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Application of Neutron – Induced Gamma Ray Spectrometry for in Situ Assessment of Coal Quality

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Application of neutron-induced gamma ray spectrometry for in situ assessment of coal quality.

Wykorzystanie wzbudzonego promieniowania gamma do oceny jakości węgla kamiennego in situ.

Использование спектрометри возбужденного гамма излучения для оценки качества каменного угля в скважинах.

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Streszczenie.

W pracy przedstawiono fizyczne podstawy profilowań spektrometrycznych metodami neutron-gamma i neutronowej aktywacji. Podano podstawowe dane jądrowe dla głównych pierwiastków tworzących węgiel kamienny. Na podstawie analiz chemicznych próbek rdzenia wiertniczego podano współzależności statystyczne pomiędzy głównymi parametrami określającymi jakość węgla kamiennego. Przedstawiono rezultaty pomiarów polowych na złożu węgla kamiennego.

Summary.

The paper presents the physical principles of the spectrometric neutron capture borehole logging method and spectrometric neutron activation borehole logging method. Nuclear parameters of major elemental constituents of coal are given. Statistical multiple correlation results of coal core samples assessment are presented for coal quality parameters. The results of in situ spectrometric measurements in a coal field are also presented.

Резюме.

В работе представлено физические основы спектрометрического метода нейтрон гамма а также нейтронного активационного коротожа. Указано ядерные константы для основных элементов входящих в состов каменного угля. Исходя из химического анализа керна создано статистическую корелацию между главными параметрами определяющими качесто каменного угля. Для сравнения приведенно экспериментальные результаты полученыиз измерений для месторождения каменного угля.

1. INTRODUCTION.

Geophysical borehole logging has become an integral component of exploration, documentation and prospection procedures for mineral deposits. Geophysical investigations of hard coal in exploration boreholes enable :

- lithological identification,
- location of coal beds and determination of the thickness of their layers,
- evaluation of homogeneity of hard coal strata,
- determination of coal quality parameters,
- stratigraphic correlation between boreholes.

Among various geophysical methods applied to evaluation of coal deposits, neutron induced gamma ray spectrometric methods are used. These spectrometric methods make possible to measure both intensity and energy of gamma rays. Although methods require rather sophisticated devices their results can be interpreted in a quantitative manner. The most widely used are spectrometric neutron capture borehole logging method and spectrometric neutron activation borehole logging method.

In both techniques the characteristic gamma rays are recorded, resulting from interactions of atomic nuclei with neutrons. The energy of gamma rays is used to identify a given atomic nucleus and the gamma ray intensity - its concentration in the rock formation. Spectrometric methods can be divided into two groups depending on the detector used. The application of high resolution semiconductor detectors permits the determination of major elemental constituents of coal

deposit as shown by Clayton et al.[1], Senftle et al.[2], Mikesell et al.[3,4],and others. The application of scintillation counters makes possible the determination of macroscopic coal parameters (Charbucinski et al.[5], Chruściel et al.[6]).

2. Some general characteristics of hard coal.

Coal is a very complex and heterogeneous substance, and can be divided into three components: organic matter, mineral substance and water. Typical concentrations of the major elemental constituents of hard coal and of the three main components vary in wide ranges as shown in table 1 from Clayton and Wormald [7].

General characteristics of the Upper Silesian Coalfield have been published by a number of investigators, among them Mielecki [8]. Here only the information concerning directly the employed measuring methods is presented. On the basis of chemical analyses of about 200 drilled core coal samples from different boreholes multivariable statistical correlations were investigated for different coal quality parameters.

Table 2 shows correlation between the following parameters: Calorific value Q, Ash content A, Moisture W, Carbon concentration C, Hydrogen concentration H, coal density ρ and concentrations of SiO_2, Al_2O_3 and Fe_2O_3 represented as Si, Al, and Fe respectively. Also are given correlation coefficients for every relation, mean standard deviation and regression equations (the variation ranges of the above enumerated coal

Table 1. The typical chemical composition of hard coal.

Coal component range of conc. [wt %] and density [kg/m^3]	Principal element	Typical conc. [wt %]
Organic matter.	C	79.0
70 - 95	H	6.0
1350	O	13.5
	N	1.5
Mineral substance.	Si	16.7
5 - 30	Al	12.5
2000 - 4000	Fe	8.3
	O	62.5
Water.	H	11.2
12 - 20	O	88.8
1000		

Table 4. Relation between ash content A, calorific value Q, density ρ. and moisture content W. [6]

Relation	Corr. coeff. R	Mean standard deviation < σ >
1. Data for 30 coal samples collected from 5 boreholes located in different places in a larger coalfield.		
A(ρ)	0.516	3.4 % w.
Q(W,A)	0.684	1880 kJ/kg
2. Data for 36 coal samples collected from 2 boreholes drilled at the same part of a coalfield.		
A(ρ)	0.939	2.2 % w.
Q(W,A)	0.917	1060 kJ/kg

Table 2. The statistical correlation between coal quality parameters.

Nr.	Relation	Regression equation	Corr. coef. R	Mean standard deviation $\langle \sigma \rangle$
1	Q(C)	Q=-2118+436.5C	0.984	616.1 kJ/kg
2	Q(A)	Q=31670-361.2A	0.787	2143.0 kJ/kg
3	Q(C,H)	Q=-1757+448.3C-231.8H	0.984	616.0 kJ/kg
4	Q(A,W)	Q=34480-362.4A-811.4W	0.971	836.4 kJ/kg
5	Q(A,W,C)	Q=36500-366.7A-803.9W-1696.0C	0.971	836.8 kJ/kg
6	Q(A,W,C,H)	Q=5018-31.43A-240.7W+370.9C-326.0H	0.989	516.4 kJ/kg
7	W(Q,A)	W=36.56-0.001Q-0.3792A	0.921	0.949 wt %
8	A(Q)	A=-103.5+85.2Q	0.889	3.471 wt %
9	A(Q,W)	A=90.50-1.071Q-1.702W	0.966	1.953 wt %
10	A(Si,Al)	A=4.018+1.099Si+0.8632Al	0.953	2.233 wt %
11	A(Si,Fe,Al)	A=1.736+1.052Si+1.132Fe+0.9845Al	0.985	1.256 wt %
12	Si(Al)	Si=-0.5612+1.463Al	0.893	1.993 wt %

for the variation ranges of coal parameters cf. table 9.

Table 3 The variation range of the principal elements in coal ash given in (%).

Bore-hole.	Number of samples	Conc. of SiO2 mean min.	max	Conc. of Al2O3 mean min.	max	Conc. of Fe2O3 mean min.	max	Conc. of CaO2 mean min.	max	Conc. of MgO2 mean min.	max
1	26	40.53 9.50	55.25	31.92 7.80	39.68	15.81 3.10	72.30	4.41 1.24	18.10	2.45 0.64	7.16
2	20	33.54 10.01	50.25	26.78 13.29	36.02	11.82 4.05	24.71	10.62 2.34	25.95	5.85 1.48	14.16
3	20	39.62 21.14	51.94	30.47 14.25	39.05	8.76 2.50	18.70	7.16 0.80	26.15	3.65 1.10	12.85
4	19	45.36 25.36	55.22	33.55 24.15	38.54	7.75 3.11	17.85	3.45 0.79	10.97	2.41 1.01	8.02
5	17	46.49 30.65	76.96	31.72 7.22	38.85	8.16 4.21	11.37	5.19 0.99	15.76	2.98 1.33	9.17
6	10	41.00 21.43	52.07	33.37 19.68	38.83	13.16 5.06	53.32	3.81 0.72	6.09	2.10 1.20	3.12
Ave-rage.	112	41.09		31.30		10.91		5.77		3.23	

parameters for the Upper Silesian Coalfield are presented in table 9). The important features of these correlations are the high correlation coefficients for relations Q(C,H), Q(A,W,ρ) and relatively low correlation coefficient for relations Q(A) and A(ρ).

Table 3 gives concentrations of the principal elements in coal ash from boreholes of different coal fields. Maximum, mean and minimum concentration values of different ash constituents are given. From this table it is evident that the major elemental constituents of ash content for different boreholes of the Upper Silesian Coal field may vary in wide ranges. These wide ranges of variation explain the fact that the property of coal has a local character. The correlation is stronger when analysed samples are retrived from the same part of a given coal field rather than from different coal fields (coal of different origin and type) as illustrated in table 4.

3. Physical principles of neutron induced gamma ray spectrometry.

3.1 Neutron interaction with matter.

The probability of neutron interactions with a given atomic nucleus depends on the neutron energy. The most frequently used neutron sources in logging practice are Po-Be, Pu-Be and ^{252}Cf. These sources emit neutrons of primary energy from zero to about 10 MeV. The most important neutron source parameters are: maximum E_m and mean <E> neutron energy, half-life time $T_{1/2}$ and neutron output Q. Table 5 contains the above

Table 5. Some parameters of the commonly used neutron sources.

Source	$T_{1/2}$	E_n [MeV]	<E> [MeV]	Q [n/Ci]	E_γ [MeV]	Intensity * γ/s
^{239}Pu-Be	24000 a	11.5	5.0	$2.5 \cdot 10^6$	0.803 3.220 4.440	0.16 0.17 0.50
^{241}Am-Be	86.4 yrs	11.5	5.0	$2.0 \cdot 10^6$	0.100	0.00013
^{252}Cf *	2.6 yrs	10.0	2.3	$2.7 \cdot 10^{12}$	soft.	

* For ^{252}Cf neutron output in neutrons per 1gram of ^{252}Cf.

Table 6. The main neutron capture reaction parameters of hard coal elemental constituents according to Herzenberg and Olson [11].

Element	Atomic mass A	E_γ [keV]	$\sigma_{n,\gamma}$ [10^{-24} cm^2]	I - Number of photons per 100 neutrons	Sensitivity factor (Io/A)
H	1.00	2223	0.3322	100.0	33.220
C	12.01	3684	0.0034	31.8	0.010
		4945		67.0	0.022
O	15.99	2180	0.0002	100.0	0.001
		3271		100.0	0.001
Na	22.98	2027	0.5350	19.8	0.460
		2754		102.4	2.383
		3982		21.6	0.502
		6395		25.7	0.598
Mg	24.30	1809	0.0649	25.2	0.067
		2828		35.7	0.095
		3054		10.8	0.028
		3916		40.8	0.109
Al	26.98	1779	0.2314	88.2	0.756
		7724		20.0	0.172
Si	28.08	2093	0.17	26.8	0.162
		3539		79.6	0.481
		4934		70.6	0.427
		6380		12.6	0.076
S	32.06	2380	0.518	19.4	0.314
		2931		18.1	0.292
		3221		19.5	0.314
		5420		42.2	0.685
K	39.09	2073	2.08	10.2	0.545
		1618		7.9	0.420
Ca	40.08	1943	0.4299	52.5	0.563
		6420		9.1	0.312
Fe	55.84	5921	2.59	8.3	0.380
		7632		27.2	1.261
		7648		22.1	1.021

mentioned parameters of the neutron sources.

A detailed description of neutron interactions with atomic nuclei can be found in a number of monographs among them Beckurts and Wirtz [10]. This paper only discusses the physical processes leading to the emission of characteristic gamma rays. Some neutron interaction processes with matter are shown in fig.1. This schematic diagram differentiates :

1. Inelastic neutron scattering – nuclear reaction $(n,n'\gamma)$
2. Fast and thermal neutron activation of atomic nuclei that is (n,α), (n,p), $(n,2n)$ reactions.
3. Radiative capture mainly of thermal neutrons and also of fast neutrons.

A neutron emitted from a neutron source loses some of its kinetic energy during the slowing down process due to collisions with atomic nuclei. The neutron after achieving thermal energy undergoes the diffusion process which ends up with for example radiative capture during which a characteristic gamma ray is emitted. Nuclear cross sections for neutron interactions with atomic nuclei of principal elements constituting hard coal are given in tables 6 and 7.

Table 6 gives some parameters of the radiative capture reaction. The important features of these parameters are the relatively small cross sections of elements like oxygen and carbon and also the sensitivity factor greater than 1.0 for hydrogen, sodium and iron. (Only gamma lines of strong relative intensities E_γ are listed) Table 7 gives parameters of useful nuclear reactions resulting from thermal and fast

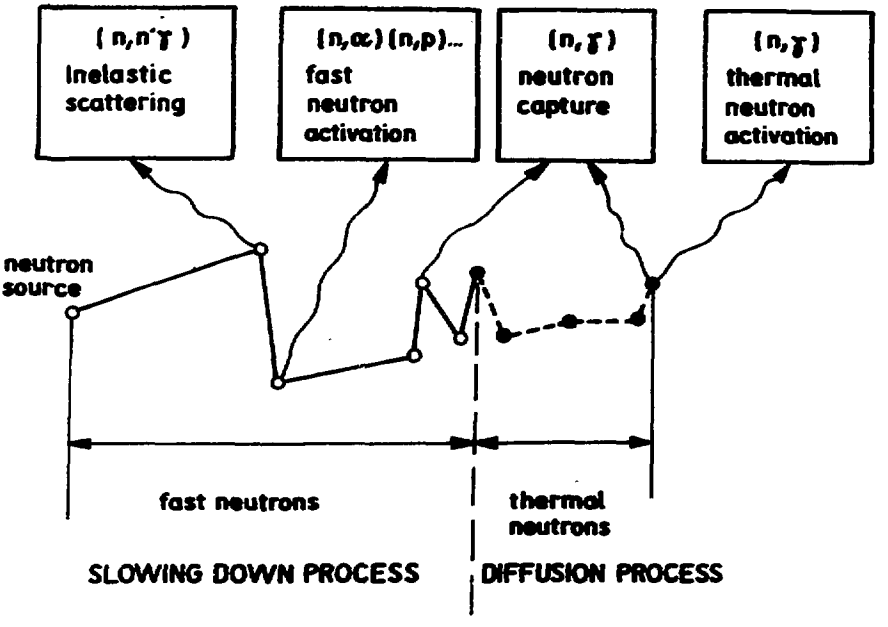

Fig. 1. Schematic diagram of neutron interactions with matter.

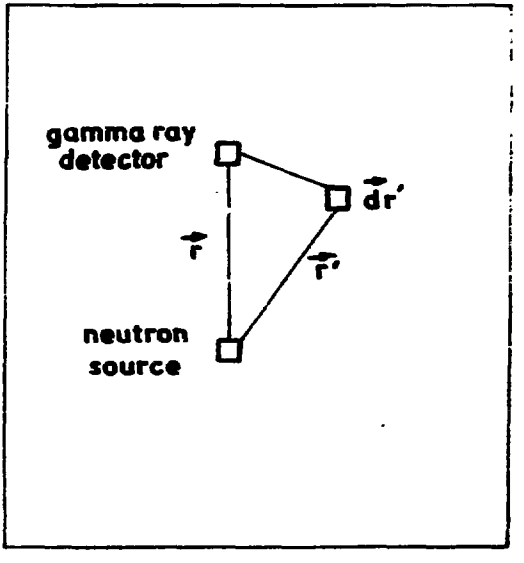

Fig. 2. The measurement geometry

Table 7. The main neutron activation reaction parameters of hard coal according to Kock [12].

Nuclear reaction	Abundance	σ_{act} [10^{-24} cm^2]	$T_{1/2}$ [min.]	E_γ (occurrence %) [keV]
$^{27}Al(n,\gamma)^{28}Al$	100.00	0.210	2.27	1779(100)
$^{27}Al(n,p)^{27}Mg$	100.00	0.079	9.45	1013(30), 843(70)
$^{28}Si(n,p)^{28}Al$	92.27	0.080	2.27	1779(100)
$^{29}Si(n,p)^{29}Al$	4.68	0.280	6.60	2430(6), 1286(94)
$^{30}Si(n,\alpha)^{27}Mg$	3.05	0.110	10.00	1013(30), 843(70)
$^{26}Mg(n,\gamma)^{27}Mg$	11.29	0.027	9.45	1013(30), 843(70)
$^{48}Ca(n,\gamma)^{49}Ca$	0.19	1.100	8.80	4050(10), 3100(89)
$^{31}P(n,\alpha)^{28}Al$	100.00	0.146	2.27	1779(100)
$^{37}Cl(n,\gamma)^{38}Cl$	24.60	0.560	37.29	2150(47)

Table 8. The chemical composition of one of the Silesian coals.

Nr.	Elements	Concentration [wt %]
1	C	64.62
2	O	10.34
3	Si	9.26
4	Al	7.53
5	H	3.79
6	S	0.72
7	Fe	0.67
8	K	0.62
9	Ca	0.48
10	Mg	0.26
11	Na	0.10
12	others	1.61

neutron activation. Only elements whose half-life time $T_{1/2}$ is shorter than 10min. are listed. The most important nuclear reactions for practical purposes are those with atomic nuclei ^{28}Al and ^{27}Mg.

3.2 Theoretical principles of spectrometric neutron capture method.

The flux of neutron-induced gamma rays depends on the space-energy distribution of neutrons in matter. The general transport equation describing the flux of gamma rays with a given energy, $I_\gamma(\vec{r})$ resulting from a neutron capture by the atomic nucleus of a given element is as follows. For notation see fig.2.

$$I_\gamma(\vec{r}) = i\iint_{EV}\Sigma_a(E)\cdot\Phi(\vec{r}',E)\cdot G(|\vec{r}-\vec{r}'|)dEd\vec{r}' \qquad (1)$$

where:

$\Sigma_a(E)$ - macroscopic neutron absorption cross section.

$\Phi(\vec{r}',E)$- space-energy distribution of neutron flux in medium.

$G(|\vec{r}-\vec{r}'|)$ - Green's function for gamma ray propagation (gamma ray detection function):

$$G(|\vec{r}-\vec{r}'|) = \frac{\exp(-\mu_o|\vec{r}-\vec{r}'|)}{4\Pi|\vec{r}-\vec{r}'|^2} \qquad (2)$$

$d\vec{r}'$- volume element.

i - number of emitted gamma rays with a given energy E_γ.

μ_o- linear absorption coefficient of a given medium for gamma rays with energy E_γ.

Solution of equation (1) is very hard to be obtained, especially in a borehole geometry. In general the space-energy distribution $\Phi(\vec{r},E)$ of the neutron flux is chiefly determined by the hydrogen content and presence of some other strong neutron absorbers in the borehole, rock and probe used. The flux of gamma rays depend on neutron slowing down and absorption properties of the medium as well as the gamma ray interaction cross section. The gamma ray flux with a given energy $I_\gamma(E)$ produced by atomic nuclei N_j is given by:

$$I_\gamma(E) \sim \frac{N_j \sigma_{(n\gamma)j}}{N_j \sigma_{(n\gamma)j} + \sum_{i=1}^{m} N_i \sigma_{ti}} \qquad (3)$$

If $N_j \sigma_{(n\gamma)j} << \sum_i N_i \sigma_{ti}$ then $I_\gamma(E)$ is proportional to the concentration of j-th element.

where:

σ_{ti} - microscopic neutron absorption cross section of i-th isotope.

N_i - number of atoms of the i-th isotope per unit volume.

m - number of different atomic nuclei..

$\sigma_{(n\gamma)j}$ - microscopic capture cross section for j-th isotope.

N_j - number of atoms of j-th isotope per unit volume.

The neutron induced gamma rays flux $I_a(\vec{r})$ resulting from neutron activation of atomic nucleus of a given element is as follows.

$$I_a(\vec{r}) = i\iint_{EV}\Sigma_{act}(E)\cdot\Phi(\vec{r}',E)\cdot G(|\vec{r}-\vec{r}'|)\cdot B(t_a,t_v)dEd\vec{r}' \quad (4)$$

The gamma ray build-up and decay factor $B(t_a,t_v)$ is given by :

$$B(t_a,t_v) = (1-\exp[(-0.693\cdot t_a)/(T_{1/2})])\cdot\exp[(-0.693\cdot t_v)/(T_{1/2})] \quad (5)$$

where :

$\Sigma_{act}(E)$ - macroscopic neutron activation cross section.

t_a - activation time, t_v - waiting time.

When only one isotope is activated the gamma-ray flux $I_a(E)$ is given by:

$$I_a(E_\gamma) \simeq \frac{N_j\cdot\sigma_{act,j}}{N_j\cdot\sigma_{act,j} + \sum_{i=1}^{m} N_i\cdot\sigma_{act,i}} \quad (6)$$

where :

$\sigma_{act,j}$ - microscopic activation cross section of j-th isotope.

If $N_j\sigma_{act,j} \ll \sum N_i\sigma_{act,i}$ then $I_a(E)$ is proportional to the concentration of j-th element.

4.0 Borehole gamma ray spectrometer type SO-3-80.

Borehole spectrometer of the SO-3-80 type used for field measurements has been described elsewhere (Pałka [13]) and the

first measurements were performed by Chruściel et al. [14]. The schematic diagram of the logging system is shown in fig. 3. The spectrometer consists of a logging probe with a scintillation NaI(Tl) crystal 35 x 70mm. The external probe diameter is 60mm and maximum length 2700mm. The distance between the neutron source and the detector can be taken as one of the three values: 200mm, 350mm and 450mm. The recorded spectrum of gamma rays is transmitted to the surface through a logging cable, 2.5km long. The surface panels, working in a modular system, consist of linear amplifier, energy scale stabilizer, 200 channel pulse height analyser, six energy-channel digital recorder (with the possibility of varying the position and width for every channel with the 0.5% precision for the whole recorded spectrum of gamma rays) and a microprocessor Meritum II equipped with the appropriate software for automatic data processing. The whole system records and collects gamma ray spectra and processes the accumulated data. Borehole spectrometer of the SO-3-80 type can be connected to a typical geophysical logging system.

4.1 Measurement of radiative capture gamma ray spectra.

Neutron induced gamma ray flux interacts with atomic nuclei in the rock formation, as well as with the probe construction material and the detector. The shape of the recorded gamma ray spectra depends on the :

- borehole parameters (its diameter, type of drilling mud, etc.)

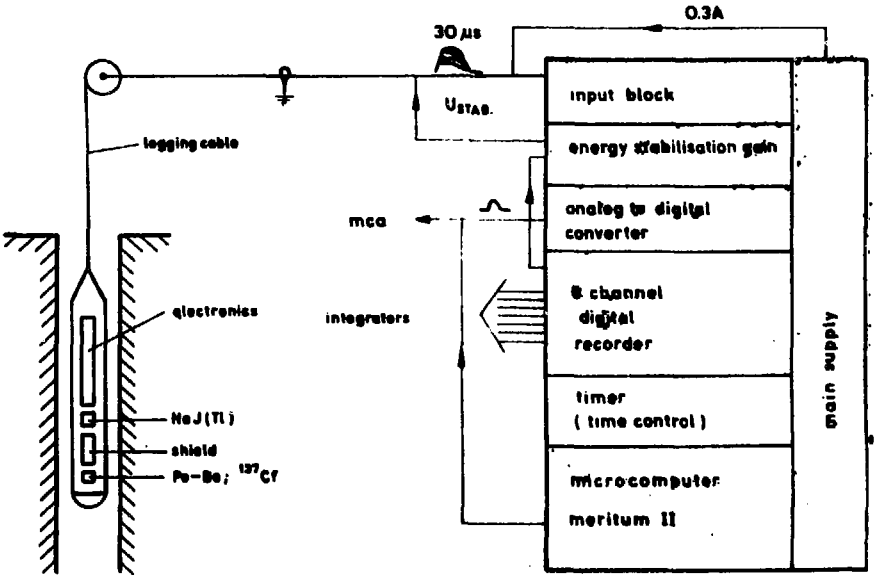

Fig. 3. The schematic diagram of the logging system.

- formation parameters (chemical composition, density, porosity, etc.)
- probe parameters (source-to-detector distance, probe diameter, etc.)

The recorded gamma ray spectrum consists essentially of three peaks: full energy peak at the energy E_γ, single escape peak at the energy (E_γ = 0.511 MeV) and double escape peak at the energy (E_γ = 1.022 MeV). However, due to limited resolution of the NaI(Tl) crystal, recorded gamma ray spectrum is poorly differentiated, so the individual peaks overlap. Fig.4 shows a typical spectrum recorded by the borehole spectrometer in coal seams. In the figure are indicated the positions of neutron capture gamma lines of strong relative intensities and full, single and double energy peaks as f,s and d respectively. Nevertheless, even for such poorly differentiated spectrum it is possible to determine quantitatively the concentration of such elements as sulphur, silicon, chlorine, iron and hydrogen. The figure also shows line spectrum of the primary radiative capture gamma rays, given in relative units (only strong relative intensities of neutron capture gamma lines are indicated). Calculations were based on coal chemical composition obtained from chemical assays of coal given in table 8.

About 80 neutron capture gamma-ray spectra were recorded in the energy range (2-8) MeV using the SO-3-80 spectrometer. These measurements were performed using a Po-Be neutron source of about 10^6 n/s output and with the source-detector spacing of

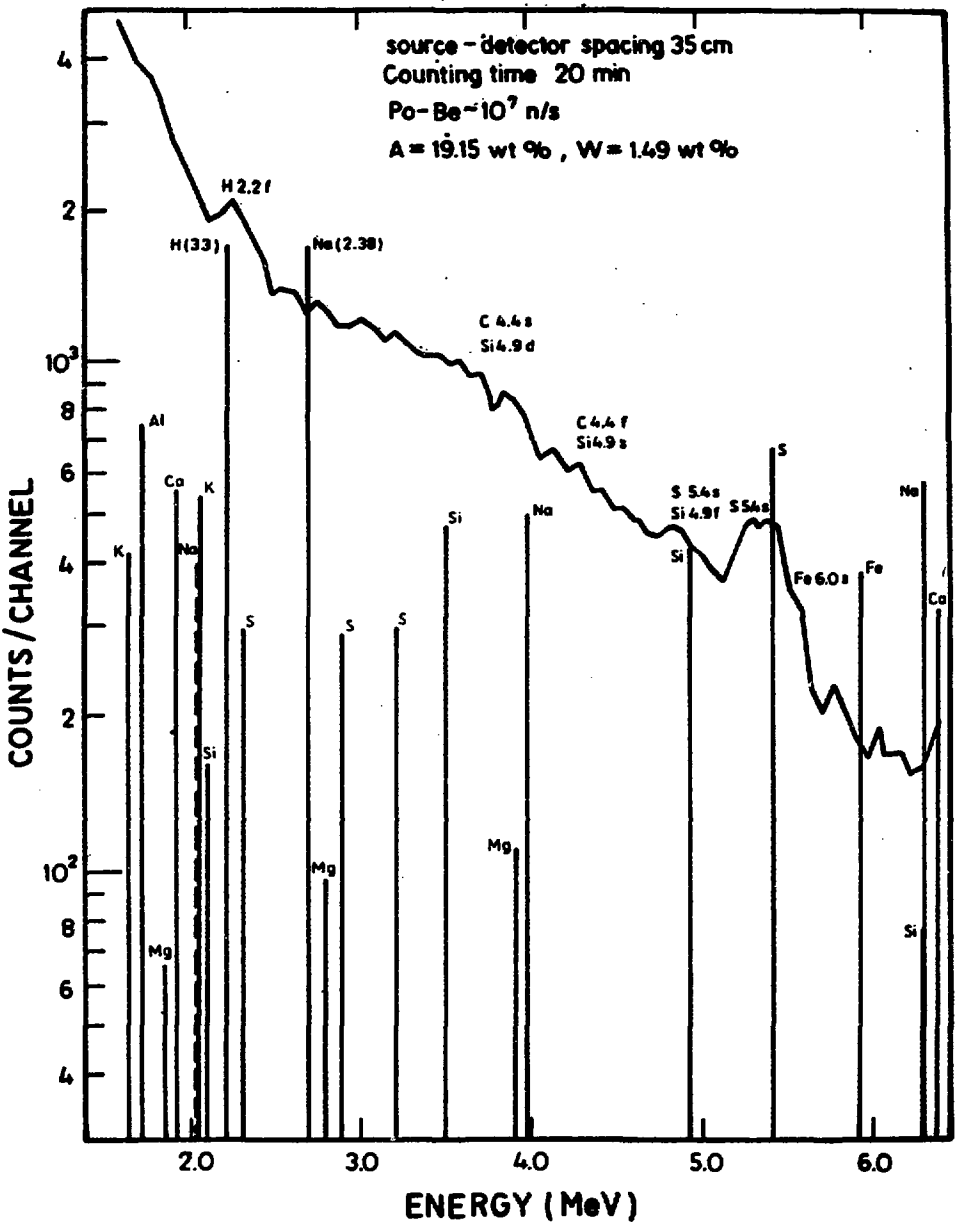

Fig. 4. Typical gamma ray spectrum recorded in the coal seams.

35 cm. Spectra analysis was based on the calculation of spectrometric parameters k_j described by Bljumentsev et al. [15]. A spectrometric parameter, k_j can be defined as :

$$k_j = \frac{\int_{E_1}^{E_2} I(E)dE}{\int_{E_3}^{E_4} I(E)dE} \qquad j = 1,2,\ldots,n. \qquad (7)$$

where:

E_1, E_2, E_3, E_4-energy limits, I(E)- recorded intensity of gamma rays with energy E, n - number of defined physical parameters.

The spectrometric parameter k_j should be chosen in such a way that it would depend strongly on the j-th physical parameter x_j while the influence of other parameters describing the physical properties of formation-borehole-probe configuration would be negligible (in practice greatly reduced). The appropriate choice of k_j depends of courseon the adequate selection of energy limits : $E_1,\ldots,E_4$.

The calibration curves for quantitative interpretation are constructed on the basis of multiple correlation analysis of the results of static measurements of k_j and the results of the chemical assays of coal samples. These calibration curves are used to determine the physical parameters of coal. Table 9 gives an example of selected and optimised energy intervals for spectrometric measurements and table 10 gives the regression equations linking some physical parameters. The

Table 9. The optimised energy intervals for spectrometric neutron-gamma method.

Nr.	Coal parameter and range of its variation	k_j	Energy values [keV] E_1	E_2	E_3	E_4
1	Moisture content (0.5 - 10) wt %	k_W	1100	1300	5750	5950
2	Calorific value (17000 - 32000)kJ/kg	k_Q	4360	5580	1940	5010
3	Ash content (2.0 - 32.0) wt %	k_A	4230	6620	1850	8300
4	Concentration of ^{12}C (43 - 72) wt %	k_C	1900	3520	4500	5650
5	Concentration of SiO_2 (0.8 - 20) wt %	k_{Si}	2340	2480	6400	6600
6	Concentration of Fe_2O_3 (0.4 - 8.6) wt %	k_{Fe}	5850	6730	5380	5810
7	Concentration of Al_2O_3 (0.5 - 10.0) wt %	k_{Al}	2230	6190	3810	6930
8	Concentration of S (9.5 - 39.6) wt %	k_S	2450	2640	3470	3500

Table 10. The regression equations linking the coal parameters with the spectrometric parameters k_j's.

Nr.	coal parameter	Regression equation	Corr. coeff. R	Mean stand. deviation $\langle \sigma \rangle$ *
1	Moisture	$W = 9.47 - 0.045\ k_W$	0.807	1.19 wt %
2	Calorific value	$Q = -4860 + 0.177k10^4\ k_Q$	0.751	1737 kJ/kg
3	Ash content	$A = 101.0 - 422.7\ k_A$	0.691	4.58 wt %
4	Conc. of ^{12}C	$C = 115.1 - 9.63\ k_C$	0.746	4.36 wt %
5	Conc. of SiO_2	$Si = 51.75 - 223.1\ k_{Si}$	0.645	2.62 wt %
6	Conc. of Fe_2O_3	$Fe = 9.26 + 9.29\ k_{Fe}$	0.710	0.97 wt %
7	Conc. of Al_2O_3	$Al = -33.81 + 15.93\ k_{Al}$	0.646	1.79 wt %
8	Conc. of S	$S = -4.47 + 1.36\ k_S$	0.665	0.65 wt %

* for the variation ranges of coal parameters cf. table 9.

static measurements in a borehole are performed according to the following procedure :

- data processing device records the gamma ray spectrum for a given coal seam
- the spectrometric parameter, depending on earlier defined energy limits from E_1 to E_4, is calculated.
- on the basis of the regression equation of the spectrometric parameters the corresponding physical parameter is determined.

Table 11 gives an example of the results of an analysis of gamma ray spectrum measured in a borehole. Calculated physical parameters are then compared with the results of chemical assays of coal samples.

In the case of the dynamic (continuous logging) measurements the measuring device makes possible to record gamma ray intensity as a function of depth. The determination of a given physical parameter requires recording of two logging curves in defined energy intervals. The quotient of the readings from both logging curves define the spectrometric parameter k_j. The physical parameter x_j is determined from the appropriate regression equation. Fig. 5 shows an example of the variations of the probe readings in two energy intervals, there by allowing the determination of carbon concentration in a hard coal [6].

Table 11. The results of an analysis of gamma ray spectrum measured in a borehole.

Coal parameter	Depth 824 m.		Depth 463 m.	
	Logging results	Laboratory results	Logging results	Laboratory results
W (wt %)	7.45	7.09	5.24	3.12
ρ (g/cm^3)	1.42	1.45	1.41	1.50
Q (kJ/kg)	23110	22138	25889	22299
C (wt %)	57.98	55.84	65.60	56.10
A (wt %)	17.43	19.36	11.50	25.46
Si (wt %)*	36.89	36.00	33.95	50.40
Fe (wt %)*	11.99	9.19	7.92	6.12
Al (wt %)*	23.75	24.20	31.34	35.97
S (wt %)	0.82	1.11	1.37	0.98
H (wt %)	3.47	3.51	3.94	3.68

* concentration in coal ash.

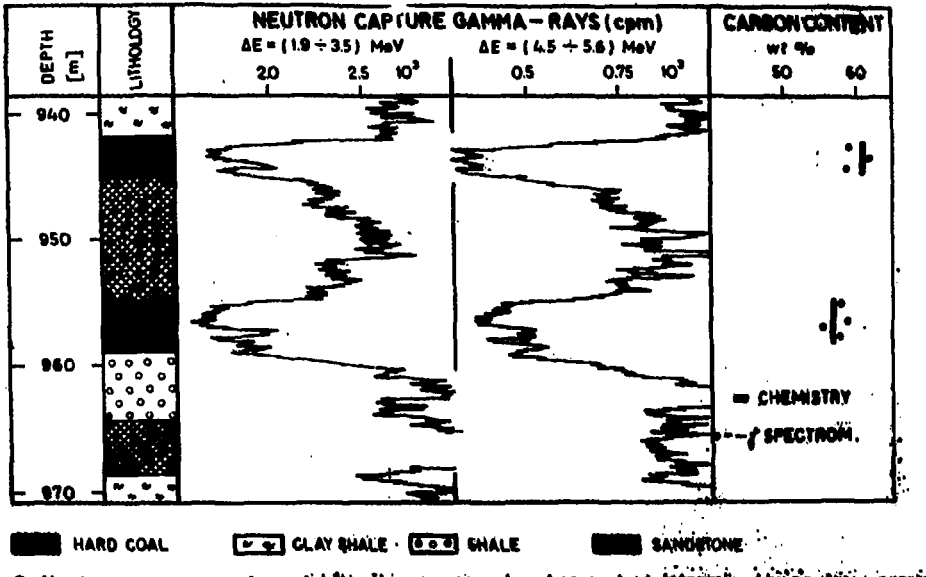

Fig. 5. Neutron–gamma spectrometric logging curves and carbon content determined by neutron–gamma spectrometry and laboratory analysis of core samples.

4.2 Measurements of gamma ray spectrum resulting from neutron activation.

Activation measurements were performed with the source-to-detector distance increased to 150cm in the scintillation borehole spectrometer of the SO-3-80 type. Static measurements were performed in such a way that the neutron source was held against the coal seams for an activation time t_a of 20min., and then replaced by the detector. The waiting time t_w, that is the time from ending of irradiation to the beginning of counting equal to 2min., and the counting time t_c of 10^3sec. were used in the point measurements. A typical pattern of delayed gamma ray spectrum recorded from coal seam is shown in fig.6.(a Pu-Be neutron source of 10^6n/s output was used). Two characteristic lines are taken from each spectrum, that is E_γ = 1779keV emitted by the products of the $^{28}Si(n,p)^{28}Al$, $^{27}Al(n,\gamma)^{28}Al$ and $^{31}P(n,\alpha)^{28}Al$ reactions as well as E_γ = 843keV generated by the $^{27}Al(n,p)^{27}Mg$, $^{26}Mg(n,\gamma)^{27}Mg$ and $^{30}Si(n,\alpha)^{27}Mg$ reactions as presented in table 7.

From the borehole and laboratory investigations data, it is evident that there exists a strong correlation between ash content A and concentrations of Si and Al for a given coal deposit. If N_1 and N_2 are the total count rates at the peaks with energy 843keV and 1779keV respectively, then the following regression equation holds :

$$A = a_0 + a_1N_1 + a_2N_2 \qquad (8)$$

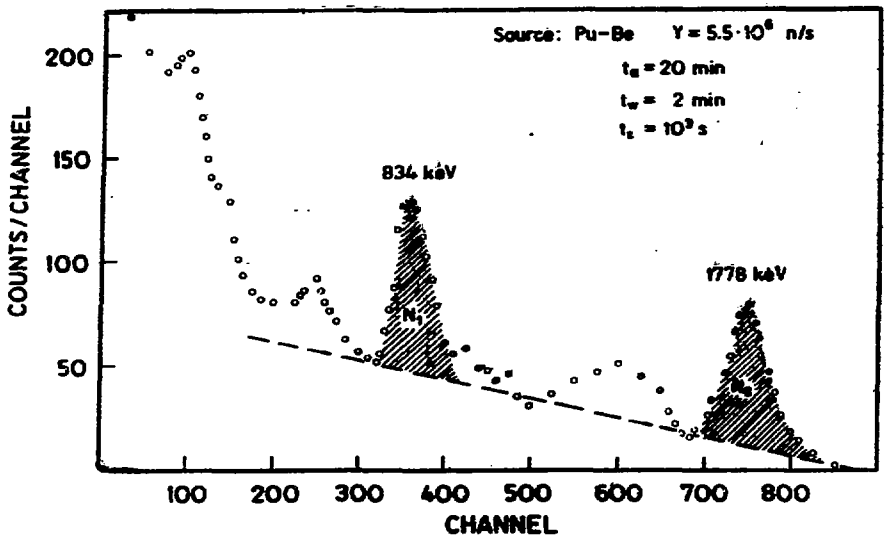

Fig.6. Typical response of delayed gamma ray spectrum recorded in coal seams.

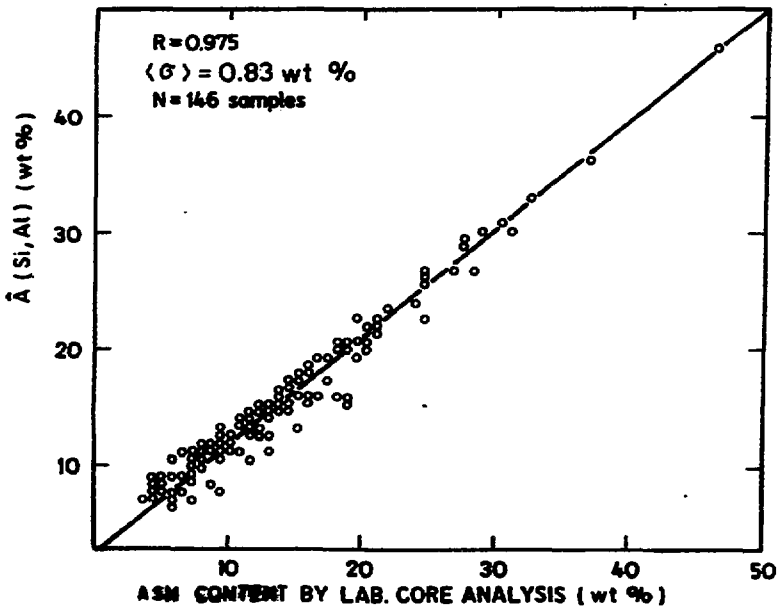

Fig.7. The correlation between ash content determined from the SiO_2 and Al_2O_3 concentration and from laboratory core analysis.

The statistical correlation between ash content determined from the chemical assays of coal samples and ash content determined from the Si and Al concentrations according to the linear regression equation is shown in fig.7.

Dynamic neutron activation measurements can also be performed with the SO-3-80 type spectrometer. The first channel of 300keV width records gamma rays energies from the 843keV region whereas the second channel of 500keV width records gamma rays from the 1779keV region. For a given source-to-detector distance l the sonde velocity v should be taken from the following relation.

$$v = (0.693 \cdot l) / T_{1/2} \qquad (9)$$

where : $T_{1/2}$ - half life of a given isotope.

These measurements are presently being performed and their results will be published later on.

5. Conclusion.

Gamma ray spectrometric methods have recently been introduced to routine geophysical methods of investigation of hard coal deposits. These methods allow the quantitative interpretation, especially in the case when drilled core samples are not available.

Field measurements performed by gamma ray spectrometer of the SO-3-80 type have shown that prompt and delayed gamma ray

methods can be successfully applied. The static measurement permits the recording of radiative capture gamma ray spectrum and the analysis of recorded spectrum can be used in order to determine the parameters of coal quality.

Because of the local properties of hard coal, the calibration curves should be constructed for every individual coal deposit.

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REFERENCES

1. Clayton C.G., Hassan A.M., Worwald M.R.: Multi-element analysis of coal during borehole logging by measurement of prompt gamma rays from thermal neutron capture. Int. J. Appl. Radiat. Isot., Vol.34, No.1. pp. 83-93, 1983.
2. Senftle F.E., Mikesell J.L.: The nuclear ratio technique applied to borehole exploration for industrial metals and coal. Nucl. Geophys. Vol.1, No.3, pp. 227-233, 1987.
3. Mikesell J.L., Senftle F.E., Tanner A.B.: Borehole elemental analysis of coal using fast neutrons. Gamma, X-ray and neutron techniques for coal industry. IAEA Vienna. pp. 26-42, 1984.
4. Mikesell J.L., Dotson D.W., Senftle F.E., Zych R.S., Koger J., Goldman L.: In situ capture gamma ray analysis of coal in an over size borehole. Nucl. Instr. Meth. 215. pp. 561-566,. 1983.
5. Charbucinski J.,Youl S.F.,Eisler P.L.,Borsaru M.: Prompt neutron-gamma logging for coal ash in water filled boreholes. Geophysics Vol. 51, No.5.pp. 1110-1118, 1986.
6. Chruściel E., Kopeć M., Niewodniczański J., Pałka K.W., Kaczmarski S.M., Wojda F.: In situ analysis of coal by scintilation gamma ray spectrometry in deep boreholes. Nucl. Geophys. Vol.1, No.4, pp. 345-352, 1987.
7. Worwald M.R., Clayton C.G.: In situ analysis of coal by measurement of neutron-induced prompt gamma rays. Int. J. Appl. Radiat. Isot. Vol.34, No.1, pp. 71-82, 1983.

8. Mielecki T.: Information on coal properties and their investigations wyd. "Śląsk" 1971. (in Polish).

9. Bak M.A., Szymanska N.S.: Neutron sources. wyd. Atomizdat. Moscow. 1969. (in Russian).

10. Beckurts K., Wirtz K.: Neutron physics. Springer-Verlag, Berlin, New York. 1964.

11. Herzenberg C., Olson I.K.: Thermal neutron capture prompt gamma emission spectra of representative coals. ANL/FE 82-6. 1981.

12. Koch R.C.: Activation analysis handbook. Academic Press. New York and London.1960.

13. Pałka K.W.: Gamma ray spectrometer for borehole logging. Symposium on methodological problems in the mineral resource investigations using borehole logging techniques. MIG, Kraków. pp. 105-114, 1983. (in Polish).

14. Chruściel E., Pałka K., Kaczmarski S., Wojda F.: Back-scattered and neutron capture gamma ray spectrometric methods for exploration of ore deposits. Tech. Poszuk. Geol. No.1, pp. 49-55, 1985. (in Polish)

15. Bljumentsev A.B., Feldman I.I., Nedostup G.A., Zeltikow A.N.: Neutron radiative capture gamma spectrometry as a method of determining the composition of iron-bearing rocks and ores.Radioisotop Instruments in Industry and Geophysics. SM-68/53, IAEA, Vol.2, 1966. Vienna.