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# POSSIBILITIES OF INCREASING LOGGING EFFICIENCY WITH SIMULTANEOUS ANALYSIS OF NEUTRON AND GAMMA FIELDS FORMED IN OIL WELLS

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*The increase in the efficacy of studying well saturation in simultaneous analysis of radiation fields by means of pulsed neutron, activation, and spectrometric logging is examined. It is shown that neutron activation logging can in principle be realized in experimental testing of an operating model of apparatus in producing geophysical objects. Technical solutions using neutron well radiators based on sealed accelerator tubes with a laser source of deuterons and magnetic insulation, as a result of a large neutron yield combined with high pulse stability, as well as a thermally stabilized $\gamma$ spectrometer, are proposed and validated.*

In the course of operating oil and gas fields, it is especially important to track the progress in bringing them into production. An important criterion of the status of an operating well is the oil saturation factor $k_{os}$. The following approximate relation can be shown to hold between the oil saturation factor, volume content of the solid phase (frame $k_f$), relative clay content in pores (clay factor $k_{cl}$), and the relative water content in pores (water saturation factor $k_{ws}$) [1]:

$$k_{os} + k_f + k_{cl} + k_{ws} \sim 1. \tag{1}$$

The sum of the well and water saturation factors corresponds to the porosity factor

$$k_p = k_{os} + k_{ws}. \tag{2}$$

In the course of the development of a field, the composition of the reservoir rock can evolve and the relation for determining the oil saturation factor may no longer be unique. To determine this factor reliably, the results of neutron and gamma logging, acoustic and electric logging, nuclear activation methods, classical methods of petrophysics, and other methods are compared.

In the present work, we discuss the possibility of increasing the reliability of the geophysical information obtained by combined analysis of the neutron and gamma fields formed in an oil well.

**Pulsed neutron logging and interpretation.** This method yields information about the condition of the developed formation in the presence of the drive pipe of the well, which creates inconveniences for other geophysical procedures [2, 3]

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as a result of time analysis of the thermal neutron field or the gamma ray field (due to radiative capture of the thermal neutrons) created in the well by the accelerator tube. Their time structure is determined by the sum of exponentials

$$n(t, z) = A_p(z)\exp(-\lambda_p t) + A_w(z)\exp(-\lambda_w t), \tag{3}$$

where $n(t, z)$ is the spatial density of neutrons or gamma rays; $z$ is the vertical coordinate; $\lambda_p$ and $\lambda_w$ are the damping decrements of the radiation field in the formation and well, respectively, as a result of radiative capture. The mathematical apparatus of separating exponentials in the (3) logging signal obtained as a result of the time analysis makes it possible to determine the damping decrements of the radiation field in the formation $\lambda_f$ and the amplitude $A_p(z)$ [3, 4].

The amplitude ratio of the formation exponential $A_p(z_1)/A_p(z_2)$ obtained for points with different coordinates $z_1$ and $z_2$ carries information about the moderating and diffusing properties of the formation, which determine its hydrogen content. The hydrogen stoichiometric coefficients for water and productive hydrocarbons do not differ much, so that this ratio will depend on the porosity factor and serve as a tool for determining it [2].

Using the rule of additivity, a relation can be established between the damping decrements of the thermal neutron density in the formation and the macroscopic radiative-capture cross-sections of its individual components by means of the relation

$$\lambda_p \sim (1+\varepsilon_w)\Sigma_f k_f + (1+\varepsilon_{os})\Sigma_{os} k_{os} + (1+\varepsilon_{ws})\Sigma_{ws} k_{ws} + (1+\varepsilon_{cl})\Sigma_{cl} k_{cl}, \tag{4}$$

where $\varepsilon_{w,os,ws,cl} \sim 0.1$ are dimensionless correction parameters obtained in model experiments and given in the form of sets of master curves; $\Sigma_{f,os,ws,cl}$ are the macroscopic cross-sections of radiative capture of neutrons in the frame, oil, water, and clay, respectively. These cross-sections can be determined by analyzing the core and its components in the neutron field of a nuclear reactor or a stationary neutron generator.

Relation (4) can be used to determine the character of the fluid saturation of the reservoir rock and the position of the water–oil boundary owing to the presence of sodium chloride and, therefore, chlorine nuclei, whose radiative capture cross-section is anomalously large. Thus, the determination of the well saturation factor using pulsed neutron logging is of an indirect character associated with a chlorine deficit. These results can be compared with a petrophysical analysis of the core and the reliability of the information can be increased by performing a correlation analysis of the data.

The practice of using pulsed neutron logging showed a sharp reduction of the contrast of the method and often its serviceability at low sodium chloride concentration in the formation water (<25 kg/m$^3$). This has a simple explanation, if relations (2) and (4) are treated as a system of linear equations for determining the unknown oil and water saturation factors. At low mineralization, the presence of chlorine nuclei will not make a large contribution to the macro radiation capture cross-section of formation water and the terms $(1+\varepsilon_{os})\Sigma_{os}k_{os}$ and $(1+\varepsilon_{ws})\Sigma_{ws}k_{ws}$ can be close. Then, the indicated system of linear equations becomes poorly conditioned and the error in determining the oil saturation factor can increase without bound. In this case, additional geophysical information must be brought in, using direct nuclear methods of determining carbon and oxygen in the formation.

Another problem is associated with the non-uniqueness introduced into Eqs. (1) and (4) by the clay factor. The amount of clay in the formation can change in the course of well operation and during core extraction from the natural bedding site. To overcome this difficulty, an energy analysis must be performed of the natural gamma ray field produced in the formation by the decay of $^{232}$Th and $^{40}$K present in the clay. This yields additional information about the clay factor.

**Possibilities of neutron logging of oil wells with direct determination of oxygen and carbon concentrations by activation methods.** The method of direct determination of oxygen and carbon using multi-channel energy spectrometers for elastic-scattering and radiative-capture gamma radiation is widely used in the study of oil wells [5]. It has an advantage over indirect identification of oil by means of the chlorine deficit, whose efficiency depends on the degree of mineralization of the formation water. However, the apparatus for implementing the method is difficult to operate, bulky, and expensive, and the mathematical apparatus of data processing is difficult for specialists with medium-level skills to use.

We shall examine as an alternative activation methods of direct determination of formation $^{16}$O and $^{12}$C via the nuclear reactions $^{16}$O$(n, p)^{16}$N and $^{12}$C$(n, p)^{12}$B. These reactions are endo-energetic with thresholds 10.23 and 13.64 MeV, respectively. The maximum energy of the neutrons emitted by the targets of small-size accelerator tubes is close to the threshold of the indicated reactions. This made it possible to fit the dependences of the micro cross-sections of the reactions on the neutron energy $T_n$ according to [6] by quadratic functions using experimental data [7]:

$$\sigma_{\mathrm{O}}(T_n) \cong 0.0215(T_n - 10.23)^{0.5};$$

$$\sigma_{\mathrm{C}}(T_n) \cong 0.032(T_n - 13.64)^{0.5}.$$

For the case of direct emission of a neutron whose direction of motion coincides with that of the deuteron, it is possible to obtain the following dependences of the micro cross-sections of activation on the kinetic energy $T_d$:

$$\sigma_{\mathrm{O}}(T_d) \cong 0.0215\{[(14.08 + 0.48T_d)^{0.5} + (0.08T_d)^{0.5}]^2 - 10.23\}^{0.5};$$

$$\sigma_{\mathrm{C}}(T_d) \cong 0.032\{[(14.08 + 0.48T_d)^{0.5} + (0.08T_d)^{0.5}]^2 - 13.64\}^{0.5}.$$

The concentration $n$ of oxygen or carbon is determined from the measured gamma activity $A$ as the logging apparatus travels over a prescribed distance (depth quantum) in the well:

$$n \sim (Q < \sigma > L)^{-1} A, \tag{5}$$

where $Q$ is the neutron flux emitted by the accelerator tube in the total solid angle; $<\sigma>$ is the energy-averaged micro cross-section of activation; and $L$ is a parameter approximately equal to the neutron travel distance before the threshold of the nuclear activation reaction. For testing the developed apparatus in well models, the latter parameter must be determined more accurately.

We shall study activation logging for the example of oxygen with two possible operating regimes. In the first regime the actuation frequency of the accelerator tube must not exceed 100 Hz, and in the second regime the repetition frequency of the neutron bursts equals 300–1000 Hz.

The low-frequency regime permits triggering the system detecting the radiative-capture gamma rays after their activity drops below 10% of the external gamma background. Calculations showed that for this to happen the time interval between two neutron bursts must be more than five times greater than the decay constant of the radiative-capture gamma-ray field in the oil formation. A time delay $\tau_d \sim$ 5–7 msec is established between the neutron burst and the start of the measurements; this delay must guarantee absence of radiative-capture radiation. In order to eliminate the interfering radiation from other radionuclides, the measurements must be performed with energy threshold $E_0$ that separates the energy range $E_\gamma > E_0$ containing $^{16}$N lines (6.13 and 7.12 MeV). The measurement of the integral photon count in this range stops before the onset of the next triggering of the accelerator tube.

The oxygen activation logging scheme described above admits simultaneous time analysis of the radiative-capture gamma-ray flux. This makes it possible to correlate two independent procedures and increase the information content of such studies.

In the second regime, it is supposed that neutron bursts are generated with frequency $f$ = 300–1000 Hz. The use for this purpose of gas-filled accelerator tubes possessing high pulse-to-pulse neutron burst generation stability simplifies the detection system considerably, eliminating a neutron flux monitor from it.

The difficulty of implementing oxygen acoustic logging in the indicated frequency regime is that the time interval between neutron bursts is small (~1 msec), which makes it impossible to separate for measurement of the induced gamma activity an interval where there is no radiative-capture radiation. In addition, a pulse-periodic flux of radiative-capture gamma rays, against whose background a constant signal must be identified, is inevitably superposed on the constant flux of gamma rays emitted by excited $^{16}$O nuclei. To separate it, a processing method has been proposed where the variable and constant components of the signal are separated by a procedure similar to [4], and at the same time information appears about the activation effect and about the damping decrement of the radiative-capture gamma-ray field.

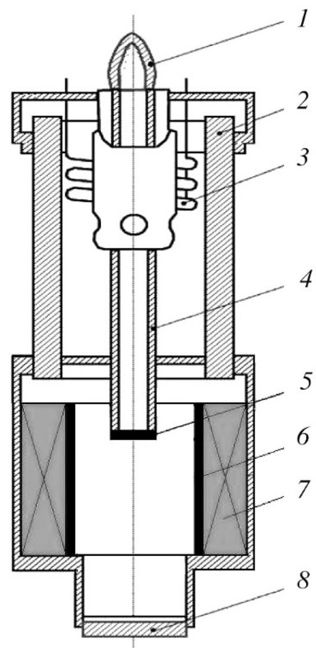


Fig. 1. Schematic diagram of a new variant of an accelerator tube with a system for suppressing electronic conduction by means of an internal permanent magnet and a laser source of deuterons: *1*) exhaust for sealing the tube; *2*) insulator; *3*) getter pump; *4*) anode; *5*, *6*) plasma- and neutron-forming target, respectively; *7*) ring magnet; *8*) window for introducing laser radiation.

The use of radiators based on gas-filled accelerator tubes has another advantage due to a more than 10-fold reduction of the pulsed flux of events at the entry into the detection channel owing to the high rate of generation of neutron bursts. The result is that the percentage of missed counts in gamma-ray detection decreases.

The fundamental possibility of implementing the activation method was shown in experimental studies of an operating model of an oxygen activation logging apparatus under the conditions of the fields in the Tataria and Western Siberia [8]. A well neutron emitter was used in the experiments [9]. The neutrons were generated in a low-frequency pulse-periodic regime with frequency $f$ = 10–20 Hz and average flux ~$10^8$ nsec$^{-1}$ in the total solid angle. An assembly comprised of a NaI crystal and a photomultiplier was used as the detector. Because the pulse-to-pulse stability of generation of the neutron bursts is low, reaching 30%, two types of monitors based on the reaction $^{11}B(n, \alpha)^8Li$ and the recoil proton method were used in the experiments. Pulse neutron logging based on the chlorine deficit with detection of radiative-capture gamma rays was conducted in parallel. A good correlation between the activation and pulsed neutron logging methods was established in determining water-oil contact.

**Requirements of well neutron radiators for efficient activation logging and prospects for its implementation.** Assessments based on relation (5) and the expressions for the cross sections of nuclear activation reactions showed that effective commercial implementation of activation logging requires well neutron radiators based on accelerator tubes that meet specific requirements.

In using the low-frequency activation-logging regime ($f \leq 100$ Hz), the integral neutron flux in the total solid angle must be ~$10^{10}$ sec$^{-1}$. In a regime with frequency $f$ = 0.3–1 kHz, the neutron flux must exceed $10^9$ sec$^{-1}$. In both cases, the deuterons must be accelerated to energy $T_d \geq 0.3$ MeV toward the target of the tube in a direction perpendicular to the well axis; the instability of neutron burst generation must not exceed 5%.

Small neutron radiators based on accelerator tubes with laser sources of deuterons with parameters adequate for activation logging are now being developed at MEPhI [10]. A special stand modeling the regimes and geometry of the developed

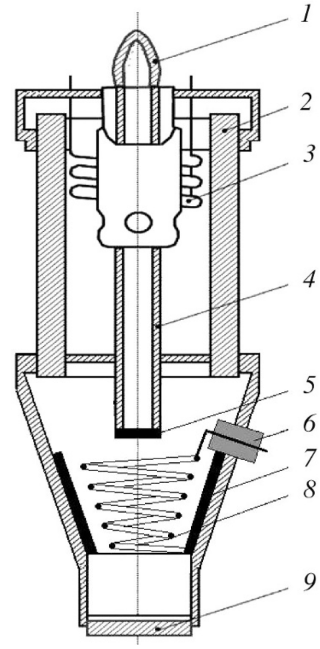


Fig. 2. Schematic diagram of a new variant of an accelerator tube with a system for suppressing electronic conduction by means of a pulsed magnetic field of a spiral line and laser source of deuterons: *1*) exhaust for sealing the tube; *2*) insulator; *3*) getter pump; *4*) anode; *5*) plasma-forming target; *6*) electric input; *7*) neutron-forming target; *8*) spiral; *9*) window for introducing laser radiation.

apparatus was developed to check the radiators experimentally [11]. Experiments with collapsible models of the new accelerator tubes – with a system for suppressing the electronic component by permanent ring-shaped magnetic elements and pulsed magnetic fields of a spiral line which are placed in the evacuated volume of the tube – have been performed using the setup [11, 12].

In the latest experiments, a specially developed 30-cascade Arkad'ev–Marks generator capable of generating in a no-load regime pulses with duration ≤100 nsec and amplitude up to 500 kV was used as the source of the accelerating voltage [13]. The use of a special synchronization system in the first two cascades of the setup ensures stable generation of neutron pulses. Moreover, owing to the short pulse duration together with the magnetic system for suppressing electronic conductivity of the diode system the requirements of high-voltage insulation of the well neutron radiator were lowered.

A solid-state laser with pulse energy ~1 J was used to obtain the plasma. Deuteron currents exceeding 1 kA accelerated in a radial direction to the neutron-forming target were obtained in the experiments. These data attest the possibility of attaining parameters of well neutron radiators meeting the specifications for effective activation logging.

It should be noted that voltage pulses with amplitude about 300 kV were formed and $\sim 10^8$ pulses were generated on the reaction $T(d, n)^4He$ within the dimensions of a well apparatus in previous experiments with an operating model of a well neutron radiator using an accelerator tube with a laser source of deuterons and an Arka'ev–Marks generator [14].

The physical modeling performed on an experimental vacuum bench resulted in the proposal of two variants of an accelerator tube for generating neutrons (Figs. 1 and 2).

**Application of the spectrometry of natural gamma fields in a well for evaluating the clay factor.** As noted above, the presence of clay in the pores of the reservoir rock makes impossible unequivocal interpretation of the data obtained from pulsed neutron logging, since the nuclear properties of the reservoir rock depend on the quantitative content and composition of the clay materials as well as the character of the distribution in the pores. This drawback can be overcome by obtaining additional information by spectrometric gamma logging in the analysis of the natural gamma radiation from rock.

The present work examines the sources of gamma radiation of rock containing $^{208}Tl$ in the thorium series (line with $E_\gamma$ = 2.62 MeV) and $^{40}K$ (line with $E_\gamma$ = 1.46 MeV). The intensity of these lines makes it possible to determine the thorium

$C_{Th}$ and potassium $C_K$ concentrations in the geophysical medium. It is shown in [15] that the product $G = 10^6 C_{Th} C_K$ depends weakly on the mineral composition of the clay and can serve as a criterion for evaluating the clay factor. The parameter $G$ is called the potassium-thorium index. A least-squares analysis of the experimental data gives the approximate empirical relation

$$k_{cl}(G) = 1.295G - 0.965G^2,$$

which can be refined subsequently on the basis of detailed experiments performed on models of formations and experimental and commercial wells. The information on the clay factor removes in relations (1) and (4) the uncertainty in the interpretation of the data obtained by pulsed neutron logging.

An effective thermally stable seven-channel well gamma spectrometer that is simple to operate has been developed for studies of geophysical objects with different geological structure and thermal conditions; the spectrometer was run at JINR [16].

**Conclusion.** The tracking of the development of new oil and gas fields by means of pulsed neutron methods clashes with the presence of a large number of wells with low mineralization of the formation water and complex geological conditions, which degrades the reliability of logging information. These problems can be solved cost-effectively by using pulsed neutron well logging, neutron activation logging, and spectrometric gamma logging using the native radioactivity with a combined analysis of the neutron and gamma fields formed in oil wells. Activation logging has been implemented in experimental testing of an operating model of the apparatus on producing wells.

Modern technology makes it possible to propose feasible technical solutions for the problems mentioned in this work using well neutron radiators based on sealed accelerator tubes. It is found that accelerator tubes with a laser source of deuterons and magnetic insulation are promising because of the large neutron yield combined with high pulse stability.

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## REFERENCES


1. S. J. Pirson, *Science of Oil Formation*, Gostoptekhizdat, Moscow (1961).
2. Yu. S. Shimelevich, S. A. Kantor, A. I. Kedrov, et al., *Physical Principles of Pulsed Neutron Methods*, Nedra, Moscow (1976).
3. Yu. S. Zamyatnin and A. E. Shikanov, *50th Anniversary of Pulsed Neutron Logging (1955–1958, G. N. Flerov)*, JINR Report RZ-2007-151 (2007).
4. A. A. Startsev, E. A. Fedyna, and A. E. Shikanov, “Algorithm for decomposition of PNL response,” *Appl. Rad. Isot.*, **48**, No. 10–12, 1329–1330 (1997).
5. *Modern Nuclear Geophysics in Searching for and Exploration and Development of Oil and Gas Deposits*, VNIIgeosistem, Moscow (2004).
6. L. D. Landau and E. M. Lifshitz, *Quantum Mechanics (non-relativistic theory)*, GIFML, Moscow (1963).
7. I. A. Maslov and V. A. Luknitskii, *Handbook of Neutron Activation Analysis*, Nauka, Leningrad (1971).
8. A. I. Kedrov, V. A. Mikhailov, A. V. Il’inskii, et al. “Investigation of oil and gas wells by oxygen activation using small-size generators of 14-MeV neutrons,” in: *Scientific Session MIFI-2003*, Vol. 7, pp. 128–129.
9. Yu. G. Bessarabskii, E. P., Bogolyubov, I. G. Kurdyumov, et al. “Controlled well neutron radiator,” *At. Energ.*, **77**, No. 3, 226–228 (1994).
10. O. B. Anan’in, A. S. Tsybin, A. E. Shikanov, and K. I .Kozlovskii, “Prospects for developing small-size neutron generator with a laser source of deuterons,” *At. Energ.*, **115**, No. 2, 115–118 (2013).
11. K. I. Kozlovskii, D. D. Pnomarev, V. I. Ryzhkov, et al., “Experimental study of a model of a small-size neutron generator with pulsed magnetic insulation,” *At. Energ.*, **112**, No. 3, 182–184 (2012).
12. A. E. Shikanov, E. D. Vovchenko, and K. I. Kozlovskii, “Neutron generation in a plasma diode with insulation of electrons by the field of a permanent magnet,” *At. Energ.*, **119**, No. 4, 210–215 (2015).

13. V. D. Vovchenko, A. A. Isaev, K. I. Kozlovskii, et al., “Accelerating voltage generator for small-size pulsed neutron sources,” *Prib. Tekhn. Eksp.*, No. 3, 241–247 (2016).
14. V. N. Dydychkin and A. E. Shikanov, “Generation of short (<100 nsec) neutron pulses in small-size accelerator tubes with laser ion source,” *At. Energ.*, **70**, No. 2, 135–137 (1991).
15. E. G. Urmanov, *Spectrometric Gamma Logging of Oil and Gas Wells*, VNGIIOENG, Moscow (1984).
16. V. I. Danilov, A. I. Kedrov, E. G. Urmanov, et al., “Spectrometric well logging apparatus,” *Prib. Tekhn. Eksp.*, No. 1, 163–164 (1998).