DOI 10.52209/1609-1825_2023_1_107 UDC 550.83

Methods of Pulse Neutron Probing in Geological and Geophysical Investigations

[1]***PAK Dmitri,** *Cand. of Tech. Sci., Associate Professor, pak_kargtu@mail.ru,*
[2]**INKIN Dmitri,** *General Director, azimut@azimut-geology.kz,*
[1]**TEBAYEVA Anar,** *Master, Lecturer, anara.tebaeva@gmail.com,*
[1]**PAK Yuri,** *Dr. of Tech. Sci., Professor, pak_gos@mail.ru,*
[1]*NPJSC «Abylkas Saginov Karaganda Technical University», Kazakhstan, Karaganda, N. Nazarbayev Avenue, 56,*
[2]*Azimuth Geology LLP, Kazakhstan, Karaganda, S. Seifullin Avenue, 105,*
**corresponding author.*

Abstract. *The problem of introducing pulse neutron probing in the process of geological and geophysical studies has been updated. The main factors that increase the sensitivity and information content of pulse methods in comparison with stationary neutron methods have been considered. It has been shown that the efficiency of pulse neutron probing depends on the length of the probe, time and energy characteristics of the equipment used. The principal features of various modifications of pulse neutron probing for solving geological and geophysical problems have been noted. The aspects of the efficient use of pulse modification in neutron gamma-ray spectrometry and inelastic scattering of fast neutrons have been discussed. Improved modifications of neutron probing based on the complex application of instrumental signals arising from inelastic scattering of fast and radiative capture of thermal neutrons have been proposed.*

Keywords: *pulse neutron probing, neutron diffusion parameters, inelastic scattering and radiative capture of neutrons, neutron-gamma radiation spectrometry, mineral quality.*

Introduction

Neutron probing provides multifaceted information of the elemental composition and properties of rocks. Moreover, neutrons and gamma quanta caused by them have a relatively large penetrating power, which ensures a sufficient depth of studies. However, due to the continuous nature of the radiation from the neutron source and the measurement of secondary radiation, it is not possible to obtain information of secondary radiation distribution in time, which makes it difficult to study separately individual processes of neutron interaction. Pulse neutron methods based on studying nonstationary neutron and gamma fields produced by pulsed neutron sources are free from these shortcomings.

The essence of the pulse neutron method is irradiating the rock with short-term neutron fluxes of the ΔT duration, following one after another after a certain period of time T, and measuring the density of neutrons or gamma quanta at given time elements Δt located within the specified time T called the period (Figure 1).

By changing sequentially the detector switching time t after the end of the next pulse of fast neutrons (the delay time), it is possible to study the density of the particles dependence on time. By registering the radiation density over time Δt at fixed values of the delay time, it is possible to obtain more selective information of the processes of neutrons interaction with matter, which are characteristic of the specified neutron lifetime [1].

The time distribution of the main processes of neutron interaction with matter occurring near the neutron source shows the importance of selecting the time parameters of various modifications of pulse neutron γ-methods (Figure 2).

Non-stationary fields of neutrons and gamma quanta are studied using pulsed (pulsating) neutron sources, neutron generators. After each successive pulse, the space-time transformation of the neutron field occurs. It is associated with the process of slowing down fast neutrons to thermal neutrons and the process of diffusion of thermal neutrons. In the process of slowing down fast neutrons (~10-100 μs), which depends mainly on the hydrogen content of rocks, their spatial displacement occurs, the result of which practically does not differ from the spatial distribution of a stationary field. In the process of diffusion that depends mainly on the neutron-absorbing properties of the medium, thermal neutrons are absorbed and spatially moved. As a result, the distribution of thermal neutrons in time at a fixed distance from the neutron generator has the form shown in Figure 1.

Classification of pulse neutron methods

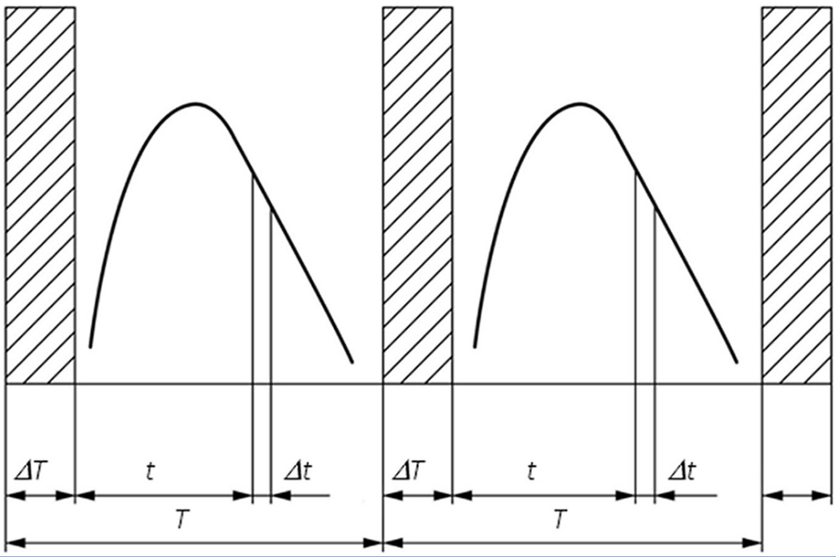


Figure 1 – General diagram of the pulse neutron method

Neutron pulse beginning	Fast neutrons slowing down		Thermal neutrons diffusion and capture
	Elastic and inelastic scattering	Elastic scattering, resonance capture, thermalization	
	Nuclei activation		
	Activated nuclei decay and radiation		

Figure 2 – Time distribution of the basic processes of neutron interaction with matter

Depending on the delay time at which pulsed secondary radiation fields (neutrons, gamma quanta) are recorded, the following pulse neutron methods are distinguished: pulse neutron-neutron method (PNNM), pulse neutron gamma method of inelastic scattering of fast neutrons (PNGM-ns), pulse neutron gamma method of radiative capture of thermal neutrons (PNGM-rc).

In the first modification of the pulse method, the intensity of thermal neutrons is measured; in the second one, the intensity of prompt γ-radiation arising from inelastic scattering of fast neutrons is measured; in the third modification, gamma radiation is recorded that accompanies radiative capture of thermal neutrons. Depending on the modification of the method, thermal neutron or gamma radiation detectors are used.

With PNNM there is registered the flux of thermal neutrons in the time interval Δt after the delay time after the end of the next neutron pulse. The time interval analyzer makes it possible to obtain the time spectrum of thermal neutrons by measuring at different delay times. Thus, the pulse neutron-neutron method, depending on the problem being solved, investigates the thermal neutron flux density in a certain time interval, or its time spectrum.

When implementing the pulse neutron gamma method, the intensity of gamma radiation is measured instead of the neutron flux. Alongside with measuring the time spectrum, it is possible to analyze the energy spectrum of gamma radiation using an energy-time pulse analyzer.

The existing modifications of the pulse neutron gamma method (in terms of inelastic scattering of fast neutrons and radiative capture of thermal neutrons) are implemented at different time parameters.

Inelastic scattering is typical only for fast neutrons, so, it occurs at the initial moments of time. Therefore, in practice, in PNGM-ns, the gamma-ray flux is recorded during the pulse of fast neutrons (the delay time is 0). There is selected such neutron pulse repetition rate T that by the time of registering the next gamma-ray flux of inelastic scattering, there is no capture gamma radiation caused by the previous neutron pulses. Thus, for the preferential registration of gamma radiation of inelastic scattering, the delay time (the time elapsed from the moment the generator is turned off until the moment the detector is turned on) is selected close to zero.

In PNGM-rc, the delay time is usually selected after the inversion region at the decay of the dependence (Figure 1).

An important feature of pulse neutron methods, in comparison with stationary ones, is that based on studies of non-stationary fields, it is possible to evaluate separately the effect of neutron-physical parameters, in particular, to highlight the role of diffusion parameters of the medium: the lifetime of thermal neutrons and the diffusion coefficient.

Pulse neutron-neutron probing possibilities

The space-energy time distribution of neutrons in rocks can be most strictly described by the neutron transport equation, which describes all the stages of their life: slowing down, thermalization, diffusion, and radiative capture. However, as applied to the pulse neutron method, which studies the patterns of changing the density of thermal neutrons with time, the transport equation can be reduced in the first approximation to the diffusion equation. Such a simplifying approach is justified by the fact that the first processes (slowing down and thermalization) take a negligible time in the total lifetime of neutrons. Compared to the diffusion of thermal neutrons, slowing down and thermalization occur almost instantaneously.

The space-time distribution of the thermal neutron flux density in a homogeneous infinite medium, according to the theory of nonstationary neutron diffusion, has the form [2]:

$$N(R,t) = \{Q/[4\pi(L_3^2 + Dt)]^{3/2}\} e^{-R^{2}/4(L_3^2+Dt)} e^{-t/\tau}, \qquad (1)$$

where Q is the number of neutrons emitted by the source;

L_3 is the length of neutron slowing down in the medium;

D is the diffusion coefficient of thermal neutrons;

τ is the average time of life of thermal neutrons.

When satisfying the conditions: $t >> t_3$ (t_3 is the time of neutron slowing down) and $Dt >> L_3^2$, formula (5.1) is simplified:

$$N(R,t) = [Q/(4\pi Dt)^{3/2}] e^{-R^{2}/4Dt} e^{-t/\tau}. \qquad (2)$$

In this expression, each of the three factors, including the delay time t, has a certain physical meaning.

The factor ($4\pi Dt$) characterizes decreasing the neutron density at the considered point at the distance R from the source due to further diffusion of neutrons. The second factor ($\exp{-R^2/4Dt}$) characterizes the neutron influx at a given point due to diffusion from the region with a higher neutron density, which is closer to the source.

The third factor, the exponent $e^{-t/\tau}$ characterizes the loss of thermal neutrons due to their absorption by the nuclei of rock elements. Hence, the analysis of formula (2) and its individual components allows noting the fundamental distinctive feature of the pulse neutron method, which consists in the fact that it is possible to evaluate separately the effect of neutron parameters and, in particular, the effect of diffusion parameters τ and D.

According to expression (2), the field of thermal neutrons at long delay times is practically independent of the neutron slowing down length and is mainly determined by the thermal neutron lifetime and the diffusion coefficient. For sufficiently large values of the delay time t, the contribution of the first two factors can be neglected due to their smallness, and the thermal neutron flux density will depend only on the average lifetime of thermal neutrons in the rock under study:

$$N(t) \backsim e^{-t/\tau}.$$

Therefore, measurements of the neutron field over time at large time delays provide the information of the neutron-absorbing properties of the rock.

Selective information of the thermal neutrons lifetime and increased sensitivity are of particular value, which favorably distinguishes the pulse neutron method from the stationary neutron method. If two rocks with different absorbing properties (τ) are studied, then their ratio of the neutron densities measured long after the neutron pulse will be:

$$\frac{N_1(t)}{N_2(t)} = e^{-t\left(\frac{1}{\tau_1}-\frac{1}{\tau_2}\right)}. \qquad (3)$$

Table shows the neutron diffusion parameters of a number of minerals and rocks.

The chemical composition of minerals has the greatest effect on the value of τ, and the diffusion coefficient is mainly determined by the hydrogen content. The widest range of changes in τ is observed in rock-forming minerals of chemical and biochemical origin. The narrowest range is for clay minerals. Similar regularities are characteristic of the diffusion coefficient [3].

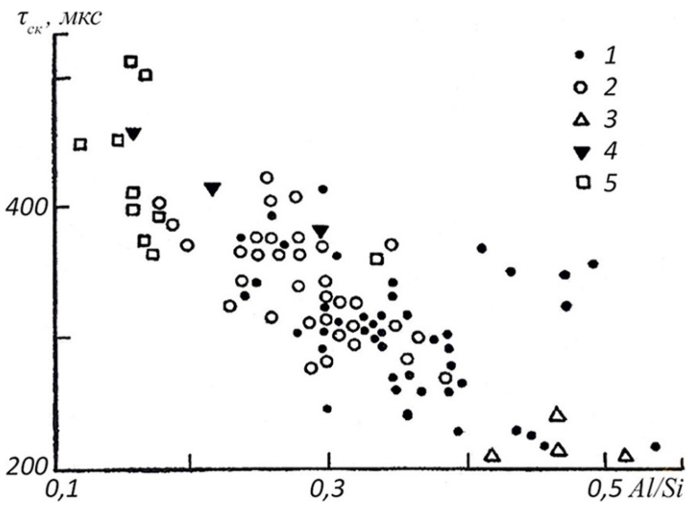
In PNM, the lifetime of thermal neutrons is one of the most important parameters for the lithological subdivision of rocks and assessment of the fluid saturation of the reservoirs.

The main rock-forming elements of sedimentary terrigenous rocks are aluminum, silicon, calcium, and iron. The predominant content of one or another element in the rock allows characterizing it tentatively. For example, the presence of aluminum in the composition of all clay minerals indicates the degree of clay content of the rock. The aluminum-silicon module (Al/Si ratio), where silicon is the main rock-forming element of lithological differences in sedimentary rocks, is considered an indicator of clay and sandiness of rocks.

Figure 3 shows the dependence of the neutron lifetime in the mineral skeleton of rocks τ_{sk} on the Al/Si ratio. The value of τ_{sk} varies depending on the aluminum-silicon module. Points corresponding to clays are located on the right side of the graph, and those for siltstones and sandy rocks are on the left. The effect of lithology (sandstone, limestone, dolomite) on the lifetime of thermal neutrons is clearly seen. The value of τ naturally decreases for all lithological differences with increasing the porosity coefficient and formation of water salinity [3].

Since the deceleration time spread is negligibly small compared to the lifetime of thermal neutrons, which characterizes their diffusion, it can be assumed

Neutron diffusion characteristics				
Minerals and rocks	**Состав (формула)**	**ρ, г/см³**	**τ, мкс**	**D·10⁵, см²/с**
Alumina	Al_2O_3	3.4	440	2.1
Kaolin	$Al_2O_3·2SiO_2·2H_2O$	2.61	360	0.8
Montmorrilonite	$Al_2O_3·4SiO_2·4H_2O$	2.1	400	0.81
Clay	Al_2O_3 – 29.7%, SiO_2 – 45.0%, $CaCO_3$ – 10.0%, Fe_2O_3 – 4.08%, H_2O – 11.0%	-	400	2.56
Marl	Clay – 50%, $CaCO_3$ + $CaMg(CO_3)_2$ – 50%	-	530	2.8
Marl	Clay – 15%, $CaCO_3$ – 85%	-	600	2.1
Quartz	SiO_2	2.65	1100	2.7
Calcite	$CaCO_3$	2.7	630	2.2
Dolomite	$CaMg(CO_3)_2$	2.9	960	1.9
Gypsum	$CaSO_4·2H_2O$	2.3	250	0.6
Anhydrite	$CaSO_4$	2.9	360	2.7
Water	H_2O	1.0	207	0.36
Naphtenic hydrocarbons	CnH2n	0.85	210	0.34



1 – clay; 2 – siltstone; 3 – marl; 4 – sandstone; 5 – sand

Figure 3 – The neutron lifetime τ_{sk} in the mineral rock skeleton dependence on the Al/Si ratio (according to D.M. Srebrodolsky, A.V. Avdeyeva, V.A. Vladimirova)

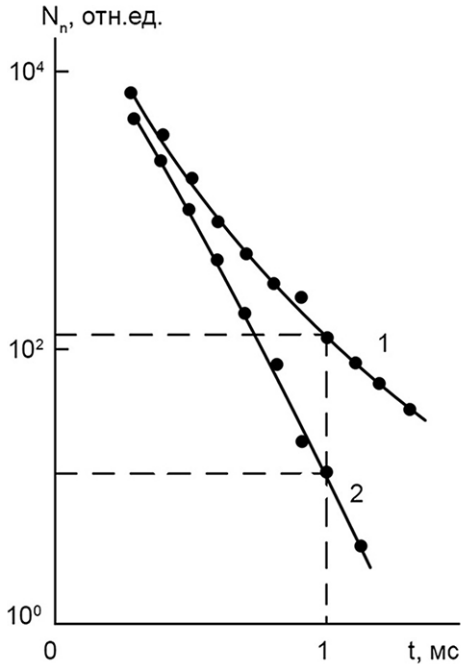
that all the neutrons are slowed down simultaneously. PNM measurements are usually obtained as the time distribution of $N(t)$ with fixed probes.

Figure 4 shows the results of measuring two layers of the same porosity that differ in the lifetime of thermal neutrons.

Approximately up to the time $t=0.5$ ms, the course of dependences against oil-bearing and water-saturated mineralized formations is practically the same. Within this time period, the effect of the well dominates. With the time delay of more than 500 μs, significant differences are observed in the damping decrements, which corresponds to the values of τ_{sm} for reservoirs saturated with oil and saline water.

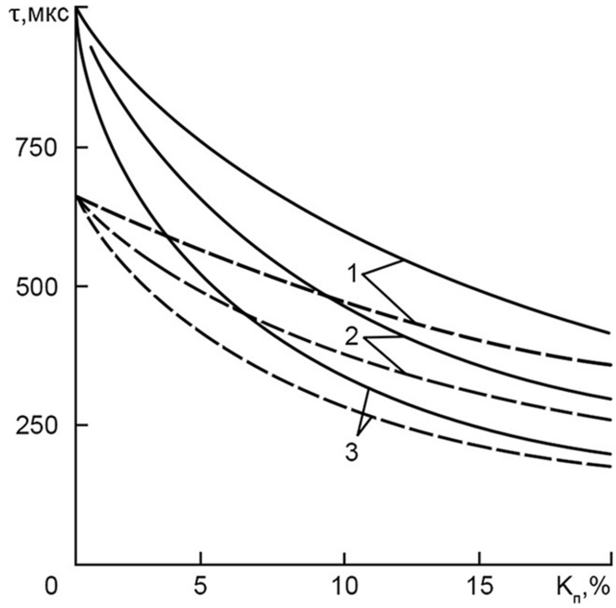
The uniqueness of the collector separation by their absorbing properties depends on the presence of a zone of the filtrate of the flushing fluid penetration. A relatively shallow zone of fresh filtrate penetration can reduce the PNM sensitivity to the neutron-absorbing activity of the formation. When a salty filtrate penetrates into an oil-bearing reservoir or a reservoir saturated with fresh water, the average neutron lifetime in the penetration zone can be intermediate between the values of τ_c and τ_{sm}. In such cases, the diffusion flow, even at large t, will be directed from the reservoir to the zone of penetration and further to the well. Therefore, the effect of the oil-bearing formation with the penetration of salty filtrate weakens more slowly than the influence of the aquifer with fresh filtrate.

The efficiency of solving the above tasks using pulse neutron methods largely depends on the



1 – oil-bearing; 2 – aquifer with water salinity 200 g/l NaCl

Figure 4 – Time distribution of thermal neutron density in a cased well against formations with different τ_{sm}



1 – oil-bearing formation, kн = 8%,
2 – oil-bearing formation, kн = 5%, 3 – aquifer

Figure 5 – Dependence of the lifetime of thermal neutrons τ from porosity k_p for dolomite (solid lines) and limestone (dotted line)

correct selection of measurement technique, in particular, the probe size and time characteristics depending on well conditions, rock lithology, and porosity variability. In the general case, at long delay times, the effect of well conditions decreases and the sensitivity of the method to changes in the absorbing properties of rocks increases.

When selecting the optimal PNM probe parameters, it should be taken into account that with increasing the probe size, the distorting effect of well conditions decreases, as a rule, the differentiating ability of the method increases, so, reliability in estimating the diffusion characteristics (D, τ) of the studied formations increases. In this case, as in the case of selecting the optimal delay time t, it is necessary to ensure sufficient statistical accuracy of the measurement [1].

Figure 5 shows the calculated dependences of the thermal neutron lifetime on the porosity of limestone and dolomite with different oil saturation factors.

The destabilizing effect of variable hydrogen content can be significantly reduced by using a two-probe technique that takes into account not only the time but also the spatial distribution of neutrons. This makes it possible to evaluate the neutron properties of the rock that are responsible for the process of slowing down and diffusion of neutrons, which are closely related to the hydrogen content.

The essence of the two-probe pulse neutron method is that hydrogen that has a relatively large cross section for both scattering and absorption of thermal neutrons, has a significant effect on both their space and time distribution. This circumstance makes it possible to compensate for the effect of hydrogen content in a certain range of its changing on the PNM readings by measuring the ratio of the readings of two probes. The lengths of the probes R_1 and R_2 and the delay times are selected to provide changes in the space and time distribution of the thermal neutron density caused by fluctuations in the hydrogen content of the rock will compensate each other.

The results of studying coal exploration wells by pulse neutron probing show the fundamental possibility of identifying coal seams and assessing the quality of coals [4].

Pulse neutron-gamma probing possibilities

PNGM-rc is designed to solve the same tasks as the above-considered PNNM. This is due to the fact that the capture gamma radiation recorded in the PNGM-rc arises as a result of the radiative capture of thermal neutrons. Therefore, the patterns inherent in thermal neutrons will also be repeated for gamma radiation accompanying radiative capture.

The space-time distribution of the RCGR density from a point source of fast neutrons can be estimated from the expression [5]:

$$N(r,t)=\frac{Q}{\left[4\pi\left(\theta+L_\gamma^2+Dt\right)\right]^{3/2}}\times \times\frac{V\tau_\gamma}{\tau}\cdot\exp\left[-\frac{t}{\tau}-\frac{r^2}{4\left(\theta+L_\gamma^2+Dt\right)}\right], \quad (4)$$

where Q is the neutron source power;

θ is the neutron Fermat age associated with the slowing down length;

L_γ is the length of the RCGR transfer depending mainly on the rock density;

τ_γ is the average lifetime of RCGR.

This analytical expression very approximately takes into account the distribution of the slowing down density and the spread of the slowing down time for different neutrons at small values of t. More accurate results of the nonstationary distribution of neutrons were obtained by the Monte Carlo method [6].

A characteristic feature of the presented dependences $N_\gamma(t)$ for PNGM is their intersection for reservoirs with the same porosity but with different chlorine content (Figure 6). This indicates the inversion nature of the PNGM readings from the delay time, which means that with the inversion delay time t_i, the equality of the intensities of the RCGR from the reference oil-saturated and reference water-saturated formations is ensured.

The qualitative interpretation of the results of PNGM is carried out according to the RCGR count rates measured at time delays t_1 and t_2, and the quantitative assessment is carried out according to the lifetime of thermal neutrons or, more often, according to the macroscopic thermal neutron capture cross section Σ_{rc}.

In foreign practice, this technique is called «sigma logging», the results of which are inversely proportional to the average neutron lifetime τ:

$$\Sigma_{\text{рз}} = \frac{1}{vt} = \frac{\ln(N_1/N_2)}{v(t_2 - t_1)}. \quad (5)$$

The difference-normalized ratio of the Ψ value as an interpretive parameter, which uses the readings of N_1 at a delay time t_1, less inversion t_p, the readings of N_2 at a delay time t_2 more than tp and the indications of the N_p method at the delay time ti, will be more differentiated to reservoir saturation (water or oil), less dependent on porosity, lithology and well conditions. The position of the oil-water contact is estimated by comparing the measured ratios:

$$\Psi_i = \frac{N_1(t_1) - N_2(t_2)}{N_p(t_p)},$$

with established a priori limit $\Psi_{\text{гр}}$ values determining the formation accessory [8].

Pulse neutron gamma method of inelastic scattering of fast neutrons consists in using the time and energy distribution of gamma radiation that accompanies inelastic scattering of fast neutrons on the nuclei of rock-forming elements. Inelastic scattering is a threshold reaction that occurs when neutron energies exceed the inelastic scattering threshold. In the process of slowing down fast neutrons, the probability of inelastic scattering sharply decreases. Therefore, the time window Δt for registering IGRNS should practically coincide with the neutron pulse duration, which is usually several microseconds. To eliminate the contribution of gamma radiation from the radiative capture of thermal neutrons, the pulse duration should not exceed the average slowdown time of neutrons in the studied rock.

The IGRNS intensity can be estimated in the zero probe approximation based on the following expression [7]:

$$N_\gamma' = \frac{Q\Sigma'}{4\pi}\left\{\left(\tau_0 + \frac{1}{\lambda}\right)\cdot\left[-R_0\left(\tau_0 + \frac{1}{\lambda}\right)\right] + \frac{e^{-R_0\left(\tau_0 + \frac{1}{\lambda}\right)}}{R_0}\right\}, \quad (6)$$

where Q is the number of neutrons in the pulse;

Σ' is the macroscopic cross section of inelastic scattering of fast neutrons;

λ is the average length of the free run of fast neutrons (14 MeV) in the rock;

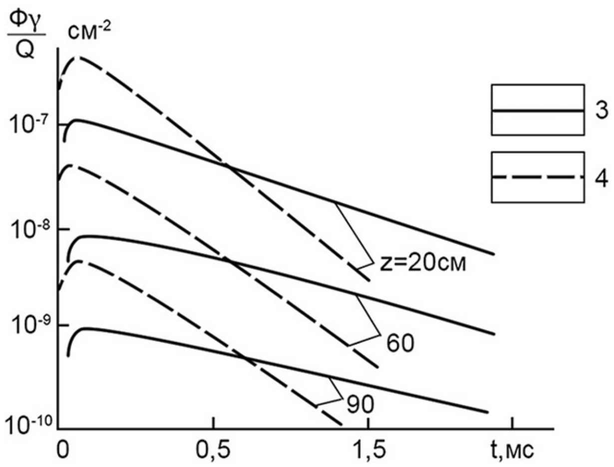
τ_0 is the linear coefficient of the IGRNS absorption;

R_0 is the radius of the spherical well.

Pulse NGL-ns is widely used in the study of oil and gas fields, in particular, in assessment of oil saturation of rocks. The value of the C/O ratio serves as an interpretative parameter-indicator. The method is called carbon-oxygen logging. A distinctive feature of pulse C/O logging is that the results are independent of the formation water salinity.

This independence favorably distinguishes pulse neutron C/O logging from pulse neutron methods associated with measuring the lifetime of thermal neutrons in water-oil saturated formations. It is widely practiced to measure the value of the Si/Ca ratio, which characterizes the lithology of the reservoirs and the type of the reservoir. Large values are typical for silicate (sandy) rocks, small values for carbonate rocks.

The prospects for further research in the field of pulse neutron methods are associated by the authors of [1] with the use of instrumental signals (interpretation parameters) in a single instrumental and methodological complex that arise during inelastic scattering of fast neutrons and radiative



——— – Fresh water (oil),
– – – – – saline water (200 g/l NaCl))
The numbers near the curves are the distance from the source, cm

Figure 6 – Time distribution of RCGR in sandstone (k_n = 20%, E_0 = 14 MeV)

capture of thermal neutrons. This provides for the further development of the theoretical and interpretation support for pulse neutron methods [9].

With regard to coal deposits, in particular, when studying coal exploration wells using pulse neutron gamma spectrometry, it is possible to expand significantly the scope of its application due to a more unambiguous identification of coal seams and increasing reliability and sensitivity of quality assessment [10]. The problem is solved in the following way. On the reference coal seam, the length of the probe is found in terms of achieving the maximum intensity of IGRNS on carbon with energy of 4.43 MeV. With the found length of the probe at the moment of the neutron pulse in the time window Δt less than the slowdown time of the primary neutrons, the intensity of the IGRNS is measured on carbon and rock-forming elements (Al, Si, S, Ca, Fe) with energy of (0.84-3.73 MeV).

On the reference layer of dense sandstone, the position of the second detector is found at the distance of at least three neutron diffusion lengths, which is used to measure the intensity of thermal neutron RCGR on the main rock-forming elements with energy of (4.96-7.73 MeV) at the delay time t in the range of 300-1200 μs, selected from the condition of ensuring the maximum contrast of the measured intensity of the RCGR with energy of (4.96-7.73 MeV) from the reference layers of coal and sandstone.

At the same time, coal seams in the section of wells are distinguished according to the maximum intensity of IGRNS with an energy of 4.43 MeV, the minimum intensity of IGRNS with an energy of (0.84-3.73 MeV), the minimum of the intensity of RCGR with an energy of (4.96-7.73 MeV), and the quality of coal seams (ash content) is determined by the value of the ratio of the intensity of IGRNS with an energy of 4.43 MeV to the intensity of IGRNS with an energy of (0.84-3.73 MeV) together with the measured intensity of RCGR with an energy of (4.96-7.73 MeV).

Conclusion

A review of theoretical and practical studies of pulse neutron probing methods shows their potential for solving many geological and geophysical problems. High sensitivity and information content of pulse neutron methods, a relatively low level of disturbing factors and fundamental possibilities of taking them into account ensure the effectiveness of their mass application in the exploration of mineral deposits.

The potential possibilities of pulse neutron probing will significantly increase with introducing high-power neutron generators, high-precision nanosecond technologies, high-energy resolution spectrometers, and developed interpretation-algorithmic quality assessment models.

REFERENCES

1. Pak Yu.N., Pak D.Yu., Madisheva R.K., Tebayeva A.Yu. Neutron physical analysis in geology and geophysics. Karaganda. Publishing house of A. Saginov KTU NJSC, 2022, 162 p.
2. Meyer V.A., Vaganov P.A., Pshenichny G.A. Methods of nuclear geophysics. Leningrad: Publishing House of Leningrad State University, 1988. 376 p.
3. Kozhevnikov D.A. Neutron characteristics of rocks and their use in oil and gas field geology. Moscow: Nedra, 1974. – 184 p.
4. Fomenko N.E., Popov V.V., Kovalenko A.S. Investigation of coal exploration wells using pulsed neutron-neutron logging. Bulletin of Tomsk Polytechnic University. Engineering of georesources. 2020. V. 331. No. 2. Pp. 151-161.
5. Pak Y.N., Pak D.Y. Nuclear technologies in geological-geophysical studies. Karaganda, 2017. 321 p.
6. Rezvanov R. Radioactive and other non-electric methods of well research. Moscow: Nedra, 1982. 368 p.
7. Filippov E.M. Nuclear geophysics. V.2. Neutronometry and integration of methods of nuclear geophysics. Novosibirsk: Nauka Publishing House. Siberian department, 1973. 400 p.
8. Pak D.Yu., Pak Yu.N., Madisheva R.K., Otubayev I.T. Status and prospects for assessing oil saturation and the position of oil-water contact in the process of well logging. University Proceedings. KTU. Karaganda, 2022. Issue 1. Pp. 81-89.
9. Method of determining density based on gamma ray and fast neutron detection using a Cs2LiYC16 detector in neutron-gamma density logging // Zhang Feng, Zhang Robin, P. Gardne, Huizhong Yan, Guoli Wu, Lili Tian, Qian Chen, Youngzhou Ti // Applied Radiation and Isotopes, 2018, v. 142, pp. 77-84.
10. Patent of the Republic of Kazakhstan No. 35626. Method of studying coal exploration wells using pulse neutron gamma spectrometry // Pak Yu.N., Pak D.Yu., Vdovkin A.V. et al. Date of issue: 04/22/2022.

Геологиялық-геофизикалық зерттеулердегі импульсті нейтронды зондтау әдістері

*[1]***ПАК Дмитрий Юрьевич,** *т.ғ.к., доцент, pak_kargtu@mail.ru,*
[2]**ИНКИН Дмитрий Анатольевич,** *бас директор, azimut@azimut-geology.kz,*
[1]**ТЕБАЕВА Анар Юлаевна,** *магистр, оқытушы, anara.tebaeva@gmail.com,*
[1]**ПАК Юрий Николаевич,** *т.ғ.д., профессор, pak_gos@mail.ru,*
[1]«Әбілқас Сағынов атындағы Қарағанды техникалық университеті» КеАҚ, Қазақстан, Қарағанды, Н. Назарбаев даңғылы, 56,
[2]«Азимут Геология» ЖШС, Қазақстан, Қарағанды, С. Сейфуллин даңғылы, 105,
**автор-корреспондент.*

Аңдатпа. *Геологиялық-геофизикалық зерттеулер процесінде импульсті нейтронды зондтауды енгізу мәселесі өзекті болып отыр. Стационарлық нейтрондық әдістермен салыстырғанда импульстік әдістердің сезімталдығы мен ақпараттылығын арттыратын негізгі факторлар қарастырылады. Импульсті нейтронды зондтаудың тиімділігі зондтың ұзындығына, қолданылатын жабдықтың уақыт пен энергетикалық сипаттамаларына байланысты екендігі көрсетілген. Геологиялық-геофизикалық есептерді шешу үшін импульсті нейтронды зондтаудың әртүрлі модификацияларының негізгі ерекшеліктері атап өтіледі. Жылдам нейтрондардың серпімді емес шашырауының нейтрондық гамма-сәулелену спектрометриясы бойынша импульстік модификацияны тиімді пайдалану бағыттары талқыланады. Жылу нейтрондарының серпімді емес шашырауы және радиациялық түсірілуі кезінде пайда болатын аспаптық сигналдарды кешенді қолдану негізінде нейтронды зондтаудың жетілдірілген модификациялары ұсынылған.*

Кілт сөздер: *импульсті нейтронды зондтау, нейтрондық диффузиялық параметрлер, серпімді емес шашырау және нейтрондардың радиациялық түсірілуі, нейтрондық спектрометрия-гамма-сәулелену, пайдалы қазбалардың сапасы.*

Методы импульсного нейтронного зондирования в геолого-геофизических исследованиях

[1]*ПАК Дмитрий Юрьевич, *к.т.н., доцент, pak_kargtu@mail.ru,*
[2]ИНКИН Дмитрий Анатольевич, *генеральный директор, azimut@azimut-geology.kz,*
[1]ТЕБАЕВА Анар Юлаевна, *магистр, преподаватель, anara.tebaeva@gmail.com,*
[1]ПАК Юрий Николаевич, *д.т.н., профессор, pak_gos@mail.ru,*
[1]НАО «Карагандинский технический университет имени Абылкаса Сагинова», Казахстан, Караганда, пр. Н. Назарбаева, 56,
[2]ТОО «Азимут Геология», Казахстан, Караганда, пр. С. Сейфуллина, 105,
**автор-корреспондент.*

Аннотация. *Актуализируется проблема внедрения импульсного нейтронного зондирования в процессе геолого-геофизических исследований. Рассмотрены основные факторы, повышающие чувствительность и информативность импульсных методов в сравнении со стационарными нейтронными методами. Показано, что эффективность импульсного нейтронного зондирования зависит от длины зонда, временных и энергетических характеристик применяемой аппаратуры. Отмечаются принципиальные особенности различных модификаций импульсного нейтронного зондирования для решения геолого-геофизических задач. Обсуждаются направления эффективного использования импульсной модификации по спектрометрии нейтронного гамма-излучения неупругого рассеяния быстрых нейтронов. Предложены усовершенствованные модификации нейтронного зондирования на основе комплексного применения инструментальных сигналов, возникающих при неупругом рассеянии быстрых и радиационном захвате тепловых нейтронов.*

Ключевые слова: *импульсное нейтронное зондирование, нейтронные диффузионные параметры, неупругое рассеяние и радиационный захват нейтронов, спектрометрия нейтронного-гамма излучения, качество полезных ископаемых.*

REFERENCES

1. Pak Yu.N., Pak D.Yu., Madisheva R.K., Tebayeva A.Yu. Neutron physical analysis in geology and geophysics. Karaganda. Publishing house of A. Saginov KTU NJSC, 2022, 162 p.
2. Meyer V.A., Vaganov P.A., Pshenichny G.A. Methods of nuclear geophysics. Leningrad: Publishing House of Leningrad State University, 1988. 376 p.
3. Kozhevnikov D.A. Neutron characteristics of rocks and their use in oil and gas field geology. Moscow: Nedra, 1974. – 184 p.
4. Fomenko N.E., Popov V.V., Kovalenko A.S. Investigation of coal exploration wells using pulsed neutron-neutron logging. Bulletin of Tomsk Polytechnic University. Engineering of georesources. 2020. V. 331. No. 2. Pp. 151-161.
5. Pak Y.N., Pak D.Y. Nuclear technologies in geological-geophysical studies. Karaganda, 2017. 321 p.
6. Rezvanov R. Radioactive and other non-electric methods of well research. Moscow: Nedra, 1982. 368 p.
7. Filippov E.M. Nuclear geophysics. V.2. Neutronometry and integration of methods of nuclear geophysics. Novosibirsk: Nauka Publishing House. Siberian department, 1973. 400 p.
8. Pak D.Yu., Pak Yu.N., Madisheva R.K., Otubayev I.T. Status and prospects for assessing oil saturation and the position of oil-water contact in the process of well logging. University Proceedings. KTU. Karaganda, 2022. Issue 1. Pp. 81-89.
9. Method of determining density based on gamma ray and fast neutron detection using a Cs2LiYC16 detector in neutron-gamma density logging // Zhang Feng, Zhang Robin, P. Gardne, Huizhong Yan, Guoli Wu, Lili Tian, Qian Chen, Youngzhou Ti // Applied Radiation and Isotopes, 2018, v. 142, pp. 77-84.
10. Patent of the Republic of Kazakhstan No. 35626. Method of studying coal exploration wells using pulse neutron gamma spectrometry // Pak Yu.N., Pak D.Yu., Vdovkin A.V. et al. Date of issue: 04/22/2022.