DOI: 10.18668/NG.2017.03.03

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# Determination of basic gas reservoir parameters from radioactive logging taking into account *PT*-conditions

The paper suggests methods for determining the basic parameters of ordinary and unconventional gas reservoirs, namely identification parameter, true porosity, gas saturation and volume gas content. The set of these parameters can be obtained in both open wells and cased wells with the help of a combination of density and neutron loggings taking into account *PT*-conditions of gas reservoirs occurrence (up to 10 km). The application of developed approaches for the estimation of the petrophysical parameters of gas reservoirs are demonstrated by the example of cased gas well.

Key words: gas reservoirs, pressure-temperature conditions, density-neutron loggings, apparent and true porosities of gas reservoirs, identification parameter, gas saturation, volume gas content.

## Określanie podstawowych parametrów gazonośnych skał zbiornikowych za pomocą kombinacji odwiertowych profilowań radiometrycznych z uwzględnieniem warunków ciśnienia i temperatury

W artykule zaproponowano sposoby wyznaczania głównych parametrów, w konwencjonalnych i niekonwencjonalnych gazonośnych skałach zbiornikowych, tzw. parametr identyfikacyjny, rzeczywistą porowatość, nasycenie gazem, objętościową zawartość gazu. Zestaw tych parametrów może być otrzymany zarówno w niezarurowanych, jak i zarurowanych otworach wiertniczych, za pomocą kombinacji radiometrycznych profilowań z uwzględnieniem zmiennych ciśnień i temperatury w skałach zbiornikowych (do 10 km). Zastosowanie przedstawionych w artykule sposobów dla liczbowej oceny petrofizycznych parametrów, gazonośnych skał zbiornikowych zademonstrowano na przykładzie odwiertu zarurowanego.

Słowa kluczowe: gazonośne skały zbiornikowe, termiczno-ciśnieniowe warunki, kombinacja odwiertowych profilowań gamma-gamma gęstościowego i neutron-neutron, pozorna i rzeczywista porowatość gazonośnych skał zbiornikowych, parametr identyfikacyjny, nasycenie gazem, objętościowa zawartość gazu.

## Introduction

The nature of saturation, porosity, gas saturation and the volume of gas content are the basic petrophysical parameters of gas reservoirs. Bulk density of the rock and its constituents, weight and volume fraction of shales and clay minerals, hydrogen indices of rock, clays and interstitial fluids are also important parameters.

Radioactive loggings are universal methods for the determination of the parameters of ordinary (conventional) and unconventional hydrocarbon reservoirs in both open and cased holes. The density logging (for determination of the bulk density and porosity), neutron logging (for determination of the neutron porosity) and gamma ray logging (as neutron logging correction for the hydrogen content in clay minerals) are effective enough logging methods for obtaining the majority of the petrophysical parameters of reservoirs [3, 6, 12].

Features of the application of radioactive logging methods for the investigation of gas reservoirs are considered by Alger and Dewal [13], DasGupta [14], Mao [8], Ijasan et al. [4]. In particular, neutron logging or density logging, separately allows determining the corresponding apparent porosity of the gas reservoirs; whereas estimation of the true porosity, gas saturation and other parameters requires combined use of these methods [5].

At the same time, the existing approaches of the combined use of neutron logging and density logging have shortcomings.

Among these are the absence of the substantiation of an optimal method of averaging the neutron- and density-apparent porosities for determining true porosity of gas reservoir and ignoring the pressure-temperature conditions of occurrence (*PT*-conditions). In addition, the potentialities of radioactive logging allow for the obtaining of such important parameters as gas saturation and volume of gas content.

Estimation of influence of *PT*-conditions in determining the parameters of gas reservoirs is a topical task due to the increasing depth of commercial gas production and existing reservoirs with abnormally high formation pressure (AHFP). Respectively, *PT*-conditions significantly affect the readings of radioactive logging tools, measured neutron- and density-apparent porosities and other parameters.

## Apparent porosities of gas reservoirs

### *Petrophysical model*

The following petrophysical model for the investigation of the principal aspects for the determination of porosity and other parameters of gas reservoirs was accepted.

The term «gas reservoirs», is meant, rocks which contain free gas in open or closed pores, or in both.

A solid constituent of the rock (matrix) consists of single mineral (quartz, calcite, dolomite), excluding shale. Pores are filled with fresh water and gas (methane $CH_4$) in various proportions. The relative volume of gas in the pores of a rock is the gas saturation. Gas saturation vary from 0 (water) to 1 (total gas saturation).

Matrix density and the density of interstitial water are accepted as constant over the considered depth interval; *PT*-conditions of gas reservoir occurrence determine gas density and its hydrogen index. Gas density and hydrogen index of gas taking into consideration *PT*-conditions, were obtained on a the basis of a gas equation of state with compressibility factor to account for the non-ideal behavior of real gas [11]. In Fig. 1 are shown the calculated depth dependences of the gas density (curve *1*) and hydrogen index (curve *2*) for the hydrostatic pressure and average geothermal gradient.

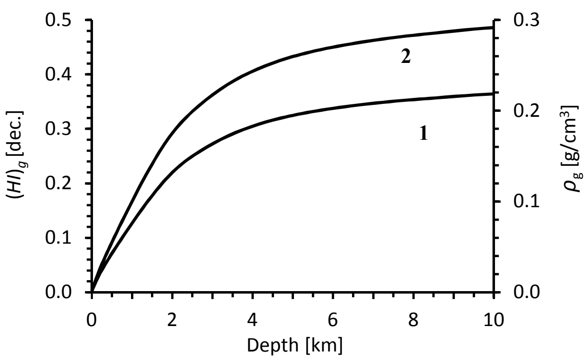


Fig. 1. Gas density $\rho_g$ (1) and hydrogen index $(HI)_g$ (2) vs depth. Pressure gradient – 10 MPa/km, thermal gradient – 30°C/km

### *Neutron-apparent porosity*

Neutron porosity is closely related to the hydrogen content in the rock. It is necessary to construct a calibration curve for the determination of neutron porosity, $\phi_N$. This calibration curve is the relation between the readings of the neutron tool and the porosity of water-filled pure rock (for example, nonshaly limestone) under the normal *PT*-conditions and the given technical conditions of the measurement.

A gas reservoir has a lower number of hydrogen nuclei in unit volume than a water-filled formation of the same porosity. When a gas-filled formation is logged, the neutron porosity $\phi_N$, which is estimated using the «water-filled» calibration curve, will be apparent.

The relative hydrogen content or hydrogen index (*HI*) of porous gas-water-filled nonshaly formation in terms of hydrogen indices of water $(HI)_w$ and gas $(HI)_g$ is written as [12]:

$$HI = (HI)_w\phi(1 - S_g) + (HI)_g\phi S_g \quad (1)$$

where $\phi$ is the porosity of the gas reservoir; $S_g$ is the gas saturation; $(HI)_w$ is the hydrogen index of the water, which was taken as 1; $(HI)_g$ is the hydrogen index of gas; for methane

$$(HI)_g = 2.25\ \rho_g/\rho_w \quad (2)$$

where $\rho_g$ is the gas density in the pores for the given *PT*-conditions, $\rho_w$ is the water density.

As a first approximation, the hydrogen index of a water-filled reservoir is equal to neutron porosity. The hydrogen index of a gas-filled formation can be approximately considered as the neutron-apparent porosity, i.e. $(HI) \approx \phi_N$. Then, from the Eq. (1) it follows that

$$\phi_N = \phi - \Delta\phi_N \quad (3)$$

where

$$\Delta\phi_N = (1 - (HI)_g)\phi S_g \quad (4)$$

According to Eq. (3), neutron-apparent porosity of gas reservoirs will be lower than the true porosity on the value $\Delta\phi_N$. In the case of a fully water-saturated reservoir ($S_g = 0$, $\Delta\phi_N = 0$), neutron-apparent porosity becomes true: $\phi_N = \phi$. In the case of a fully gas-saturated reservoir ($S_g = 1$), neutron-apparent porosity takes a minimum value: $\phi_N = (HI)_g\phi$.

### *Density-apparent porosity*

The results of density logging are due to the electron density of rock, which, in turn, is closely connected with the bulk density. The total porosity of water-saturated reservoirs obtained from the density logging is expressed as:

$$\phi_D = (\rho_{ma} - \rho^{\gamma\gamma})/(\rho_{ma} - \rho_w) \tag{5}$$

where $\rho_{ma}$ is formation matrix density, $\rho_w$ is the water density, $\rho^{\gamma\gamma}$ is the log reading of the bulk density [2, 3, 12].

The bulk density of gas-water-saturated reservoirs $\rho$ is determined by the following equation:

$$\rho = \rho_{ma}(1 - \phi) + \rho_w\phi(1 - S_g) + \rho_g\phi S_g \tag{6}$$

Taking into account that $\rho^{\gamma\gamma} \approx \rho$, and substituting Eq. (6) in Eq. (5), we get the expression for the density-apparent porosity of gas-water-saturated reservoirs:

$$\phi_D = \phi + \Delta\phi_D \tag{7}$$

where

$$\Delta\phi_D = (\Delta_g - 1)\phi S_g \tag{8}$$

Here $\Delta_g$ is the dimensionless density parameter ($\Delta_g > 1$), which at the given $\rho_{ma}$ = const and $\rho_w$ = const is determined by the gas density $\rho_g$ under reservoir conditions:

$$\Delta_g - (\rho_{ma} - \rho_g)/(\rho_{ma} - \rho_w) \tag{9}$$

According to Eq (7), density-apparent porosity of the gas reservoirs is higher than the true porosity by the value $\Delta\phi_D$.

In the case of a fully water-saturated reservoir, density-apparent porosity becomes true: $\phi_D = \phi$. In the case of a fully gas-saturated reservoir, density-apparent porosity takes a maximum value: $\Delta_D = \Delta_g\phi$.

As an example for gas-saturated sandstone at 10% porosity, the results of estimating the neutron- and density-apparent porosities on the basis of Eqs. (3)–(4) and Eqs. (7)–(9), respectively, for various gas saturations $S_g$ depending on the occurrence depth are shown in Fig. 2.

Fig. 2 shows that depth dependences of the apparent porosities $\phi_N$ and $\phi_D$ are nonlinear, in so doing the nonlinearity grows with increasing $S_g$. For reservoirs which lie deeper than about 4 km, porosities $\phi_N$ and $\phi_D$ relatively weakly depend on the *PT*-conditions for all values of $S_g$.

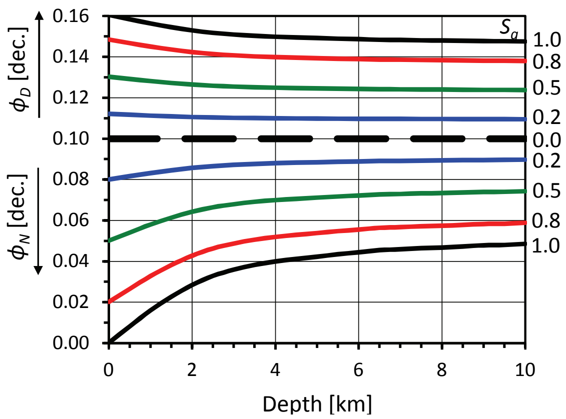


Fig. 2. Apparent porosities vs. depth for sandstone with $\phi$ = 0.10 at different gas saturation. Pressure gradient – 10 MPa/km, thermal gradient – 30°C/km

## Identification parameter of gas reservoirs

Determination of the nature of saturation (gas, water) is impossible using neutron logging or density logging separately, whereas their combined use solves this problem. One known way of qualitatively solving the problem of gas reservoirs identification, is to compare neutron- and density-apparent porosities as borehole logs [3].

Disagreement between density and neutron porosities along the geological section of the borehole can serve as the identification parameter of gas presence in rocks [16]:

$$I_g = \phi_D - \phi_N \tag{10}$$

For water-saturated rocks the identification parameter is zero ($I_g = 0$). For gas-bearing bed, wherein both density porosity and neutron porosity are apparent, this parameter is a positive value. Parameter $I_g$ increases with both porosity and gas volume in pores.

In Fig. 3 are shown the calculated depth dependences of the parameter $I_g$ at various gas saturations for nonshaly sandstone with 10% porosity.

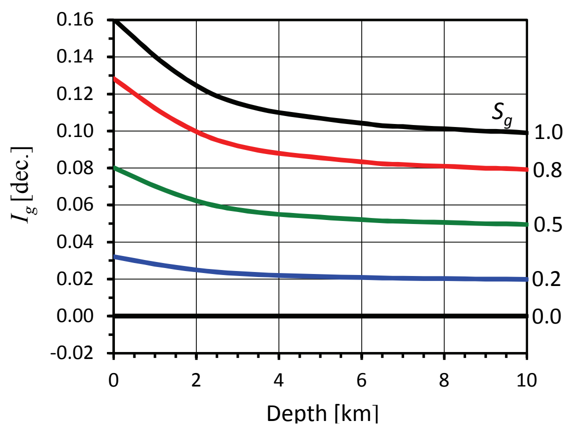


Fig. 3. Identification parameter vs depth for sandstone with $\phi$ = 0.10 at different gas saturation. Pressure gradient – 10 MPa/km, thermal gradient – 30°C/km

## True porosity of gas reservoirs

The true porosity of a gas reservoir may be determined as the weighted arithmetic mean of the neutron- and density-apparent porosities with the corresponding weight factors [15, 16]:

$$\phi = \alpha_1\phi_D + \alpha_2\phi_N \tag{11}$$

Weight factors $\alpha_i$ ($i$ = 1, 2) are, by definition, the real non-negative numbers which are less than 1. Weight factors $\alpha_i$ are normalized as such, that their sum is equal to 1:

$$\alpha_1 + \alpha_2 = 1 \tag{12}$$

The following values of the weight factors $\alpha_i$ can be obtained by using Eqs. (1) – (4) and (5) – (9):

$$\alpha_1 = (1 - (HI)_g)/(\Delta_g - (HI)_g), \quad \alpha_2 = (\Delta_g - 1)/(\Delta_g - (HI)_g) \tag{13}$$

Hence, weight factors (13) used for obtaining the true porosity of gas reservoirs by Eq. (11) depend on the following: matrix density, which is related with the lithology of reservoir, densities and hydrogen indices of interstitial water and gas, as well as $PT$-conditions, which are the governing, for density and hydrogen, index of gas.

In Fig. 4a is shown the depth dependence of weight factor $\alpha_1$ for main lithologies with conditional hydrostatic pressure (curves 1, 2 and 3) as well as for the lower and upper limits of the pressure gradient for AHFP in sandstone (dashed curves 4 and 5). Also shown are examples of values $\alpha_1$ for AHFP in gas fields (points) [7, 9, 10].

Thus, as follow from Eqs. (13) and Fig. 4a, weight factors $\alpha_i$ in the considered approximation possess the following properties:

- $\alpha_i$ substantially depends on $PT$-conditions (primarily on reservoir pressure) through changes of both gas density $\rho_g$ and hydrogen index of the gas $(HI)_g$;
- conditions of AHFP particularly strongly influence the values of $\alpha_i$;
- $\alpha_i$ depends on lithology (through the matrix density $\rho_{ma}$);
- $\alpha_i$ are independent of both porosity and gas saturation.

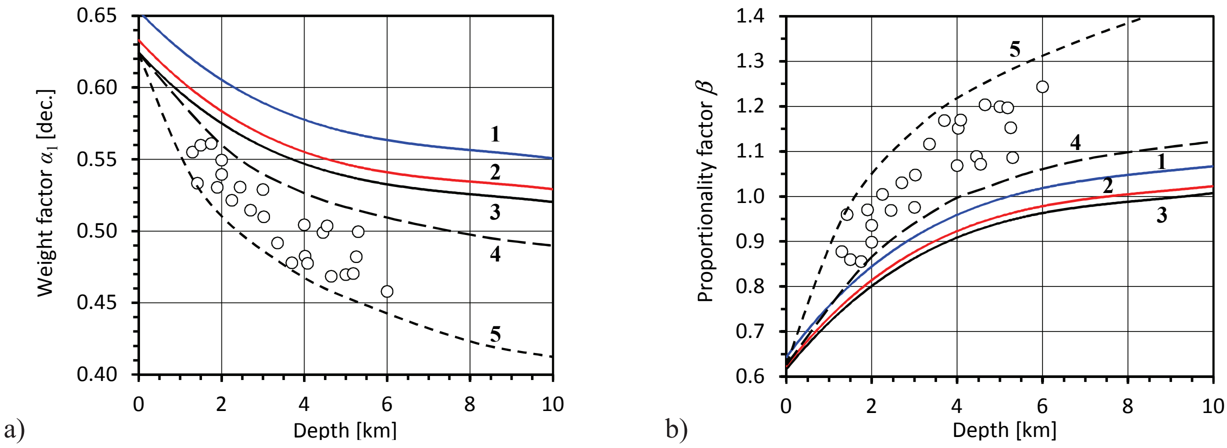


Fig. 4. Weight factor $\alpha_i$ (a) and proportionality factor $\beta$ (b) vs reservoir depth: 1 – dolomite, 2 – limestone, 3-5 – sandstone. Pressure gradient: 1-3 – 10 MPa/km, 4 – 13 MPa/km, 5 – 23 MPa/km; geothermal gradient – 30°C/km; ○ – examples of AHFP

## Gas saturation

At two-phase filling of the pores (gas–water), gas saturation $S_g$, is related to water saturation $S_w$, as follows: $S_g + S_w = 1$.

In an open borehole the water saturation $S_w$ of ordinary reservoirs, is determined by electric logging [1–3, 12]. However, in high-resistivity reservoirs and unconventional low permeability reservoirs as well as in cased wells, this approach to determining gas saturation ($S_g = 1 - S_w$) is nonworking.

We have proposed a method [15] which allows to determine $S_g$ with the help of a combination of radioactive loggings, in all the cases of absence of a mud-filtrate-invaded zone in a reservoir. For open boreholes with a mud-filtrate-invaded zone, the proposed method allows to determine residual gas saturation.

According to this method, the parameter $S_g$ can be obtained as a value, which is proportional to the ratio of difference between density- and neutron-apparent porosities to true porosity:

$$S_g + \beta I_g/\phi \tag{14}$$

where $\beta$ is the proportionality factor, $I_g$ and $\phi$ are determined by Eqs. (10) and (11), respectively.

Within the approach adopted in this paper, the proportionality factor $\beta$, takes the form:

$$\beta = 1/(\Delta_g - (HI)_g) \quad (15)$$

Hence, dimensionless parameter $\beta$, depends on matrix, water and gas densities as well, depend on the hydrogen index of the gas.

Since the parameters of the gas (density and hydrogen index) are dependent on *PT*-conditions, the factor $\beta$, varies correspondingly. In Fig. 4b are shown the depth dependencies of proportionality factor $\beta$, for main reservoir lithologies with pressure gradient, which corresponds to conditional hydrostatic pressure (curves 1–3), and with average geothermal gradient. Also in Fig. 4b are shown calculation results for factor $\beta$ (points) for AHFP by the example of gas fields occurring at various depths, according to the data from [7, 9, 10]. Dashed curves (4 and 5) correspond to lower and upper limits of the pressure gradient for AHFP. As can be seen from the Fig. 4b, abnormally high *PT*-conditions strongly effect the values of $\beta$.

## Volume gas content

A product of the porosity and gas saturation is the important complex parameter that characterizes the content of free gas in the open and closed pores of the rock [15].

$$G_V = \phi S_g \quad (16)$$

Within the adopted petrophysical model, the parameter $G_V$ is the ratio of gas volume in the pores to the total reservoir volume ($G_V = V_g/V$), i.e. $G_V$ is the volume gas content in the rock (gas content per unit volume) or gas porosity.

Namely the volume gas content, taking into account reservoir *PT*-conditions, characterizes the reservoir, in terms of its gas presence, whereas taking into account the volume of gas-bearing rocks, this parameter can be used for the estimation of potential gas reserves of a particular gas field.

## Example of borehole determination of basic gas reservoir parameters

Fig. 5 gives radioactive logs (curves 1–3) obtained in a cased gas well in the absence of an invaded zone. Geologic section of the well is terrigenous. Also in Fig. 5 is shown neutron porosity log (4), which is corrected for clay minerals effect with the help of gamma ray logging, and density porosity log (5). Gas reservoirs were identified by the disagreement between density- and neutron-apparent porosity in the following intervals (m): 1123÷1130, 1135÷1140, 1141÷1150, 1159÷1165. Petrophysical parameters of gas reservoirs were also determined.

Also in Fig 5 are given the following curves: true porosity of reservoir $\phi$ (6), gas saturation $S_g$ (7) and parameter $G_V$ (8), which characterizes the volume gas content along the geological section of the borehole.

The Table gives the results of the determination of gas reservoir petrophysical parameters in the same borehole, namely, apparent porosities $\phi_D$ and $\phi_N$, identification parameter of gas reservoirs $I_g$, true porosity $\phi$, gas saturation $S_g$, volume gas content $G_V$.

Table. Example of determination of gas reservoir petrophysical parameters in the cased borehole

| № | Interval [m] | $\phi_D$ [%] | $\phi_N$ [%] | $I_g$ [%] | $\phi$ [%] | $S_g$ [%] | $G_V$ [%] |
|---|---|---|---|---|---|---|---|
| 1 | 1123÷1126 | 19.8 | 13.4 | 6.4 | 18 | 24 | 4.2 |
| 2 | 1126÷1130 | 22.2 | 3.1 | 19.1 | 16 | 80 | 12.4 |
| 3 | 1135÷1140 | 19.1 | 13.3 | 5.8 | 17 | 22 | 3.8 |
| 4 | 1141÷1147 | 21.8 | 14.8 | 7.0 | 19 | 24 | 4.6 |
| 5 | 1147÷1150 | 15.5 | 9.6 | 5.9 | 13 | 29 | 3.8 |
| 6 | 1159÷1162 | 19.6 | 13.0 | 6.6 | 17 | 25 | 4.3 |
| 7 | 1162÷1165 | 23.0 | 5.4 | 17.6 | 17 | 68 | 11.4 |

## Conclusions

The paper is focused on the development of theoretical and applied aspects of gas reservoirs investigation, with the help of a combination of radioactive loggings, on the basis of an adopted petrophysical model, as well as simplified relations between measured density and neutron porosities and corresponding petrophysical parameters. This allows to take into account the principal properties of the subjects under investigation and to obtain basic parameters

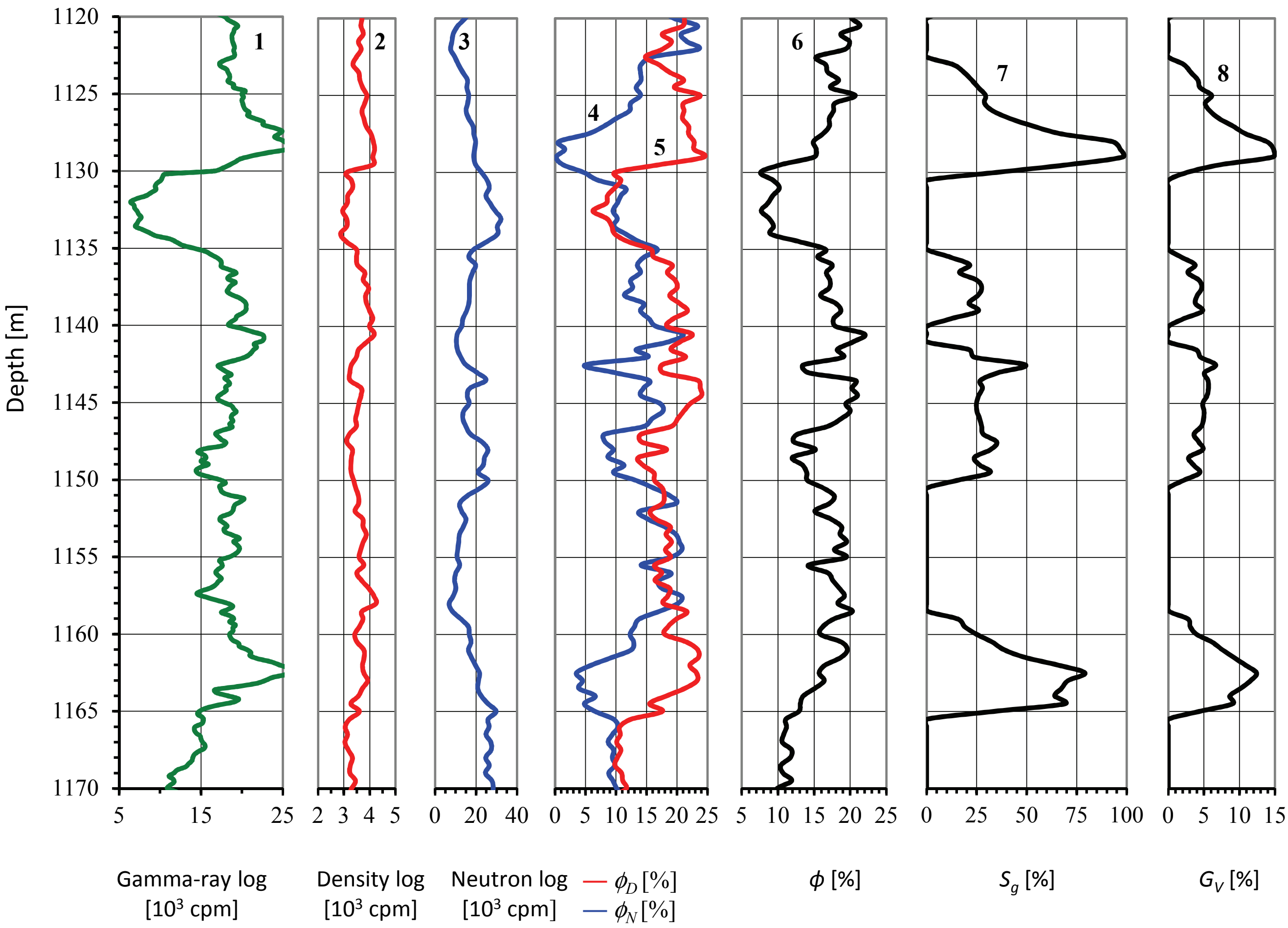


Fig. 5. Diagrams of radioactive logging in gas well (1 – gamma-ray log, 2 – density log, 3 – neutron log; cpm – counts per minute) and petrophysical parameters (4 – neutron porosity, 5 – density porosity, 6 – true porosity, 7 – gas saturation, 8 – volume gas content)

of gas reservoirs in an explicit form, taking into account *PT*-conditions.

1. Identification parameter differentiates gas and water reservoirs by combination of radioactive loggings. The parameter is determined as the disagreement between density and neutron porosities, and can be represented in the form of a bed diagram along the investigated borehole section.
2. In the general case, the true porosity of gas reservoirs is determined as a weighted arithmetic mean value of the measured density- and neutron-apparent porosities, with weight factors, which depend on *PT*-conditions. The estimation of values of weight factors for hydrostatic pressure and for abnormally high formation pressure was carried out.
3. A method for determining gas saturation by a combination of radioactive loggings has been proposed. The method allows determining the gas saturation in the absence of a mud-filtrate-invaded zone in a reservoir; in the presence of mud-filtrate-invaded zone this method allows to determine residual gas saturation.
4. A parameter, which characterizes gas content in unit volume of gas reservoir (volume gas content or gas porosity), has been considered. The parameter, expressed in terms of previously measured porosity and gas saturation, is usable for the estimation of potential gas reserves of a particular gas field.
5. Efficiency of the developed approaches is demonstrated by the example of the cased gas well in the absence of a mud-filtrate-invaded zone.

The developed approaches admit the generalization towards taking into account, more realistic petrophysical and calculation models. The combination of the radioactive loggings and other logging methods (electric logging, acoustic logging) allows extending the capabilities of well logging.

Please city as: Nafta-Gaz 2017, no. 3, pp. 162–168, DOI: 10.18668/NG.2017.03.03

Article contributed to the Editor 7.06.2016. Approved for publication 14.12.2016.

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