Determination of Coal Ash Content by Neutron-Neutron Logging

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Abstract. The research is aimed at assessing the possibility of studying the ash content of coal seams using neutron-neutron logging in coal exploration wells drilled at the outcrops of coal seams under loose deposits using the materials of experimental work in the South Yakutsk coal basin. The prospects of using neutron-neutron logging to study coal well sections, on the one hand, is determined by the fact that hydrogen content in coal seams normally exceeds its content in the host rocks, and, on the other, by the small cross-sections of neutron capture by carbon. Within the same coal grade, an increase in its ash content both means a decrease in its hydrogen content and an increase in the content of elements with a higher capture cross section. Experimental studies were carried out at the Syllakh coal deposit. An IBN-8-1 type plutonium-beryllium source with an output of $5 \times 10^4$ neutrons/s was used as a fast neutron source, and a highly efficient SNM-17 type helium gas-discharge counter was used as a slow neutron detector. The logging depth provided by the equipment was 10 - 30 cm. During the processing of the obtained field data, a correlation was established between the count rate of neutron-neutron logging and coal ash content. It should be noted that the functional dependence of the count rate of neutron-neutron logging on ash content is not continuous – in the range of ash content of 45 - 55% a certain discontinuity point is observed, after which the functional dependence changes. To simplify the assessment of the dependence, the range of rock ash content above 45% is neglected since bituminous coals with an ash content of more than 45% are classified as carbonaceous rock and are not of industrial interest. A close correlation is established between the count rate of neutron-neutron logging and coal ash content. According to the results of statistical processing, the correlation coefficient is 0.97, which makes it possible to quantitatively determine the ash content according to neutron-neutron logging data. The absolute errors in ash content determination by neutron-neutron logging over the entire dataset are up to 3.625 %. The degree of analytical moisture influence on the data of neutron-neutron logging in determining coal ash content is estimated. No regular changes in the count rate of neutron-neutron logging due to a change in the analytical moisture index have been established. It is noteworthy that, with a sufficiently large dispersion value of the analytical moisture index, the trend line of this parameter regularly changes synchronously with the trend lines of ash content and count rate.

1. Introduction
Ash content is one of the most important quality indicators of coal seams, which determine their conditionality when calculating reserves. At the same time, this is one of the most variable indicators both in terms of the distribution area and across the coal seam sections [1].
The main method for determining the coal seam ash content used in coal exploration is the laboratory analysis of core samples.

The geological and geophysical techniques based on correlation and multidimensional relationships between the coal ash content and geophysical parameters are most efficient and economical [2, 3].

The prospects of using neutron-neutron logging to study coal well sections, on one hand, are determined by the fact that hydrogen content in coal seams usually exceeds its content in the host rocks, and on the other hand, by the small cross-sections of neutron capture by carbon. Hydrogen is an effective neutron moderator. The largest amount of hydrogen is contained in coals with a low degree of coalification. With an increase in the degree of coalification from brown coals to anthracites, the hydrogen content decreases. The deposits of bituminous coals, where the experimental studies were carried out, occupy an intermediate position between brown coals and anthracites. Within the same coal grade, an increase in its ash content means both a decrease in its hydrogen content and an increase in the content of elements with a higher capture cross section [4-8].

Table 1 shows the data on the elemental composition of the coal combustible mass. The works devoted to the issue of using neutron logging in the study of coals [9] have shown that coals contain a significant amount of hydrogen, which makes it possible to use neutron methods to study coal seams in the well section.

| Coal variety          | Elemental content, % |
|-----------------------|----------------------|
|                       | C  | H      | O       | N   | S    |
| Anthracite            | 92-97 | 2-2.7 | 2-3 | <1 | 1-4 |
| Bituminous coal       | 75-93 | 2-5.5 | 1.5-15 | 1-2 | 0.6-8.0 |
| Brown coal            | 67-78 | 5-7    | 5-7 | -  | 0.2-10 |

Note: C - carbon, H - hydrogen, O - oxygen, N - nitrogen, S - sulphur

2. Experimental studies
During research work in the South Yakutsk coal basin at the Syllakh deposit, neutron-neutron logging was carried out on a limited number of coal exploration wells. During testing, VPGR-1 serial equipment was used [10].

Initially, neutron-neutron logging (NNL) was introduced to assess the possibility of dividing the section of coal exploration wells in the cryolithozone into the permafrost and thawing zones.

Nevertheless, the simplicity and speed of automatic processing of geological exploration data allowed NNL to be applied for determining the coal ash content in the section of exploration wells [11].

Research into the application of neutron logging of coal exploration wells was previously carried out in neutron gamma logging, neutron activation logging, and pulsed neutron-neutron logging modes. However, it should be noted that these studies were carried out for the purpose of lithological dissection of the geological section and the extraction of coal seams in well sections [12-14].

The VPGR-1 set of equipment used for research was originally designed for rapid measurements of the moisture content of sandy and clay soils and grounds in the field [10]. An IBN-8-1 type plutonium-beryllium source with an output of $5 \times 10^4$ neutrons/s was used as a fast neutron source, and a highly efficient SNM-17 type helium gas-discharge counter was used as a slow neutron detector. The logging depth provided by the equipment was 10 - 30 cm.
The stages of data processing of neutron-neutron logging included the assessment of correlation between NNL data and coal ash content for the samples of various degrees of averaging; obtaining the regression equation $A^d = f (I_{NNL})$; the construction of histograms of ash content according to NNL data and core sampling for the studied wells; and the assessment of the degree of reliability of NNL quantitative determinations.

Figure 1 shows a correlation between the NNL count rate and coal ash content ($A^d$). The graph uses data for all NNL points (data for each sampling point correlates to the data on ash content in the interval). The density of the data cloud is high; the correlation coefficient is 0.8637. The large dispersion of the NNL count rate values within one interval of ash content can be explained by the difference in the principles of sampling, i.e. the value of NNL count rate is due to the discrete value of the coal seam ash content at the sampling point, while the ash content from the core sample is an integral value. To reduce the variance of NNL count values, at the second stage of data processing when comparing the ash content of core samples and NNL count rate, it is necessary to obtain the integral value of NNL count rate over the core sampling interval. The further procedure for assessing the correlation dependence was carried out according to the technique already tested on gamma-gamma logging [11], i.e. averaging the count over the interval of core sampling and averaging the count in a sliding window (Fig. 2). The resulting correlation coefficient of 0.9704 has justified an attempt to quantify the ash content according to NNL data.

Figure 3 shows the graph of $A^d = f (I_{NNL})$ function. It should be noted that the functional dependence of count rate of neutron-neutron logging on ash content is clearly not continuous - in the range of ash contents of 45 - 55%, a certain discontinuity point is observed, after which the functional dependence changes. To simplify the assessment of the dependence, the range of rock ash content above 45% is neglected since bituminous coals with an ash content of more than 45% are classified as carbonaceous rock and are not of industrial interest.
Figure 2. Correlation dependence of NNL count rate on coal ash content; NNL count rate is averaged in a sliding window

Thus, the equation $A^d = f(I_{NNL})$ acquires the form:

$$A^d = 38.12951 \times \ln(I_{NNL})^4 - 729.3559 \times \ln(I_{NNL})^3 + 4472.1617 \times \ln(I_{NNL})^2 - 7855.8215 \times \ln(I_{NNL}) - 5666.13 \quad (1)$$

Let us perform a statistical evaluation of the results. A quantitative estimate of the error in determining the average ash content of coal seam sections is given in Table 2. Column 2 ($A_{d1}$) shows the data on the average ash content of coal seam sections according to NNL data without data outliers; column 3 ($A_{d2}$) contains the data on the average ash content of coal seam sections according to the NNL data. The intervals with an ash content of more than 80% are removed from the dataset (as mentioned above, the obtained regression equation works in the ash content range from 0 to 45%). Column 4 ($A_{d3}$) contains the data on the weighted average ash content of coal seam sections according to core sampling data. $\Delta_1$ and $\Delta_2$ are the absolute errors in determining the ash content over the entire dataset and over the dataset without the outliers of high ash intervals included, respectively.

The data in column 6 (Table 2) clearly indicate the possibility of using NNL for a quantitative assessment of the ash content of coal seams in the interval of the average coal seam ash content.

Table 2. Hata! Yer işaretleri tanımlanmamış. Errors in determining ash content according to NNL data

| Well No. | $A_{d1}$, % | $A_{d2}$, % | $A_{d3}$, % | $\Delta_1$, % | $\Delta_2$, % |
|----------|--------------|--------------|--------------|----------------|----------------|
| 1        | 2            | 3            | 4            | 5              | 6              |
| 116/k2   | 26.13        | 19.44        | 15.65        | 8.48           | 3.79           |
| 143/k    | 25.12        | 19.35        | 19.84        | 5.28           | -0.49          |
| 50/k     | 17.8         | 12.22        | 11.76        | 6.04           | 0.46           |
| 51/k     | 20.7         | 20.7         | 20           | 0.7            | 0.7            |
| Average value | 3.625        |              |              | 1.115          |                |
In the core samples, the data of which were used to construct the calibration curve, the analytical moisture content (W_a), according to laboratory analyses, varies from 0.2 to 1.4%. A brief study was carried out to assess the degree of possible influence of analytical moisture on the NNL data.

It seems logical to use a well-established method of data visualization [11], i.e. the construction of the plots of the characteristics of core sampling intervals (ash content - A_d, analytical moisture - W_a, I_{NNL} - NNL count rate); the samples are arranged in ascending order of ash content (Figure 4). For greater clarity, polynomial trend lines are used.
No regular changes in NNL count rate due to the change in the $W^a$ are observed. The exception is the range of coal ash content from 45% to 100%. Some correlation of the parameters in this interval is clearly visible, but the quantitative assessment of their relationship has not been carried out. It is noteworthy that, with a sufficiently large dispersion value of the $W^a$ analytical moisture index, the trend line of this parameter regularly changes synchronously with the trend lines of ash content and count rate.

3. Conclusions
The experimental data obtained during studies at the Syllakh deposit of the South Yakutsk coal confirmed the high accuracy and reliability of neutron-neutron logging for separating coal seams in well sections and determining their ash content. The change in analytical moisture in the intervals of neutron-neutron logging of coal seams does not lead to any regular changes in the count rate of neutron-neutron logging. Supplementing the standard set of geophysical studies of coal exploration wells with neutron-neutron logging will significantly increase the efficiency of geological exploration at coal deposits.

References
[1] P. Yu. Kuznetsov, N. N. Grib, Yu. N. Skomoroshko, “The assessment of heterogeneity and spatial variability of coal quality indicators”, Gornyi Zhurnal, vol. 3, pp. 47–48, 2017. (In Russ.)
[2] N. N. Grib, A. A. Sysasko, A. V. Kachaev, “Resource-saving technology for studying coal seams”, Fundamental research, vol. 5, pp. 477–480, 2014. (In Russ.)
[3] N. N. Grib, V. M. Nikitin, “Study of coal quality indicators and mining and geological conditions for the development of coal deposits based on the results of geophysical studies of wells”, Science and education, vol. 4, pp. 34–40, 2015. (In Russ.)
[4] V. V. Grechukhin et al., “Geophysical methods for studying the geology of coal deposits”, Moscow: Nedra, 477 p., 1995 (In Russ.)
[5] E. S. Kuchurin “Sposob opredeleniya zolnosti i teplotvornoy sposobnosti iskopaemykh ugley [A way of determining ash and calorific value of fossil coals]”, Available at: www.findpatent.ru/patent/207/2075099.html (accessed 04/15/2021)
[6] Z. Feng, Z. Robin, P. Gardne, H. Yan, G. Wu, L. Tian, Q. Chen, Y. Ti, “A method for determining density based on gamma ray and fast neutron detection using a Cs$\alpha$LiYCl$\beta$ detector in neutron-gamma density logging”, Applied Radiation and Isotopes, vol. 142, pp. 77–84, 2018.
[7] Th. Gan, B. Balmain, A. Sigbatullin, “Formation evaluation logoff results comparing new generation mining-style logging tools to conventional oil and gas logging tools for application in coalbed methane (CBM) field development”, Journal of Natural Gas Science and Engineering, vol. 34, pp. 1237–1250, 2016.
[8] K. Can, K. Hamza, D. A. Serhat, D. Askin, “Estimation of the presence of coal using at the Soma Basin”, Asia Pacific Confederation of Chemical Engineering Congress 2015: APCCHE 2015, incorporating Chemeca 2015. Melbourne: Engineers Australia, pp. 1029–1041, 2015.
[9] V. M. Filippov, “Nuclear exploration of minerals”, Kiev: Naukova Dumka, 576 p., 1978. (In Russ.)
[10] VPGR-1 Surface-deep radioisotope moisture meter. Technical description and instruction manual. Poltava, 43 p., 1982. (In Russ.)
[11] A. A. Sysasko, N. N. Grib, Yu. N. Skomoroshko, V. M. Nikitin, “Technology of geological and geophysical study of outcrops of coal seams in the permafrost zone”, Yakutsk: YaP GU Publishing house of the SB RAS, 160 p., 2004. (In Russ.)
[12] N. E. Fomenko, V. V. Popov, A. S. Kovalenko, “Investigation of coal exploration wells using pulsed neutron-neutron logging”, Bulletin of the Tomsk Polytechnic University. Engineering of georesources, vol. 331(2), pp. 151–161, 2020. (In Russ.)
[13] P. Hatherly, “Overview on the application of geophysics in coal mining”, International Journal of Coal Geology, vol. 114, pp. 74–84, 2013.
[14] V. V. Popov, “Complexes of geophysical research in coal exploration wells”, Karotazhnik, vol. 105, pp. 80–89, 2003. (In Russ.)