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# Universal apparatus module of radioactivity logging for the investigation of oil-and-gas reservoirs while drilling

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Logging-while-drilling (LWD) is the most advanced technology in geophysical well logging. It is widely used for determining the petrophysical and other parameters of oil-and-gas reservoirs in vertical, deviated, and horizontal boreholes.

The LWD is particularly important for horizontal boreholes, obtained by directional drilling from vertical boreholes into predetermined hydrocarbon reservoirs. Horizontal boreholes allow multiplying the yield of hydrocarbons, increasing overall production, and using effectively both new vertical boreholes and exploited ones, as well as old boreholes. The opportunity of horizontal drilling to local (isolated) deposits, which are at a certain distance from vertical boreholes, is of also essential importance. All these factors are favourable for increased hydrocarbon production, which is of great significance for Ukraine.

This paper concentrates on the apparatus developments aimed at creating a new module of radioactivity logging for LWD; the module is universal in the sense that it can be used in drill collars, which are employed while drilling all types of boreholes. The tool implements neutron-neutron logging, neutron-gamma logging, gamma-gamma logging, and gamma-ray logging. It allows a direct and combined determination of a broad set of petrophysical reservoir parameters.

The advantages and disadvantages of the known nuclear logging modules for the LWD have been analyzed, and the features and merits of the proposed one are shown. During the laboratory and borehole operations with a pilot sample of the module, trends for its improvement were outlined.

As an example of using the new module for LWD, the results of determining the petrophysical parameters of oil reservoirs of varying lithology in three horizontal boreholes are given. The process of LWD measurements demonstrated high technologicness and efficiency of the module. Comparison of the obtained parameters of the reservoirs with the data of independent measurements carried out in the open hole of the same boreholes using the PEX tool (Schlumberger) showed a qualitative consistency and a quantitative convergence of the results.

**Key words:** oil-and-gas borehole, logging-while-drilling, combination of radioactivity logging methods, universal apparatus module, petrophysical parameters of reservoir.

**Introduction.** Until relatively recently, wireline logging was the basic technology of geophysical investigations in oil-and-gas boreholes (open and cased ones). Since the end of the last century, logging-while-drilling (LWD) has come into wide use for determining the petrophysical and other parameters of oil-and-gas reservoirs. In many cases, the LWD has undeniable advantages over wireline and other types of logging.

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The main merits of LWD are the measurement results being obtained and transmitted in real time; the formations remaining practically undisturbed (missing or minimal invaded zone, absence of mud cake and clogging zone, low rugosity); obtaining results in boreholes that need immediate casing; efficiency and significant reduction of the costs; gain in time, especially for the vertical deep (~4—6 km)[1] and ultra-deep (over ~6 km) boreholes.

The LWD measurements are important in horizontal boreholes, obtained by directional drilling from vertical boreholes into predetermined reservoirs. In this case, LWD is performed in layers with approximately known general data: occurrence depth, bed thickness, extension, lithology, nature of saturation (oil, gas), as well as supposed reservoir properties — approximate porosity, assessed oil or gas saturation factor, water salinity in pores, etc. All these and other data and properties are subject to a more accurate determination while drilling a horizontal borehole.

Horizontal boreholes allow an increase the yield of hydrocarbons 3—4 times (and in some cases by dozens of times), larger overall production, and efficient use of new vertical boreholes and exploited ones, as well as old boreholes. The opportunity of horizontal drilling to local (isolated) deposits, which are at a certain distance from vertical boreholes, is also important. All these factors bolster hydrocarbon production, which is exceedingly important for Ukraine.

This paper concentrates on the developments performed at the Institute of Geophysics of the National Academy of Sciences of Ukraine (IGPh), including in close cooperation with LLC «Ukrspetsprylad». The work aims to create a new universal apparatus module of radioactivity logging (UMRL) for investigating oil-and-gas reservoirs during LWD. The module can be used in drill collars (DC) of various diameters and wall thicknesses while drilling vertical, deviated, and horizontal boreholes. The developed universal module contains a set of RL devices: dual-spaced neutron-neutron logging (2NNL), dual-spaced neutron-gamma logging (2NGL), dual-spaced gamma-gamma logging (2GGL), and gamma-ray logging (GR). It allows determining more petrophysical parameters of oil-and-gas reservoirs during LWD.

As an example of using the UMRL, the results of determining the petrophysical parameters of oil reservoirs in horizontal boreholes in beds of different lithologies are given. In particular, the advantages of the proposed density neutron-gamma logging (DNGL method) are compared to density gamma-gamma logging (DGGL method). The LWD results were compared with independent measurements by the PEX tool (Schlumberger) in the same boreholes after drilling.

**1. Features of logging-while-drilling.** Logging-while-drilling is different from wireline logging in many ways. The logging speed of LWD is uniquely related to the penetration rate, making it relatively slow and irregular (~10—80 m/h). The low speed provides to an increase in the statistical accuracy of radioactivity logging; significant homogeneous intervals of the formation being investigated in the case of horizontal boreholes are also favorable for it.

If necessary, the trajectory of a horizontal borehole can be purposefully changed while drilling. For this, it is necessary to control the making borehole within the selected bed and the relationship between the length of the borehole (measured depth) and the true vertical depth of the drill bit position. Basic LWD data are transmitted in real time using special telemetry, and the complete information is recorded in a memory unit.

While drilling, measuring devices are exposed to strong mechanical loads (vibration, shock, torsion) for a long time. This imposes high demands on the components and their mounting, requires special shock absorbers, and the like.

The key feature of LWD is related to the necessary obtaining information about the properties of formations in the presence of a thick-walled drill collar (∅ from ~100 to ~200 mm) with a wall thickness of ~15—60 mm and with an internal diameter of ~70 mm. The DC is the bottom of the drillstring; the mo-

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[1] Here and elsewhere sign «~» corresponds to «about».

dules of radioactivity logging, induction logging, acoustic caliper, etc., are placed in DC at certain distances from the drill bit.

## 2. Conventional modules of nuclear logging for logging-while-drilling.

**2.1. *Module of radioactivity logging based on GGL and NNL.*** When investigating the oil-and-gas reservoirs while drilling with the help of radioactivity logging, it is common to employ the neutron-neutron logging (NNL) to determine the neutron porosity and the gamma-gamma logging (GGL) to determine the density and estimate lithology [Allen et al., 1989; Logging-While-Drilling…, 2002; Ellis, Singer, 2008]. We will denote the appropriate module of radioactivity logging (RL) for LWD with «windows» in the drill collar as the RL(GGD) module (where GGD stands for gamma-gamma density).

The device for implementing the NNL method contains a polyenergetic AmBe source of fast neutrons and two thermal neutron detectors (a 2NNL device). In a 2GGL device, there are $^{137}$Cs gamma-ray source ($E_{0\gamma}$= =0.662 MeV) and two gamma-ray detectors.

A RL(GGD) module was made by placing the 2NNL and 2GGL devices in drill collars of various diameters (depending on the whether the drilling borehole was vertical, deviated, or horizontal). The devices were built into the drill collars which simultaneously served as protective housings for the RL modules. The 2NNL device is placed on the section of the whole drill collar, and for the 2GGL device, special «windows» are equipped opposite the source and detectors of gamma rays.

The «windows» made in the steel pipe favor the penetration of gamma rays from the $^{137}$Cs source into the rock and the transmission of Compton and low-energetic gamma rays from the rock to the 2GGL detectors. The windows and the 2GGL device pressed against the DC wall establish favorable conditions for determining the formation density by detecting gamma rays scattered by electrons and estimating lithology using the photoelectric factor.

With the described design of the RL module, the drill collar with devices built into it serves as the measuring tool for LWD («DC tool»). This leads to a need for a set of extremely heavy and bulky «DC tools», thus complicating LWD measurements, calibration of RL devices, transportation, and the like. For example, the «DC-tool» LWD-ADN [Logging-While-Drilling…, 2002] weighs 907 kg and has a length of 6.62 m.

The informativity of the methods used in the conventional RL(GGD) module is not always sufficient to determine the necessary petrophysical parameters of oil-and-gas reservoirs. For example, the absence of a GR detector in the RL module makes it difficult to obtain parameters of shaliness and porosity of reservoirs, considering the shale's hydrogen index. Also, this does not allow correcting for the natural gamma radiation.

The insufficiently high initial energy of the $^{137}$Cs source leads to some decrease in the already low depth of investigation using the GGL method. This lowers the accuracy of density determination due to standoff, composition change of the borehole mud during drilling, during the invasion of the mud filtrate, etc.

***2.2. Module of nuclear logging based on pulsed neutron generator.*** Essential limitations of the GGD (in particular, the small depth of investigation and so high sensitivity to borehole factors) and a desire to replace radioactive chemical sources of neutrons and gamma rays with safer ones, prompted the search for other ways to measure the density and other parameters during the LWD.

The neutron-gamma method for determining density (neutron-gamma density, NGD) using a pulsed D-T neutron source ($E_{0n}$=14.1 MeV) was developed [Yu et al., 2011; Allioli et al., 2013; Reichel et al., 2013; Tkabladze et al., 2017]. Together with the NGD method, one can simultaneously determine the hydrogen index (neutron porosity, $\phi_n$), the thermal neutron capture cross-section $\sum$, and the content of individual elements (elemental capture spectroscopy) [Reichel et al., 2013].

Based on a pulsed neutron generator, the nuclear logging module (NL(NGD)) is built into a single-piece (7.9 m) drill collar («DC tool») [Reichel et al., 2013].

Fast neutrons from the D-T generator pass almost freely through the DC wall and, at an energy above the threshold, interact inelastically with the nuclei of rock elements. Excited nuclei drop back to the ground state, emitting high-energy gamma rays ($E_\gamma \leq 7.1$ MeV). The primary distribution of these gamma rays in the rock has the shape of a spatially inhomogeneous «cloud» [Allioli et al., 2013], which takes up a certain, relatively large volume of the rock and serves as a source of high-energy gamma rays when determining the density (instead of a point source of $^{137}$Cs in the GGD method).

After a series of Compton scatterings on the rock's electrons, these gamma rays pass through the DC wall and are recorded by the detectors. The count rate of these detectors is related to the rock's density.

The main geophysical advantage of the NGD method over the GGD method is a significant (~2.5 times) increase in the depth of investigation (up to ~25 cm) [Yu et al., 2011; Allioli et al., 2013; Reichel et al., 2013; Luycx, Torres-Verdin, 2019] due to the two-component neutron-gamma field expanded in the rock volume and the use of high-energy gamma rays.

Because of the greater depth of investigation of the NGD method, the influence of the near zone and related factors is reduced. However, inaccuracies in determining the density by the NGD arise due to the complicated interaction of the neutron-gamma field components with some constituents of the reservoirs (shales, mineralized pore water, gas).

In general, together with certain merits and, in some cases, successful application of the NGD, there are certain disadvantages [Yu et al., 2011; Reichel et al., 2013; Luycx, Torres-Verdin, 2019]:

– density errors in total are somewhat greater in comparison with the GGD method performed under favorable LWD conditions;

– sonde readings are sensitive to standoff, especially for large-size boreholes;

– uncontrolled parameters of the drilling mud (cuttings, salinity, shale content) impair the accuracy and sensitivity of measurements;

– accuracy of determining the density of shale reservoirs is significantly underestimated (in shales, up to ~thrice) in comparison to the GGD;

– the accuracy of measurements of the density of gas reservoirs is unsatisfactory.

Another approach [Inanc, Gilchrist, 2013] to determine the density using a D-T neutron generator fundamentally differs from the conventional NGD method. Here, the inelastic neutron scattering and other (n, γ) processes based on the radiative capture of thermal neutrons are used as a source of gamma-rays.

According to [Inanc, Gilchrist, 2013], besides the rock gamma rays, gammas from specially selected materials inside the tool (for example, graphite and cadmium) are sources when determining rock density. This approach is acceptable for open and cased boreholes since the corresponding tool must have a relatively large diameter. However, it is inefficient for conditions of the LWD measurements.

**3. Universal module of radioactivity logging for performing LWD.** We proposed [Kulyk, Bondarenko, 2021; Danyliv et al., 2022] a new approach to create an RL module for the LWD. The module realizes four RL methods: NNL, NGL, GGL, and GR. The module operates in whole (windowless) drill collars of all diameters and wall thicknesses when performing the LWD of vertical, deviated, and horizontal boreholes. Such a module is called here the universal module of radioactivity logging for the LWD (UMRL). The method for determining the density by the NGL [Kulyk et al., 2023] will be denoted by DNGL, and the method of density GGL (in a drill collar without windows), by DGGL.

***3.1. Universality of module.*** The new module for investigation of oil-and-gas reservoirs while drilling has properties of a universal nature, which are as follows:

– the LWD measurements in boreholes of all types for all used DC do not require special «windows»;

– it is possible to determine more petrophysical parameters of reservoirs using a combination of the RL methods (also applying induction logging) — shaliness (shale content, clay content), neutron and true porosity (including gas reservoirs), open and closed porosity, bulk density, nature of saturation (water, oil, gas), oil-saturation and gas-saturation factors, mineralization, lithology, etc.;

– it is possible to determine the rock density by the proposed density NGL method (with the corrections related to the characteristics of formations) for all borehole diameters and for all diameters and wall thicknesses of drill collars are used for the LWD;

– the radioactivity logging is efficiently combined with the induction logging due to the high depth of investigation of the NGL;

– the specific design of the module is favorable for all work stages, from manufacturing to graduation, transportation, and the LWD measurements.

***3.2. Features of UMRL module.*** The main differences between the proposed UMRL module and the traditional RL(GGD) one are the following.

1. The UMRL module is a self-reacting tool (independent of a specific DC), i.e., it can be used in DC of various diameters and wall thicknesses by placing the RL module in a whole drill collar (without specially equipped «windows» for the GGL). The compact self-reacting RL module includes dual-spaced devices 2NNL, 2NGL, and 2GGL, and a GR detector which also permits recording the gamma-ray background (GB) of the GGL and NGL detectors. All devices are optimally mounted in a protective housing of small diameter. The RL module is inserted into the DC directly before the LWD measurements.

2. Increasing the informativity of the universal RL module.

Several RL methods can be implemented using the same source of fast neutrons. The informativity of the UMRL module is increased by the addition of the 2NGL device to the device 2NNL.

The use of the density NGL method, which has a relatively high depth of investigation, significantly reduces the effect of local heterogeneities and inhomogeneities associated with the borehole. This permit (upon correcting for the rock properties) to determine the true density and porosity of formations for all drill collars, including the thick-walled ones.

3. Using the $^{60}$Co isotope as a gamma-ray source for the GGL.

$^{60}$Co ($E_{0\gamma}$=1.17 and 1.33 MeV) emits gamma rays of much higher energy than $^{137}$Cs employed in the traditional GGD device (see subsection 2.1). Due to the higher energy, the gamma rays of $^{60}$Co source have an increased penetrating power and provide a slightly increased depth of investigation. However, a high-density layer (iron walls of drill collar) impairs their efficiency in determining rock density by the DGGL method; thus, the wall thickness of a drill collar for this method should be limited.

4. Increasing the accuracy of the DNGL and DGGL results during the LWD measurements by placing a gamma-ray detector in the RL module to take into account the contribution of the gamma-ray background (GB device, the very same GR sonde).

It is reasonable to place the GB detector between the far detectors of the 2GGL and 2NGL devices, provided no interference from the gamma-ray and neutron sources. In this case, it is advisable to choose all three adjacent gamma-ray detectors of the same type and with the same setting.

5. Implementing a universal (applicable for drill collars and boreholes of all diameters) UMRL module in the form of two submodules with a connector, whereby both submodules are connected when establishing the module in the drill collar before LWD.

The application of two small-sized and lightweight submodules, placed in a protective housing of a sufficiently small diameter, makes the proposed RL module usable and technologically effective (compared to the «DC tool») when performing the entire cycle of work related to the LWD measurements.

6. To improve the statistical accuracy of measurements and increase the penetrating power of radiations, in the ideal case, it is advisable to make the protective housing of the RL module from different materials, rather than homogeneous (iron, titanium). One of these materials should be favorable for neutrons (for example, reactor zirconium), and the other one, for the gamma rays (for example, beryllium bronze).

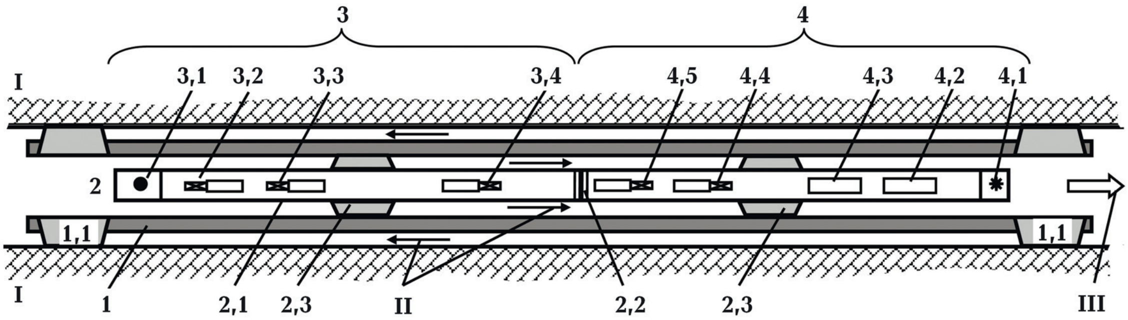

Fig. 1. Scheme of the optimal configuration of the universal UMRL module: I — rock; II — direction of mud circulation; III — direction of drilling; *1* — drill collar (1.1 — centralizer-stabilizer); *2* — RL module (*2.1* — protective housing of module; *2.2* — connector of submodules; *2.3* — centralizer-shock absorber); *3* — submodule 2GGL+GR (*3.1* — gamma-ray source, *3.2*; *3.3* — near and far gamma-ray detectors of the 2GGL device; *3.4* — gamma-ray detector of the GR device); *4* — submodule 2NNL+2NGL (*4.1* — neutron source, *4.2*; *4.3* — near and far neutron detectors of the 2NNL device, *4.4*; *4.5* — near and far gamma-ray detectors of the 2NGL device).

The module is centered in the drill collar, which, in turn, is centered in the drilling borehole.

***3.3. Scheme of the optimal variant of the module and its embodiment.*** The construction optimality of the UMRL module consists of minimization of length, dividing it into two submodules, and optimizing the placement of sources and detectors.Three configurations are possible for the DNGL method:

1) 2NGL device with both detectors behind the far detector of the 2NNL device [Danyliv et al., 2022];

2) 2NGL device with the near NGL detector between the 2NNL detectors, and the far NGL detector behind the far detector of the 2NNL [Kulyk et al., 2023];

3) 1NGL device with the gamma-ray detector following the far detector of the 2NNL [Kulyk, Bondarenko, 2021].

Hereafter, the first configuration is accepted as the main one.

Fig. 1 shows a scheme of the optimal variant of the universal UMRL module.

The distance between the neutron source and the GR (GB) detector should be enough that the gamma rays from the radiative capture of neutrons do not affect the GR (GB) detector readings. Accordingly, the distance between the gamma-ray source and the detector must be sufficient to escape the influence of the gamma-ray source.

The UMRL module is inserted into the whole drill collar before carrying out the LWD and centered in the DC with the help of centralizer-shock absorbers; in addition, the DC itself is centered in the borehole by means of centralizer-stabilizers.

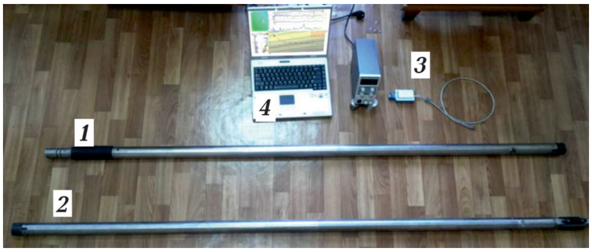

Fig. 2. Pilot sample of the universal UMRL module: *1* — submodule 2GGL+GR, *2* — submodule 2NNL+2NGL, *3* — power supply unit, *4* — software unit.

Fig. 2 shows a photo of a pilot sample of the universal module UMRL, produced by the company «Ukrspetsprylad» with the participation of IGPh. The housing has a diameter of 48 mm and is made of titanium; the total length of the module is ~4 m, and the weight is ~30 kg; the length and weight of each submodules is approximately 2 m and 15 kg.

***3.4. Metrological aspects related to the UMRL module.*** We will use the following definitions and terms when measuring with the universal module of radioactivity logging.

Absolute readings are *count rates* (counts per second, cps) by detectors of devices of RL module: $I^{\gamma}$ is count rate of gamma-rays by GR detector (which is also a detector of gamma-ray background, GB); $I_i^{\mathrm{nn}}$ is neutron detector count rate of 2NNL device ($i$=1; 2); $I_i^{\mathrm{n}\gamma} = I_i^{\mathrm{n}\gamma+\gamma} - I^{\gamma}$ is gamma-ray detector count rate of 2NGL device minus the GB ($i$=1; 2); $I_i^{\gamma\gamma} = I_i^{\gamma\gamma+\gamma} - I^{\gamma}$ is the gamma-ray detector count rate of 2GGL device minus the GB ($i$=1; 2).

Relative readings are *readings in conventional units* (c.u.). These readings may be used when plotting logs for individual sondes of devices of the universal RL module:

$$B_i^{\mathrm{nn}} = I_i^{\mathrm{nn}} \Big/ I_{0,i}^{\mathrm{nn}}\,,\ B_i^{\mathrm{n}\gamma} = I_i^{\mathrm{n}\gamma} \Big/ I_{0,i}^{\mathrm{n}\gamma}\,,$$
$$B_i^{\gamma\gamma} = I_i^{\gamma\gamma} \Big/ I_{0,i}^{\gamma\gamma}\,,\ i = 1, 2\,, \tag{1}$$

where $B_i^{\mathrm{nn}}$, $B_i^{\mathrm{n}\gamma}$, $B_i^{\gamma\gamma}$ are dimension less relative readings of 2NNL, 2NGL, and 2GGL devices expressed in conventional units $I_{0,i}^{\mathrm{nn}}$, $I_{0,i}^{\mathrm{n}\gamma}$, $I_{0,i}^{\gamma\gamma}$, respectively.

For the conventional units, it is appropriate to take the detector count rates of the 2NNL, 2NGL, and 2GGL devices in freshwater («water» units). It is advisable to obtain «water» units using the system «drill collar together with RL submodule» when the relevant submodule is centralized in the piece of the drill collar. This piece must correspond (in diameter and wall thickness) to the drill collar used in drilling. It should also be noted that conventional units $I_{0,i}$ in all cases must be obtained with the same neutron and gamma-ray sources used for logging.

It is common practice to express the readings of the GR device in the form of GR index (relative difference parameter) $\Delta I^{\gamma}$:

$$\Delta I^{\gamma} = \left(I^{\gamma} - I_{\min}^{\gamma}\right) \Big/ \left(I_{\max}^{\gamma} - I_{\min}^{\gamma}\right), \tag{2}$$

where $I_{\min}^{\gamma}$ and $I_{\max}^{\gamma}$ are the GR device readings for reference formations with minimum and maximum gamma-ray activity, respectively.

Along with relative readings (1), in some cases, it makes sense to use inverse relative readings $A_i = (B_i)^{-1}$:

$$A_i^{\mathrm{nn}} = I_{0,i}^{\mathrm{nn}} \Big/ I_i^{\mathrm{nn}}\,,\ A_i^{\mathrm{n}\gamma} = I_{0,i}^{\mathrm{n}\gamma} \Big/ I_i^{\mathrm{n}\gamma}\,,$$
$$A_i^{\gamma\gamma} = I_{0,i}^{\gamma\gamma} \Big/ I_i^{\gamma\gamma}\,,\ i = 1, 2\,, \tag{3}$$

We use the direct and inverse relative readings of individual sondes when determining the petrophysical parameters of the reservoirs. In addition, using inverse readings, in some cases, it is possible to evaluate the quality of the logging performed or to identify incorrect results and to find how to correct them.

An important parameter of dual-spaced RL devices (2NNL, 2GGL, 2NGL) is the ratio of the readings of two sondes, usually near-spaced to far-spaced ones. When interpreting logging data, this ratio is used in two variants.

Variant 1 is the ratio of absolute readings, i.e., the ratio of near-to-far count rates of the corresponding RL devices of concrete tool:

$$R^{\mathrm{nn}} = I_1^{\mathrm{nn}} \Big/ I_2^{\mathrm{nn}}\,,\ R^{\gamma\gamma} = I_1^{\gamma\gamma} \Big/ I_2^{\gamma\gamma}\,,$$
$$R^{\mathrm{n}\gamma} = I_1^{\mathrm{n}\gamma} \Big/ I_2^{\mathrm{n}\gamma}\,, \tag{4}$$

Variant 2 is the ratio of inverse relative readings (3) $A = A_2/A_1 = B_1/B_2$:

$$A^{\mathrm{nn}} = C_0^{\mathrm{nn}} \cdot I_1^{\mathrm{nn}} \Big/ I_2^{\mathrm{nn}}\,,\ A^{\gamma\gamma} = C_0^{\gamma\gamma} \cdot I_1^{\gamma\gamma} \Big/ I_2^{\gamma\gamma}\,,$$
$$A^{\mathrm{n}\gamma} = C_0^{\mathrm{n}\gamma} \cdot I_1^{\mathrm{n}\gamma} \Big/ I_2^{\mathrm{n}\gamma}\,, \tag{5}$$

where $C_0$ is the ratio of far-to-near readings of dual-spaced RL devices in a freshwater tank together with a drill collar.

All variants of relative readings are convenient because they have compensation properties; in particular, they do not depend on the strength of neutron and gamma-ray sources.

Generally, by *readings*, we will contextually mean any of the above specific terms.

We will also use, following [Lobankov, 2016], the following terms: «graduation characteristic» and «calibration function».

By graduation characteristic, we will mean the dependence of the readings for a specific device of the UMRL module in the geometric conditions of LWD on the standard values of a given petrophysical parameter.

For example, the graduation characteristic of the NNL sondes $I_i^{\mathrm{nn}}(\phi)$ is the approximate dependence of the neutron count rate by the near-spaced sonde ($i$=1) and the far-spaced sonde ($i$=2) on the porosity values $\phi_1$, $\phi_2$, $\phi_3$,… of the working medium of physical models (including a tank with fresh water). In so doing, the models are equipped with boreholes and centralized DC. The graduation characteristic can also be presented in relative readings, inverse relative readings, near-to-far readings ratio, etc.

The graduation characteristics of the devices of the universal module UMRL were obtained using full-scale standard physical models of limestone and sandstone formations equipped with different diameter boreholes into which the corresponding drill collar was inserted. In particular, the borehole and drill collar diameters should agree with the geometrical parameters of the horizontal well planned for drilling.

The following working material was used for the models: a monolith of pure limestone and the crushed-down limestone of various fractions saturated with fresh water (porosity $\phi$=0.8; 15.9; 35.2 %; density $\rho$=2.70; 2.44; 2.11 g/cm$^3$); a quartz monolith and different-grain quartz sand saturated with fresh water ($\phi$=0.0; 16,6; 32.5 %; $\rho$=2.65; 2.38; 2.12 g/cm$^3$); a freshwater tank with drill collar centralized in it ($\phi$=100 %; $\rho$=1.00 g/cm$^3$).

The calibration function is the dependence of a measured petrophysical parameter on the readings of a given RL device. The calibration function is defined as the inverse function of the graduation dependence and is used to obtain reservoir parameters during LWD measurements.

Note that the desired petrophysical parameter does not necessarily coincide with the true one, since the borehole conditions of measurements can differ significantly from measurements on the standard physical models, which are used for determining calibration function. In such cases, it is necessary to apply the appropriate corrections to obtain the true parameter; also, additional measurements on the models are appropriate.

The calibration functions are constructed individually for each specimen of the one-type RL module [Lobankov, 2016]. In doing so, the errors of each individual calibration function of the corresponding devices should be estimated, including the errors of physical models, the errors of approximation of the graduation characteristic and calibration function, etc.

***3.5. Graduation characteristics of UMRL module.*** Graduation characteristics of the pilot sample of universal module UMRK for LWD were obtained on full-scale physical models of limestone and sandstone formations saturated with fresh water. The drill collar was centered in the borehole, and corresponding submodules of 48 mm in diameter were centered in the drill collar. Other geometric parameters: borehole diameter ($d_b$), drill collar diameter ($d_{\mathrm{DC}}$), DC wall thickness ($\Delta_{\mathrm{DC}}$), gap between wall of borehole and DC ($\Delta_g$) are the following:

1) $d_b$=124 mm, $d_{\mathrm{DC}}$=99 mm, $\Delta_{\mathrm{DC}}$=15 mm, $\Delta_g$=12.5 mm;
2) $d_b$=156 mm, $d_{\mathrm{DC}}$=120 mm, $\Delta_{\mathrm{DC}}$=26 mm, $\Delta_g$=18 mm;
3) $d_b$=216 mm, $d_{\mathrm{DC}}$=132 mm, $\Delta_{\mathrm{DC}}$=32 mm, $\Delta_g$=42 mm.

Graduation characteristics *1* and *2* in Fig. 3 correspond to the range of geometric parameters for deviated and horizontal boreholes; dependencies *3* refer to vertical boreholes.

Graduation characteristics (Fig. 3) for devices of the UMRL module demonstrate the following.

1. GR index $\Delta I^{\gamma}$ (Eq. 2) as a function of the total mass shaliness of rocks (Fig. 3, *a*) does not depend on the lithology. It is the same for all combinations of borehole diameter, wall thickness, and diameter of the drill collar.

2. The near/far sonde ratio of 2GGL device $R^{\gamma\gamma}$ (Eq. 4) as a function of the bulk density of rock (Fig. 3, *b*) weakly depends on the lithotype of the reservoir. However, it is very sensitive to the geometric parameters of the drill collar and the borehole (cf. curves *1*, *2*, *3*).

The sensitivity of the ratio $R^{\gamma\gamma}$ to density falls sharply with an increase in the borehole and drill collar diameters due to the shallow depth of investigation of the GGL. In particular, for a vertical borehole (curve *3*), the sensitivity is so low that it is practically impossible to determine the reservoir density. This indicates that in the considered embodiment of the 2GGL device, the density GGL method actually works only for relatively small borehole diameters (i.e., for horizontal and deviated boreholes).

The graduation characteristics of the 2GGL device show that even a slight difference (millimeters) in the geometry of LWD measurements from the model parameters results in significant errors in the determined density for horizontal boreholes. Therefore, it is necessary to strictly adhere to the identical geometric conditions of modeling and LWD or to develop appropriate corrections that lead to the same geometric conditions of measurements.

3. Graduation characteristic of the compensated neutron logging method (CNL), which uses dependence of near/far sonde ratio of 2NNL device $R^{nn}$ (Eq. 4) on porosity, is shown in Fig. 3, *c*.

Graduation characteristics of CNL, regardless of geometry, are relatively close for both reservoir lithotypes and depend much more heavily on the geometrical parameters of the drill collar and the borehole, especially at high porosities (curves *1*, *2*, *3*). At the same time, the overall sensitivity of $R^{nn}$ readings to porosity is high enough, almost the same for limestone and sandstone for each set of geometric parameters, and relatively weakly depends on the diameter of the borehole and drill collar.

In general, as a benefit of the sufficient depth of investigation of NNL, the CNL method for determining (neutron) porosity operates well when the LWD measurements for all

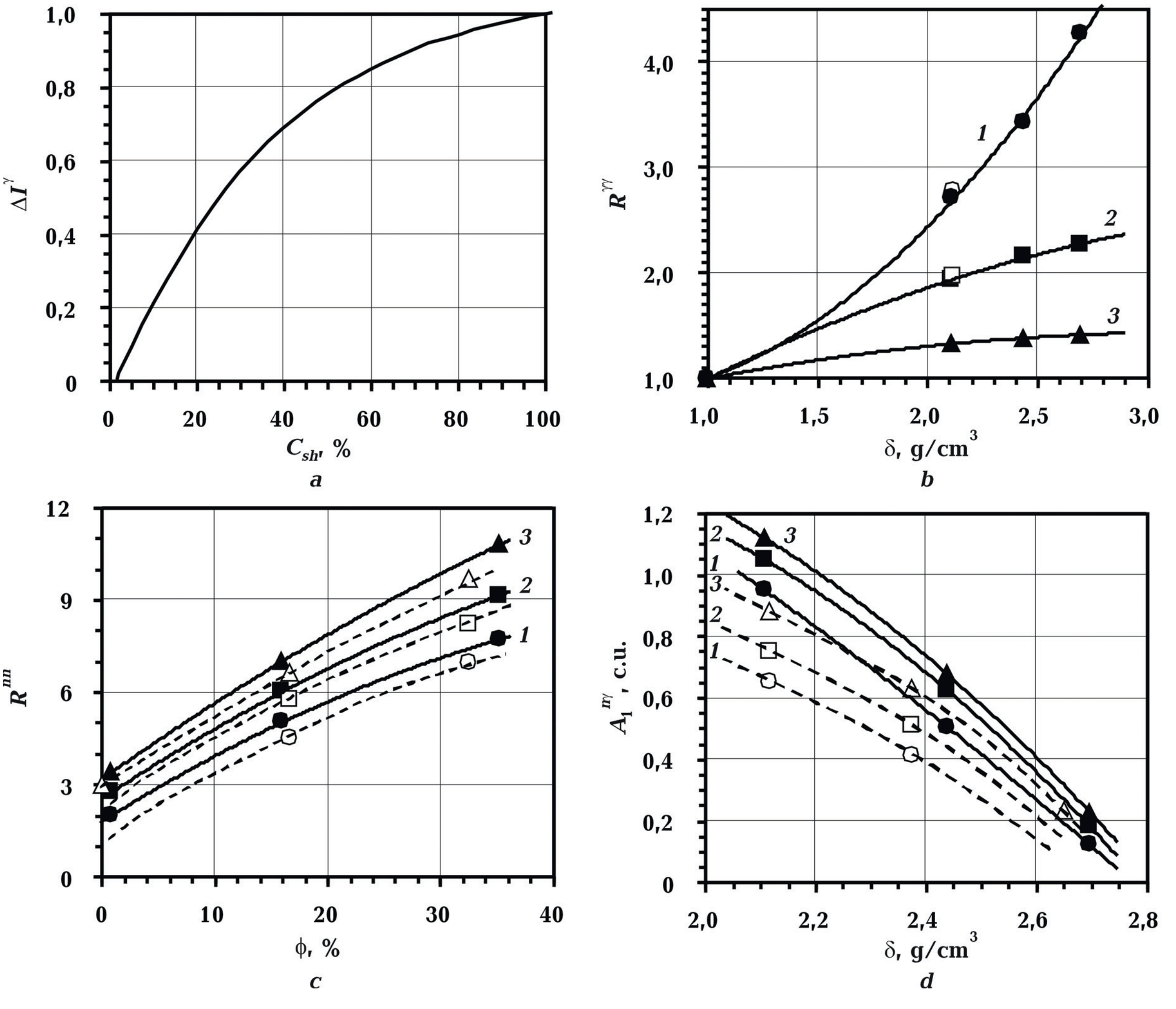

Fig. 3. Graduation characteristics of the UMRL module: *a* — GR index $\Delta I^{\gamma}$ versus mass shaliness $C_{sh}$; *b* — near/far sonde ratio of 2GGL vs. density; *c* — near/far sonde ratio of 2NNL vs. porosity; *d* — near sonde readings of 2NGL vs. density. Values of $d_b$ and $d_{DC}$ (mm): *1* — 124 and 99; *2* — 156 and 120; *3* — 216 and 132. Physical models of formations: ●, ■, ▲ — limestone, o, □, Δ — sandstone.

of borehole and drill collar diameters, i.e. for vertical, deviated and horizontal boreholes.

4. Graduation characteristics for the DNGL method as a dependency of near-spaced sonde readings of 2NGL device $A_1^{n\gamma}$ (Eq. 3) on density is shown in Fig. 3, *d*.

The total sensitivity of readings to density is high enough in all cases for each lithotype and all diameters of boreholes and drill collars. Due to the high depth of investigation of the NGL method, a slight difference in the geometry of LWD measurements from the model ones does not affect the accuracy of density determination.

The results of the determination of density by the NGL method depend heavily enough on the formation lithotype, which must be taken into account in the LWD measurements.

The density NGL method for LWD measurements in the considered version is effective for horizontal and deviated boreholes as well as for the vertical ones.

The presented results for the near-spaced sonde of the 2NGL device show the possibility of a universal and accurate enough determination of the density of reservoirs by the density NGL method in a single-spacing version, which we proposed [Kulyk et al., 2023]. At that, the length of the near-spaced sonde (60 cm) lies in the range of the maximum information depth of the NGL method [Larionov, 1969; Kantor et al., 1985].

We also note the following. Experimental work on physical models physical models and subsequent LWD measurements showed that the far-spaced sonde (80 cm) of the 2NGL device does not give positive results when determining the density individually or in combination with the near-spaced sonde. Thus, the big sondes are not efficient for the NGL method under LWD; therefore, it is necessary to abandon the use of such sondes in LWD measurements in the future.

For this reason, in the future, it is necessary to create and carefully study the 2NGL device in configuration 2 (see subsection 3.3) with the near NGL detector put between the detectors of the NNL device.

In the next section, to obtain the petrophysical parameters of the reservoirs under LWD of horizontal boreholes, the graduation characteristics of the devices of the UMRL module with a sign of *2* ($d_b$=156 mm, $d_{DC}$=120 mm) in Fig. 3 were used. The corresponding calibration functions are obtained from graduation dependencies *2* as inverse functions of these dependencies.

**4. Examples of determining the parameters of reservoirs in horizontal oil boreholes.** Horizontal boreholes along previously known (from earlier investigations) oil beds are obtained by drilling branch holes from existing vertical boreholes of oil fields.

The UMRL module was tested under LWD in a number of horizontal oil boreholes. The efficiency of LWD measurements was evaluated in two boreholes by control logging in an open hole with Schlumberger combined PEX tool [Platform…, 2001].

It should be noted that logging after drilling is done in somewhat different conditions: the depth of caverns in shale formations may be increased, the invaded zone of mud filtrate may be expanded, the filter cake may be formed, the parameters of the drill mud may be changed, etc. In addition, the PEX tool has a relatively large diameter and lies on the borehole wall while logging. Therefore, some results *a priori* may not coincide in an open hole and under LWD, regardless of the measurements' accuracy.

### *4.1. Parameters of carbonate formations and the comparison of results by the UMRL module during LWD and PEX tool in an open hole.*

Borehole № 1. Fig. 4 shows the results of determining the parameters of rocks by UMRL module when LWD in a horizontal borehole and corresponding data by PEX tool after drilling. According to the *a priori* data, the rocks are represented by limestone, dolomitic limestone, and intervals of shale rocks. The reservoirs have relatively a low porosity (up to ~20 %) and high oil saturation (up to ~80 %), and formation water salinity is ~100 g/l.

The interval of investigation is 500 m, with the vertical depth practically unchanging (Fig. 4, *a*, *1*). The DC diameter is 120 mm, the bit diameter is 152 mm (Fig. 4, *b*, *2*), the depth of caverns in shale formations by PEX data reaches ~20 mm (Fig. 4, *b*, *3*); in some intervals of porous formations, filter cake is observed.

The mass shale content $C_{sh}$ (Fig. 4, *c*, *4*) was determined by the GR data of the UMRL module using the corresponding calibration function for index $\Delta I_\gamma$. The value of shale content $C_{sh}$ by the LWD data coincides with the control data of the PEX tool (curve *4*′).

The neutron porosity of rocks $\phi^{nn}$ (Fig. 4, *d*, *5*) was determined while drilling by the compensated neutron logging method (CNL). The LWD neutron porosity practically coincides with the corresponding control result in the open hole (curve *5*′).

The rock density was determined by the near/far sonde ratio of the 2GGL device of the

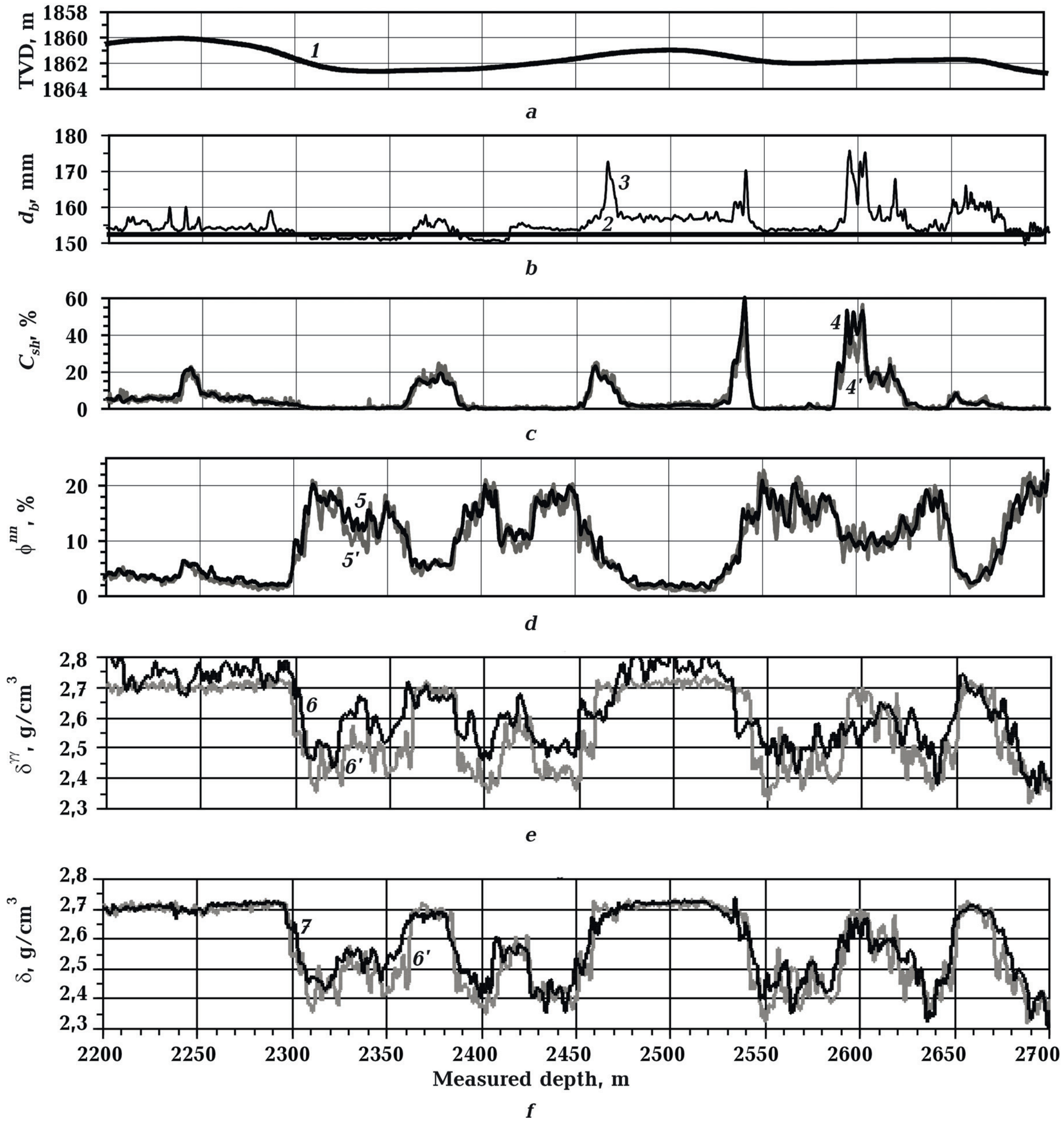

Fig. 4. Rock parameters by logging data in the horizontal borehole № 1: *1* — true vertical depth (TVD), *2* — bit diameter (152 mm), *3* — caliper log, *4* — mass shale content by GR, *5* — porosity by 2NNL, *6* — density by 2GGL, *7* — density by 1NGL; *4*—*7* (▬) — results of UMRL, *4*′—*6*′ (▬) — control logging by PEX tool (Schlumberger) in open hole.

UMRL module (Fig. 4, *e*, *6*). Compared to the density obtained by the PEX tool in an open hole (curve *6*′), the LWD density is qualitatively matched but mostly overestimated (up to ~0.05 g/cm$^3$ in tight formations, up to ~0.15 g/cm$^3$ in porous formations). Quantitative differences can be caused by the calibration function with a different borehole diameter in the model than the LWD diameter and changes in the near zone that occurred after drilling.

Using the newly developed method of density NGL, the rock density was determined by the near detector readings of the 2NGL device of the UMRL module, and the effect of shale content was taken into account (Fig. 4, *f*, *7*). Density curve *7* by DNGL+GR agrees with the control curve *6*′.

<u>Borehole № 2.</u> The borehole logs in Fig. 5 were plotted based on the results of determining the rock parameters by the UMRL module and PEX tool in a deviated-and-horizontal borehole similar to the borehole № 1.

According to the *a priori* data, the rocks are pure low-porous limestone, the oil saturation of the reservoir is 80 %, and the formation water salinity is ~100 g/l.

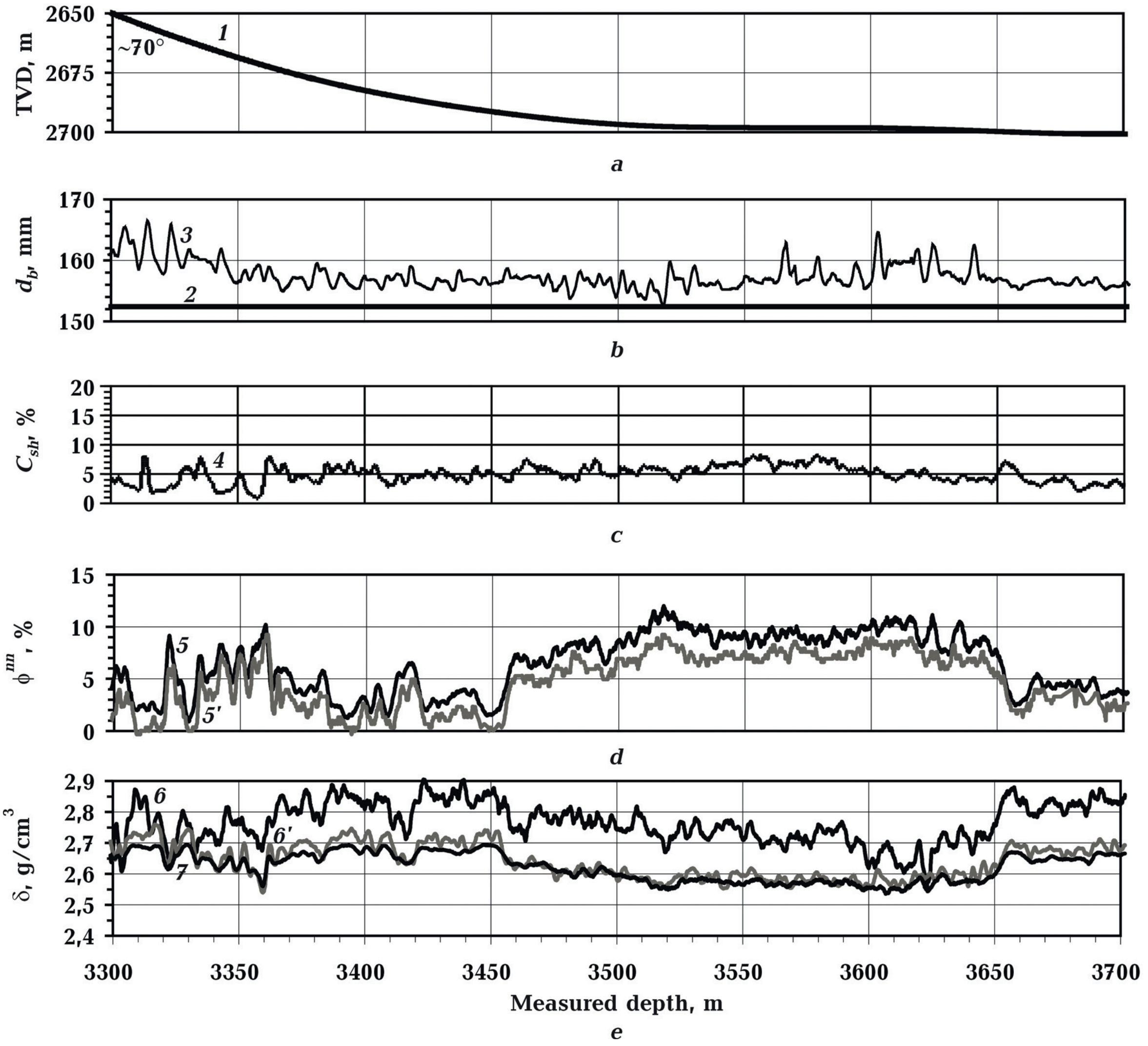

Fig. 5. Rock parameters by logging data in the deviated-and-horizontal borehole № 2: *1* — true vertical depth (TVD), *2* — bit diameter (152 mm), *3* — caliper log, *4* — mass shale content by GR, *5* — porosity by 2NNL, *6* — density by 2GGL, *7* — density by 1NGL; *4*—*7* (▬) — results of UMRL, *5*′—*6*′ (▬) — control logging by PEX tool (Schlumberger) in open hole.

The interval of investigation is 400 m; at that, in half of the survey section, the vertical depth changes by 50 m; the inclination angle of the borehole is ~70° (Fig. 5, *a*, *1*), and then the borehole becomes horizontal. The DC diameter is 120 mm, the diameter of the bit used in drilling is 152 mm (Fig. 5, *b*, *2*). The PEX caliper log gives a borehole diameter of ~155—165 mm (curve *3*).

The mass shale content ($C_{sh}$≤5 %) was determined according to the GR data by the UMRL module (Fig. 5, *c*, *4*).

Using the CNL method, the neutron porosity of rocks ($\phi^{nn}$≤10 %) was determined while drilling (Fig. 5, *d*, *5*). The neutron porosity by UMRL qualitatively agrees with the corresponding control results of the PEX (curve *5'*), and quantitatively it is higher by ~1—2 %.

The rock density was determined accor-

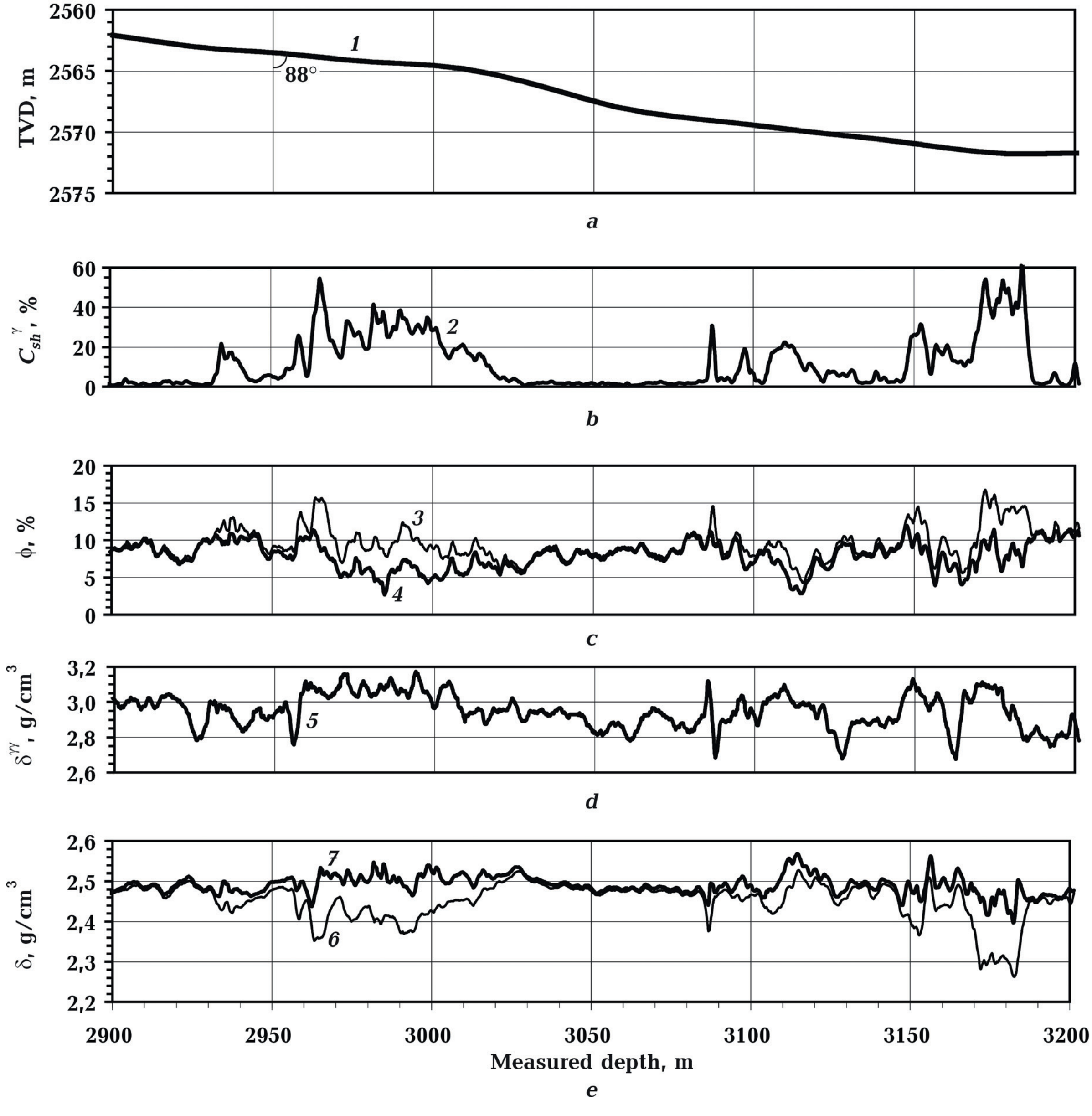

Fig. 6. Rock parameters by data of UMRL in the horizontal borehole № 3 ($d_b$=143 mm): *1* — true vertical depth (TVD), *2* — mass shale content by GR, *3* — neutron porosity by 2NNL, *4* — porosity by 2NNL+GR, *5* — density by 2GGL, *6* — density by 1NGL, *7* — density by 1NGL+GR.

ding to the sonde ratio of the 2GGL device of the UMRL module (Fig. 5, *e*, *6*). Compared to the density obtained by the PEX tool in an open hole (curve *6*′), the density by the 2GGL is in qualitative agreement. However, quantitatively, it is significantly overestimated (up to ~0.10—0.15 g/cm$^3$) due to the uncontrolled influence of borehole factors.

The density of rocks by the near detector readings of the 2NGL device of the UMRK module (Fig. 5, *e*, *7*) qualitatively and quantitatively corresponds to the control curve *6*′ by the PEX data.

***4.2. Parameters of terrigenous formation by the data of UMRL module.*** The borehole logs in Fig. 6 were plotted based on the results of determining the rock parameters in a horizontal borehole № 3.

According to the *a priori* data, the rocks are terrigenous differences from pure sandstones to low-shale and shale ones. The reservoirs are characterized by low porosity and high oil saturation; formation water salinity is ~ 100 g/l.

The investigation interval is 300 m with a drop of depth of 10 m (Fig. 6, *a*, *1*). The diameter of the DC is 120 mm; the diameter of the bit used in drilling is 143 mm.

The mass shale content $C_{sh}$ was determined according to the GR data by the UMRL module (Fig. 6, *b*, *2*); at some intervals, $C_{sh}$ reaches ~30 and ~50 %.

Using the CNL method, the neutron porosity of rocks $\phi^{nn}$ was determined while drilling (Fig. 6, *c*, *3*), and true porosity was determined with the help of CNL+GR combination (log curve *4*); the true porosity is ~5—10 %.

The rock density was determined while drilling according to the near/far sonde ratio of the 2GGL device of the UMRL module (Fig. 6, *d*, *5*). The obtained density is significantly overestimated (up to ~0.3—0.5 g/cm$^3$) and does not correspond to the density of terrigenous rocks. This is largely because a calibration function with a borehole diameter of 156 mm was used, while in LWD, the nominal borehole diameter was 143 mm.

By the near detector readings of the 2NGL device of the UMRL module, the density of low-shale sandstones corresponds to their porosity, and the density of shaly rocks is significantly underestimated (Fig. 6, *e*, *6*). Applying a semi-empirical correction [Kulyk et al., 2023] to the influence of shale content (log curve *7*) leads to the density according to 1NGL+ GR, which corresponds to the *a priori* data on rocks.

***4.3. Summary of results of borehole testing.*** Surveys of carbonate and terrigenous reservoirs of relatively low porosity (<20 %) with high oil saturation (up to 80 %) and pore water salinity of about 100 g/l in horizontal wells were carried out. Based on the LWD measurements done using the UMRL module and comparison with the data of independent logging in an open hole by the PEX tool, we conclude the following.

1. The results of the GR and the corresponding parameters of shaliness, obtained under LWD and in uncased boreholes, completely coincide.

2. The neutron porosity by LWD and open-hole logging in the same boreholes are in satisfactory agreement.

3. The rock density, determined from the data of density GGL of the UMRL module, is qualitatively consistent with the results of the PEX tool but quantitatively overestimated. This overestimation of density is largely because the borehole diameters in the used calibration function and under LWD are different; it leads to an error in density because of the high sensitivity of the DGGL to near-zone factors (shallow depth of investigation of the GGL).

In this regard, it is necessary to strictly adhere to the identical geometric conditions for modeling and LWD or to develop appropriate corrections that lead to the same geometric conditions of measurements.

4. The density of the reservoirs according to the data of the density NGL of the UMRL module, taking into account the GR-correction for shale content, practically coincides with the results of control measurements of the density by the GGL of the PEX tool in the open hole.

**Conclusions.** 1. The universal apparatus radioactivity logging module (UMRL) was proposed, developed, and produced as a pilot sample. The module is aimed to determine the parameters of oil-and-gas reservoirs while drilling vertical, deviated, and horizontal boreholes.

The new module has high technologicness at all stages of work related to logging-while-drilling (LWD).

2. The universality of the new RL module lies in the possibility of carrying out LWD measurements by high-informative radioactivity logging combination for all used drill collars (without their special preparation, for example, equipping «windows») by placement of the module, as an independent tool of small diameter, in the drill collar directly before drilling.

3. The main innovation in the creation of the UMRL module is the neutron-gamma logging device (NGL) and its use to determine the density of formations.

Due to the increased depth of investigation of the NGL method, the influence of local heterogeneities and inhomogeneities associated with the near zone is significantly reduced. This provides (when making appropriate corrections related to the properties of rocks) the ability to determine the reservoir density when LWD for all used drill collars (including large-size boreholes).

In addition, the relatively high-depth NGL method is rationally combined with electrical methods, particularly induction logging.

4. Besides the device of density NGL, the UMRL module contains the dual-spacing neutron-neutron logging device 2NNL to determine neutron porosity, the dual-spacing gamma-gamma logging device 2GGL to estimate density (for relatively small boreholes), gamma-ray logging device (GR) to determine shale content and to make a correction for shaliness to obtain true porosity and true density of shale formations by NGL.

5. The combination usage of RL methods (in some cases, together with induction logging) makes it possible to additionally determine other parameters – true porosity of gas reservoirs, open and closed porosities, the nature of saturation, factors of fluid saturation, volume content of hydrocarbons, etc.

6. Measurements by the UMRL module, carried out while drilling a number of horizontal wells, showed its high technologicness and efficiency. Concrete examples of comparison of the reservoir parameters, obtained using the module, with the data of independent measurements by PEX tool (Schlumberger), carried out in the same boreholes after drilling, showed a qualitative consistency and a quantitative convergence of the results.

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# Універсальний апаратурний модуль радіоактивного каротажу для дослідження нафтогазових колекторів у процесі буріння

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Каротаж у процесі буріння (*англ.* logging-while-drilling — LWD) є найбільш передовою технологією промислової геофізики і широко використовується для визначення петрофізичних та інших параметрів порід-колекторів нафти і газу у вертикальних, похилих і горизонтальних свердловинах. Особливе значення має LWD горизонтальних свердловин, які отримують напрямленим бурінням з вертикальних свердловин у наперед визначені пласти-колектори вуглеводнів. Горизонтальні свердловини дають змогу: багатократно збільшити дебіт вуглеводнів; підвищити загальний обсяг видобування; ефективно використовувати як нові вертикальні свердловини, так і ті, що перебувають в експлуатації, а також свердловини старого фонду. Важливу роль відіграє можливість підведення горизонтальних свердловин до локальних (ізольованих) покладів, що розміщуються на певній відстані від вертикальних свердловин. Всі ці фактори сприяють нарощуванню видобування вуглеводнів, що особливо важливо для України.

У статті розглянуто апаратурні розробки щодо створення нового модуля радіоактивного каротажу (РК) для LWD, універсального в сенсі можливості його використання у товстостінних бурильних трубах, застосовуваних при бурінні всіх видів свердловин. Розроблений універсальний модуль РК реалізує методи нейтрон-нейтронного каротажу, нейтрон-гамма каротажу, гамма-гамма каротажу та гамма-каротажу. Це дає змогу визначати прямо і комплексно широкий набір петрофізичних параметрів колекторів.

Виконано аналіз переваг і недоліків відомих модулів ядерного каротажу для LWD, показано особливості і переваги запропонованого модуля. У процесі лабораторних і свердловинних робіт з експериментальним зразком модуля намічено напрями його вдосконалення.

Як приклад використання нового модуля для LWD наведено результати визначення петрофізичних параметрів нафтових колекторів у пластах різної літології в трьох горизонтальних свердловинах. Процес LWD-вимірювань показав високу технологічність і ефективність модуля. Порівняння отриманих параметрів колекторів з даними незалежних вимірювань, виконаних у відкритих стовбурах тих самих свердловин приладом PEX фірми Шлюмберже, показали якісну узгодженість і кількісну збіжність результатів.

**Ключові слова:** нафтогазова свердловина, каротаж у процесі буріння, комплекс методів радіоактивного каротажу, універсальний апаратурний модуль, петрофізичні параметри колектору.