST1604 and ST1605 used in compensated neutron logging in coal (or petroleum) well[6]. The sidewall neutron porosity logging tool was developed in Jianghan logging research institute and eight sets were produced in 1986.

In 1998, The Research Center of Shengli Well Logging Company developed SL3000 series logging tool, including nuclear logging tools as natural gamma, compensated neutron, compensated density logging tool and so on. Since 2003, this center kept developing SL6000 series tools, including LDT series lithology density, compensated neutron, natural gamma spectrum well logging tool and so on. Till 1990s, Shengli Logging Company had already possessed the ability of developing unitized equipments and exporting abroad.

In 1996, Department of Engineering Physics of Tsinghua University successfully developed HH-CNL-8331 compensated neutron logging tool, adopting Li-glass thermal neutron detector, which has the characteristics of un-deliquesce, thermal shock resistance, stable property and long life of service. And it's the first time to use Ti alloys as tool housing in our country.

In 1998, Huali Research Center of Petroleum Equipment of Beijing Seventh Institute successfully developed BZC-IB compensated neutron tool, that is a new tool improved and innovated on the base of CNT-GA tool produced by Schlumberger, with a 16 Ci Am-Be neutron source and two He-3 detectors of different sensitivity[7]. It was mainly used to calculate formation porosity, also can determine formation lithology combining with acoustic wave and density curves. Also comparing the compensated neutron curves in open hole and cased hole, we can determine gas layers.

CN241 compensated neutron logging tool produced by Xi'an Petroleum Instrument Factory includes a 20 Ci Am-Be neutron source and two He-3 tubes. The internal pressure of the two tubes is 10 atm and 4 atm (1 atm = 101 325 Pa) respectively, length is 10 cm and 30 cm and its spacing is 32 cm and 64.3 cm. In 2003, 100 K high accuracy telemetry compensated neutron tool[8] with 90 mm diameter was developed, and it used a 20 Ci Am-Be neutron source. Its detector adopted new type of He-3 proportional counter tube, whose detection efficiency is 2 ~ 3 times of 2435XA long space detector. Later, EILOG logging system[9] was developed by China Petroleum Logging Co. Ltd., wherein CNLT5420 compensated neutron log is the key equipment in EILOG logging system.

In 2007, DG-I series compensated neutron logging tool was successfully developed by Dagang Oil Field Logging Company. It promised the same technical performance as related tools of ECLIPS-5700 series while perfecting the integrity and mating usability of the research of ECLIPS-5700 series nuclear logging tool unitized equipment, which improves the overall technical power and impelling the process of localized production of nuclear logging tools of 5700 image logging system. By adding ball latch positioning device to two sides of source compartment, the angle between folding and unfolding was controlled and it can be positioned randomly between 0 and 80 degree, the stereotype of loading and unloading of radioactive source was changed, making it more convenient and shortening the operating process, the time of radiation injury to operators and contact distance to the radioactive source were reduced, also providing effectively technical support in terms of improving the prescription of nuclear logging and safe mass.

FG-751 neutron-gamma logging tool involved a Am-Be neutron source and a NaI detector[10,11]. Its diameter was 89 mm, detector crystal size was Φ 35 mm ×55 mm, energy resolution was 7 % and the error of counting statistic was great. After improved, detector crystal size was Φ 50 mm×300 mm, energy resolution was 9.1 %, the temperature range of photomultiplier was increased from −25 ~ 100 Celsius to −25 ~ 125 Celsius and DC power supply was changed to AC power supply.

Chlorine logging tool was once developed by Jianghan Logging Research Institute and Logging Engineering Department to distinguish oil zone and highly mineralized water layers. Chlorine logging was not used widespread because the formation water salinity was relatively low in most of oil fields of our country.

Wide energy neutron gamma spectrum logging tools and ECS tools haven't been developed and most are depended on logging services provided by America and Russia service companies. The principles and practicability are being researched by scientific and technical personnel in petroleum universities and oil fields.

2.2 The development of isotopic neutron source and calibration system

2.2.1 The development of isotopic neutron source in logging

Since 1980s, the Am-Be neutron source produced by Atomic Hi-Tech Industry Division Department were being used in civil oil fields all the time. However, since 2003, the countries who had the ability to produce ^{241}Am provide few amount worldwide, resulting in the short supply of raw materials of ^{241}Am, and the production of Am-Be neutron source was affected severely, thus the development of logging industry was limited. It took Atomic Hi-Tech Industry Division Department two years to develop Pu-Be neutron source which was the substitute of Am-Be neutron source.

2.2.2 The development of calibration system

Till now, only compensated neutron logging has set up the complete calibration system among the isotopic neutron source logging tools in civil oil industries. The calibration standard SY/T6179-1996 of compensated neutron logging was enacted in 1996, stipulating procedures and methods of second-level calibration and field calibration and being applicable to the calibration of CL3700 series compensated neutron logging tools, wherein 2437XB main calibrator was composed with horizontal hollow graduated cylinder with a support, the internal diameter was 146.05 mm, wall thickness was 8.26 mm, 0.625 m^3 of water-soluble pure second ethanol propylene and 1.28 m^3 fresh water were filled in the cylinder and the checker of 400 mCi Am-Be neutron source and 20 Ci Am-Be neutron source were contained; calibration charts were enacted by calibration device[12].

Different types of neutron logging tools have different response function. To 2435XA compensated neutron logging tool, the ratio of counting rate is 4 × (short space count/long space count); to 2490XC or 2420XA compensated neutron logging tool, the counting rate is 8 × (short space count/long space count). Chen Yongcai et al. compiled the calibration management system software of neutron logging specific to 2437XB calibrator[13]. Logging operating engineers need not to point wise calculate the calibrating data and decide whether the calibrating data is accurate or not more conveniently, accurately and directly according to the figures generated real-time automatically.

Compensated neutron logging tool can be calibrated in the man-made calibration well. The calibration well is consisted of three-layer limestone formation and is filled with fresh water. The formation porosity is respective Austin limestone 27 %, Indiana limestone 15 % and Boshan limestone 0.6 %. Man-made formation is made of natural limestone [14].

The calibration standard SY/T 6582.4-2003 of compensated neutron logging was enacted in 2003, setting up neutron porosity standard well group, wherein the well diameter was 20 cm, well fluid was fresh water, salinity was less than 1 000 mg/L, formation matrix is limestone, the content of CaO was more than 53 %, nominal values were 0.1, 5.0, 13.2, 20.2, 23.5, 30.0, 37.2, 52.9, 100 p. u. (porosity unit), operating type wells had the same construction of standard well group and contained three wells with the nominal values between 0 and 30 p. u.[15]

3 The research of civil isotopic neutron source well logging technology

Civil isotopic neutron source well logging technology has already changed from the stage of depending on technology abroad entirely to the stage of independent R&D. Related personnel had done numerous works on the areas of theory method, tool design, data processing and interpretation evaluation method, of which research using methods such as numerical simulation technology, petrophysical experiment and so on, and obtained lots of achievements.

3.1 The research of numerical simulation technology of isotopic neutron source logging technology

When a new neutron logging tool is improved or designed, spacing is one of important parameters determining the property of tool. Hu Zhong et al. made use of the numerical simulation technology to choose the spacing in neutron logging, used the methods of multigrain P1 approximation and finite element to calculate the counting rate ratio of different spacing combination under different formation conditions of lithology and porosity when the tool is triaxially off-center and calculated relative sensitivity and resolution of porosity[16].

Xie Zhongsheng et al. utilized the theory of multigroup P1 approximation to construct model well to simulate neutron logging under different conditions such as lithology, borehole diameter, formation water salinity, formation temperature and so on, study the depth of investigation of neutron logging and obtain correction charts of logging response[17].

Xia Lingzhi et al. made use of Monte Carlo method to study the tool design proposal of compensated neutron logging, simulated the influence of tool structure parameters such as the locomotion of CN241 source, the length change of source, locomotion of far detector, effective length change in sensitive area of near detector on the ratio of counting rate[18]. Qiu Yixiang et al. used Monte Carlo simulation method to study the benchmark experiments specific to CN241 compensated neutron logging[19]. Based on the measurement, the reason of difference between MC calculation result and measurement were raveled to try to reasonably adjust the calculation models and related parameters of MC to reduce the error.

Li Guijie et al. used the Monte Carlo simulation method to study the influence of gas layer in sand-shale formation on compensated neutron porosity[20]. Yu Huawei et al. used Monte Carlo numerical simulation method to study the influence of investigation characteristic of cuttings of horizontal wells and inclined wells on compensated neutron porosity[21, 22].

3.2 The research of data processing and interpretation method

Among isotopic neutron source logging technology, the data processing of compensated neutron porosity logging and neutron gamma logging is relatively simple, but the data processing and interpretation method of ECS and chlorine spectrum logging play an important role in the result of formation evaluation.

3.2.1 The improvement of interpretation model in chlorine spectrum logging

The interpretation model before being improved in chlorine spectrum logging is the relationship between porosity, oil saturation and the counting rate of thermal neutron, the counting rate of neutron-capture gamma rays in chlorine spectrum. The relationship is expressed as:

$$P_{Cl} = C \times \frac{1 - \varphi}{\varphi} \times \left(\frac{I_{Cl}}{I_n} - 1\right) \quad (1)$$

$$S_W = \frac{P_{Cl}}{P_W} \quad (2)$$

Where, I_{Cl} is the count rate of neutron-capture gamma rays in chlorine spectrum; I_n is the neutron count rate; φ is the formation porosity; P_W is the chloride ion salinity of reservoir formation water; P_{Cl} is the average chloride ion salinity of fluid in porosity; S_W is the water saturation in reservoir; C is the local well bore coefficient.

Wan Jinbin et al., on the base of numerous core experiments and model calibration wells, concluded the quantitative interpretation charts of chlorine spectrum and built new interpretation model[23]. Using the difference of counting rate between chlorine gamma rays and neutron counting rate, the difference between neutron and gamma rays determined at certain porosity mainly reflected the change of salinity of fluid in porosity and the effect of shale and matrix in formation could be overcome at some extent. The improved interpretation model of chlorine spectrum is expressed:

$$D = D_W \times [1 + k \times (\varphi_W - \varphi)] \quad (3)$$

$$DD_t = 1 - \frac{D_t}{D} \quad (4)$$

$$S_W = a \times DD_t^3 + b \times DD_t^2 + c \times DD_t + d \quad (5)$$

Where, D is the normalized difference of chlorine curve and neutron curve in fresh water formation whose porosity is φ; D_W is the normalized difference of chlorine curve and neutron curve in fresh water formation whose porosity is φ_W ; k is the coefficient varied with salinity; φ is the formation porosity; D_t is the normalized difference of chlorine curve at any depth and neutron curve; a, b, c, d is the local coefficient; S_W is the reservoir water saturation;

Comparing with the interpretation method by using ratio as parameter, the interpretation method by using difference as parameter more effectively fetch information of the measurement response to formation water salinity, thereby improving the interpretation accuracy.

3.2.2 The processing method of neutron gamma spectrum data

Huang Longji et al. studied spectrum data processing method of neutron-gamma rays generated in the interaction of formation elements and neutron radiated from isotopic neutron source, consulted related technology abroad to give us the relationship between the content of absolute element and element relative yield, and used the closed model that the mass percent of oxide and carbonate of all elements was 1 to determine the content of minerals, wherein the mass percent of K was determined using natural gamma spectrum, the mass percent of Al was determined using activation logging, the effect of Mg in closed model was ignored and the content of Mg could be determined by using photoelectric absorption coefficient[24]. This processing method, based on the mineral content, had some applications such as identifying lithology, determining the type of clay and so on.

4 The application of isotopic neutron source logging technology

4.1 The application in oil and gas exploration

Isotopic neutron source logging technology plays an important role in the exploration and development of oil and gas. It can provide the direct measurement basis on lithology identification, reservoir delineation, reservoir parameter calculation, hydrocarbon reservoir identification, and measurement of gas-water interface or gas-oil interface, oil well operation effect check and so on.

4.1.1 The application of compensated neutron logging

Using overlap of compensated neutron porosity logging curve and compensated density logging curve, lithology can directly and quickly be identified as illustrated in Fig. 3, and porosity and gas layers can be identified and evaluated. Hu Nianyou et al. used compensated neutron logging to estimate the density of oil and gas[25]. The investigation depth of compensated neutron logging is mainly in flush zone and usually compensated neutron logging response is greatly affected by the fluid property and saturation in flush zone. Comparing with the formation filled with water, when porosity contains oil and gas, hydrogen index measured by compensated neutron logging has an added value. The higher the saturation of hydrocarbon in flush zone is, the smaller the added value of hydrogen index in compensated neutron logging, more sensitive the hydrocarbon density response to logging is. When the density of hydrocarbon is 0.75 g/cm^3, the added value of hydrogen index in compensated neutron logging is 0; The bigger or smaller the density of hydrocarbon is, the amplitude of added value of hydrogen index in compensated neutron logging is and this characteristic has a strong recognition capability towards natural gas zones and heavy oil layers. So, the density of fluid in hydrocarbon zone can be calculated by using of the additive effect of hydrogen index in compensated neutron logging. Based on this, oil layers, we can identify natural gas pool and gas pool containing carbon dioxide, study the distribution of the hydrocarbon density in thick hydrocarbon reservoir varied with depth, judge whether the barrier effect of inter-bed shale group inter-bed works or not, and know whether there is high density crude oil in the bottom of oil layers or not.

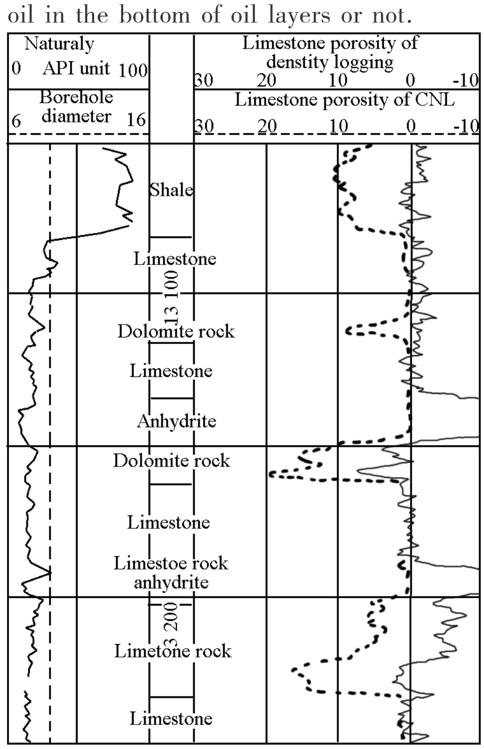

Fig. 3 The overlap of neutron-density porosity curve

In LWD, compensated neutron logging can also be used to determine porosity. The principle, affecting factor and application prospect of compensated neutron logging while drilling have already been studied by related sholars in our country. For example, Liu Zhidi et al. analyzed the environmental affecting factor of neutron logging while drilling, expounded the change discipline of apparent porosity in LWD under the conditions such as borehole diameter, tool off-center, mud salinity, hydrogen content of mud cake, salinity of formation water and so on[26].

4.1.2 The application of neutron gamma logging

Neutron gamma logging can combine with GR logging to identify lithology, gas pool and high salinity water layers. If there is not other information, porosity can be approximately calculated using this logging data.

Wang Guoyong et al. used neutron gamma to find residual gas in Liaohe oil field. In a new drilling well, the gas pool is at original state and keeps the original gas saturation[27]. After a long time of exploring, the combination of oil, gas and water underground is changed, the gases migrates and the part of pore gas in reservoir is replaced by oil and water, leading to the reduction of gas saturation in reservoir, ascent of oil-water saturation and uprise of hydrogen content in formation. When the gas pool is flooded, the change of gas saturation can be manifested in the neutron gamma curve, based on this, residual gas can be found. While evaluating residual gas, the basic factor such as porosity, gas saturation, shale content in reservoir, the size of borehole case, control fluid and so on should be considered.

Song Yanjie et al. used the overlap of neutron and gamma logging to identify gas pool and producing level of gas pool, adopted the normalized method of neutron gamma overlap logging curve, built the parameter of identifying the gas pool and introduction parameter of producing level of gas pool and obtained relative good result in the practical application[28].

Jiang Wenda et al. made use of the technology of measuring-infiltrating-measuring in neutron gamma logging to determine the remaining oil saturation[29]. By using the neutron gamma logging tool, base line is measured before injecting tracer with a high thermal neutron cross section into reservoir, then the tracing curve is measured after the tracer penetrates into the reservoir and the difference between base line and tracing curve is the basis of determining remaining oil saturation. The water flooding level can be divided according to the percent of movable water saturation in the space of movable fluid and relatively static and dynamic files of reservoirs.

4.1.3 The application of chlorine spectrum and ECS

Chlorine spectrum logging can be used to directly find hydrocarbon layers and supervise behaviors of reservoir in the cased well, but has less application. And ECS is widely used in the process of prospect and development of hydrocarbon reservoirs.

Wang Yongjun et al. used ECS to identify lithology in volcanic rock formation[30]. The lithology of volcanic rock can be better identified in the perspective of rock content, on the base of chemical analysis of rock in the cored interval and the main measurement of ECS. In study area, the element such as Si, Al, Fe, Gd can be used as indictor elements to identify lithology.

Cheng Guohua et al. used ECS data to evaluate the change of lithology in complex lithology formation, analyzed the effect of shale content aiming at the change of elemental abundance in carbonate rock, compared the elemental abundance of dolomite rock and limestone and content of U and Th in silicate and carbonate[31]. That was obtained relative good application in complex lithology reservoir.

Yuan Zugui et al. made use of ECS to evaluate oil-water layer. If the reservoir contained oil, the content of H and C increased but the content of Al, Cr and Ti reduced[32].

Cheng Guohua et al. utilized ECS to determine content of reservoir clay, combined with the microscopic logging characteristic such as content of formation, content of Th and K in formation measured in natural gamma ray spectroscopy and so on to distinguish and calculate the content and type of formation clay, at the same time, distinguish shale from high-level radioactive sand formation[33].

Yuan Zugui used ECS data to study depositional environment[34]. The change of abundance and combined characteristic of some elements in the sedimentary rock of different geologic time could reflect situation of change of depositional environment at that time. The elements such as Th, Al, Ti and so on could be used as the tracer of depositional source and Ca/(Ca + Fe) could reflect geochemical index of water media salinity when depositing.

4.2 The application of other mineral resource prospect

Zhou Minglei et al. and Zhang Jingkao et al. applied the technology of compensated neutron logging to exploration of solid minerals[35,36]. The application of neutron logging in exploration of solid minerals dated from 1980s and the main use was to identify gypse layers. The main difference between gypse and anhydrite is gypse mineral combinations contain crystal water. So neutron counts are down and the neutron porosity is great. If there is associated limestone in the same borehole, the main difference between limestone and gypse layers is that the neutron porosity in gypse is much bigger than in limestone layers and the bulk density of limestone outclasses the gypse's; At the same time, the main difference between limestone and anhydrite is that the bulk density of anhydrite is much bigger than that of limestone and the same of the electron density index and resistivity.

Tang Zhenqing applied the technology of neutron porosity logging in coal exploration as interpreting lithology, dividing geological age interface, determining the leakage point, judging the strength of water abundance, interpreting coal bed and structure, analyzing coal quality indictor and dividing the category and level of coal[37].

Zhao Baozhong studied the application of neutron logging in coal bed gas well[38]. In coal bed gas well, neutron logging uses isotopic neutron source and thermal neutron detector to obtain the content of hydrogen molecule. In coal bed gas reservoir, the high content of hydrogen lets neutron logging manifest false high porosity, and in actually the porosity of coal bed is very low, but coal bed is organic compound consisted of C, H and O and has a high hydrogen index plus the existence of coal bed methane, so neutron logging manifests high porosity.

Niu Yixiong et al. used neutron logging to determine whether there is hydrated mineral in crystal rock in continental scientific drilling and based that to divide lithology, illustrated in Fig. 4[39]. The change of compensated neutron logging (CNL) could indict whether external water intervenes or not when there is metamorphism or retrograde metamorphism. Though the minerals consisted of eclogue don't contain crystal water and constitution water, its porosity is less than 3 % but the average value of subordinate porosity can reach to 5.6 %, that indicts there is construction water with the form of OH^- and H^+ hiding in the microscopic flaw of mineral crystal.

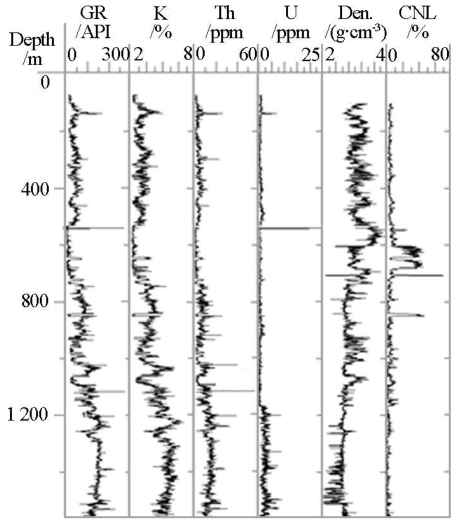

Fig. 4 Nuclear logs of a continental scientific well in China

5 Conclusions

At the present, civil isotopic neutron logging technology plays an important role in hydrocarbon reservoir and other fields, and great technology level has been achieved in tool research and manufacture, especially the compensated neutron porosity logging tool; the basic research of isotopic neutron source logging technology has a certain scale. Numerous researches of theory method, tool design, affecting factors and so on are opened by using numerical simulation technology; at the same time, standard wells of different borehole size, lithology and formation porosity are built and the national calibration standards are set up to provide the production and application of tools with experimental **basis and calibration conditions. It is widely used in the prospect and production of hydrocarbon reservoirs and other fields.**

However, the technological level of civil isotopic neutron source logging is not high comparatively, the technological gap with abroad is large, the research of basic theoretical method is weak and research findings with proprietary intellectual property rights are seldom. Therefore, related technicists should carry out some original basic researches in the future as follows:

1) Studying the technology of wide energy domain neutron gamma spectrum logging, research the method of neutron and gamma directed to the characteristics of isotopic neutron source logging technology, collect more data information and obtain more physical measurement parameters as far as possible, thus gain more geological parameters to improve the technological level of isotopic neutron source logging;

2) Beginning the research of neutron logging technology "without source", start the research of logging technologies such as pulsed neutron compensated neutron porosity, ECS and so on as isotopic neutron source logging technology is more and more affected by many factors such as environment, cost and so on and pulsed neutron logging technology is the tendency of logging in the future;

3) Fully drawing lessons from the latest research findings of adjacent unclear fields, choose isotopic neutron source, detector and technology with better property, develop and mass produce high-quality neutron logging tools with proprietary intellectual property rights, improve the processing method of nuclear data to enhance the statistical accuracy.

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Author

Zhao Jingwu, male, born in 1959, graduated from Nanjing University in 1982 with a bachelor degree and in 1986 with a master degree. Now he is an associate professor at Nanjing University. He has published two books and over 30 papers. His current research is applied neutron physics and nuclear medicine imaging. He can be reached by E-mail: jwzhao@ nju. edu. cn

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Author

Zhang Feng, male, born in April 1970, Shandong Province, associate professor, councilor of Industrial Application of Nuclear Technology Branch of Chinese Nuclear Society, graduated from Qufu Normal University in 1991, received doctor's degree of Geological Resource and Geological Engineering from China University of Petroleum in 2008, mainly undertakes educational works including nuclear physics, electromagnetic field theory, nuclear logging principle, logging method and comprehensive interpretation and so on, engages in fundamental researches of logging methods, optimal design of nuclear logging tools, data processing and application of nuclear logging, nuclear petrophysical experiment and Monte Carol numerical simulation, publishes 17 dissertations as the first author, among which 3 are embodied by SCI and 5 are embodied by EI, in periodicals such as *High Energy Physics and Nuclear Physics*, *Chinese Journal of Geophysics*, *Atomic Energy Science and Technology*, *Journal of China University of Petroleum*, *Well Logging Technology*, *Isotope* and so on, compiles a textbook—*The Foundation of Nuclear Geophysics*. Mr. Zhang can be reached by E-mail: zhfxy_cn@ upc. edu. cn or zhfxy_cn@ sina. com