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AIR PARTICULATE MASS MONITORING WITH A BETA RADIATION DETECTOR

The theory of beta attenuation and the design of various instruments reviewed in the literature are reported. The absorption of beta particles from radioactive sources has been measured and interpreted on the basis of stopping powers. The mass absorption coefficient of typical atmospheric aerosols deposited on filters have been determined. The calibration procedure of measuring setup is described. It is concluded that beta absorption mass monitoring of particulates can provide a reasonably correct measurement of atmospheric aerosols suspended in ambient air or removed by filtration or impaction.

1. INTRODUCTION

The attenuation of beta radiation as it passes through dust particles is being used to measure the particle mass concentration of atmospheric areosols or dust deposit. The technique is especially suited to measurements in stacks where high particle concentrations occur. In recent years emission control devices based on the beta absorption phenomena have been applied to the fossil fuel combustion sources, coal mines, cement plants and steel mills emitters.

A monitor employing the beta attenuation technique consists of a beta radiation source and a beta radiation detector. The mass determination is determined by the intensity of beta radiation transmitted through the detected particles. Measurement of the gas flow rate through stack gives in the particle mass concentration.

Many specific instrument designs have been previously described and tested. CLAPP and BERNSTEIN [4] described a beta attenuation thickness gauge. By employing a $^{90}Sr-^{90}Y$ source which has high beta transition energy ($E_\beta = 2.16$ MeV) they had no element independent device. To detect the beta particles the authors used an ionization chamber. They, however, had not discussed the linear relationship between the logarithm of activity and the absorber thickness. This device was to be calibrated for each absorber material. A device which used the attenuation of low energy beta radiation for determining absorber mass was built by PETERSON and DOWNING [15]. They used a ^{14}C source and a quartz fiber electroscope for detecting beta particles. It has been found that the relation between

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the logarithm of the discharge time and the weight in mg/dm^2 of thin cellophane films and aluminum foils is almost linear. Several beta emitters ^{14}C, ^{137}Cs, ^{204}Th were studied by NADER and ALLEN [14] ; a ^{14}C source and a glass flow end-window proportional counter were chosen. While investigating several relative source–absorber–detector distances and source diameters, they have stated that with this absorber the optimal geometry is relatively close to a small diameter source. They have also found that the typical background due to radioactivity in the aerosol deposit is negligible compared to the beta source intensity. This work also demonstrated the feasibility of the beta absorption technique for use in the automated tape samplers. Many researchers have reported the studies on beta ray absorption and transmission aimed at application in dust monitoring [5, 11, 13, 16].

In the recent years many monitors based on the interaction of beta rays with matter have been in operation. The RAC Model 2345 Automatic Stack Monitor is a sampling system designed to estimate concentrations of particulate matter in flue gases [2]. The sample is drawn from the stack through a probe which faces the stream of the exhaust gas. This sample is blended with a stream of clean dry air obtained from a compressed air line. One third of the diluted sample is drawn through a tape sampling device, while the other portion is expelled through the air injector. The use of this flow system permits isokinetic sampling of the stack gases and prevents condensation of any water vapor which may be present in warm or hot stack gases. The amount of particulates collected on the filter tape is estimated by the degree of the attenuation of beta radiation from a sealed ^{14}C source. A Geiger-Mueller counter is used to compare the numbers of beta particles which pass through the tape before and after deposition of particulates. Calibration is made taking the number of grains of particulates per cubic foot of stack gas.

The Gelman Stack Monitor is a system designed for industrial stack sampling [8]. It can used to sample, measure and record automatically the mass of emitted particles from a stack or duct system. The gas from the sampling probe is drawn through a paper tape filter and the solid particles are collected on the filter tape. A low energy beta ray emitting source (^{14}C) is located beneath the filtertape in the sampling port while a G.M. tube situated on the opposite side functions as the sensor. The absorption is proportional to the mass of the object being independent of any other physical properties. Keeping the flow rate and sampling time constant, the volume/mass ratio can be found by using nomograms.

TEISSEYRE et al. [12] designed a radioisotopic dustmeter, characterized by an automatic compensation of measurement errors. The dustmeter consists of a periodically shifting filtration tape, located between the source and the detector. A part of the filter tape is covered with dust in a filtration chamber. One detector is located over part of tape covered with dust, the other (compensation one) over the uncovered part. Compensation unit supplies information on dust concentration, the errors due to the tape properties, temperature, efficiency of beta ray sources etc. being neglected.

Advanced dust monitors: Model 101, 201 and 301 have been developed by the Krater Co. in cooperation with GCA Co. [3] for the determination of respirable and total airborne dust. These instruments allow direct mass measurement, respirable or total mass measurement, digital readout in milligrams, measurement independent of environmental variations and dust composition, total dust collection by high efficiency filter, automatic flow control. They are portable and completely self-contained etc. The dust monitors are intended for ambient monitoring and stationary or mobile source measurement by absorption of beta radiation through a high efficiency filter tape.

2. THEORY

In their interaction with matter, beta particles are absorbed either by ionizing collisions or by radioactive processes. For low energy electrons ($E_\beta < 0.5$ MeV) energy loss chiefly due to ionization (inelastic scattering) with atomic electrons. Beta radiation is attenuated exponentially according to the following equation:

$$I = I_0 \cdot e^{\mu_m \cdot x} \tag{1}$$

where I and I_0 are the beta counts with and without an absoring medium, μ_m is the mass absorption coefficient and x is the thickness of absorber, usually given in mg/dm^2 with the actual thickness multiplied by the density. For low energy beta emitters, the mass absorption coefficient is nearly independent of the chemical composition or the physical characteristics of the absorber. [6, 11]. This is due to the absorption of electrons colliding with beta particles passing through the absorber. This absorption depends on the absorber electron density, i.e. on the number of electrons per unit mass. Therefore, the absorption of particles depends of the ratio of atomic number to the mass number Z/A. Although this ratio decreases with the increasing atomic mass nevertheless for low energy beta emitters the effect of this variation on μ_m is not high. When the thicknesses of absorbing foils expressed by $x \cdot Z/A$ are plotted versus count rate, the resulting absorption curves are not independent of atomic number. Figure 1 shows the series of such curves, obtained

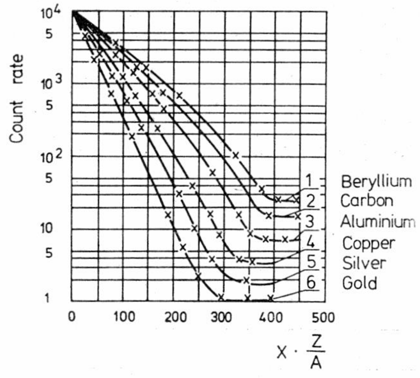


Fig. 1. Absorption curves for ^{32}P beta particles

Rys. 1. Krzywe absorpcji dla źródła ^{32}P

with a thin ^{32}P source [1]. Equivalent thicknesses of the absorber i.e. those resulting in the same counting rates are plotted in figure 2, in terms of $Z^{1\ 3}$. The linearity of the plots

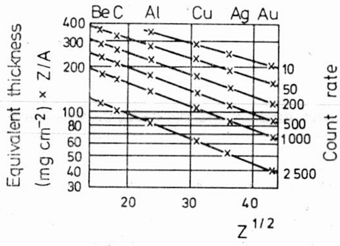


Fig. 2. Equivalent thickness as a function of atomic number

Rys. 2. Ekwiwalentna grubość absorbera jako funkcja liczby atomowej

shows that the relations between equivalent thicknesses x number of electrons/cm^2 and atomic number is given by the formula

$$\lg X = B - A \cdot Z^{1/3}\,. \tag{2}$$

The lines in figure 2 are not quite parallel so that A is nearly, but not quite, constant.

The value of μ_m has been found to be a function of the maximum energy of the beta particles E_{max}, and practically independent of the properties of the absorber. The function is of the form:

$$\mu_m = a(E_{max})^{-b} \tag{3}$$

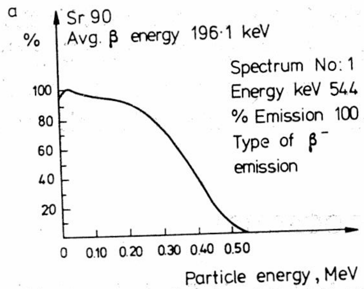
where μ_m is given in cm^2/mg, and E_{max} in MeV. The experimental values of a and b presented by different investigators vary considerably, as shown in table 1.

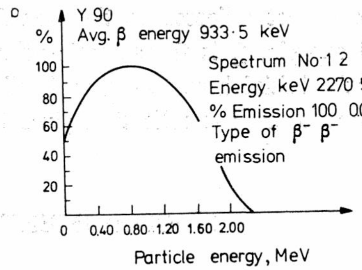
The energy distribution curves for ^{90}Sr and ^{90}Y are shown in figures 3a and 3b. Beta particles of these isotopes have relatively high energy i.e. higher than 1 MeV$\cdot$$^{14}C$ is the typical low energy beta source; the beta ray spectrum is shown in figure 3c.

Table 1

Values of the constants a and b for determining the mass absorption coefficient μ_m, given by various authors

Authors	a	b
Shumilovskii and Milttsen [14]	0.022	1.33
Evans [15]	0.017	1.14
Hart [16]	0.0151	1.50
Gleason, Taylor and Tabern [17]	0.017	1.43





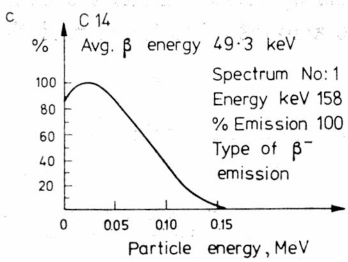


Fig. 3. The beta ray spectrum and average beta energy of: a) ^{90}Sr, b) ^{90}Y, c) ^{14}C

Rys. 3. Widmo promieniowania beta i średnia energia dla: a) ^{90}Sr, b) ^{90}Y, c) ^{14}C

The dust monitoring requires that the value of μ_m should be known they can be obtained experimentally. If for the certain dust μ_m is known then the attenuation of beta radiation is a functions of the absorber thickness. This be comes clear if the following equations are discussed

$$\frac{I}{I_0} = e^{-\mu_m x}, \tag{4}$$

$$\ln\frac{I}{I_0} = -\mu_m X, \tag{5}$$

$$X = \frac{1}{\mu_m}(\ln I_0 - \ln I), \tag{6}$$

$$m = F\cdot X = \frac{F}{\mu_m}(\ln I_0 - \ln I), \tag{7}$$

$$c = \frac{m}{V} = \frac{F\cdot X}{Q\cdot t_s} = \frac{F}{\mu_m Q t_s}(\ln I_0 - \ln I), \tag{8}$$

$$c = k(\ln I_0 - \ln I) \tag{9}$$

where k is constant equal to $\frac{F}{\mu_m Q t_s}$, X is the thickness of collected dust in mg/cm^2,

m is the mass of dust collected on the area F, c is the dust concentration, V is the volume of monitored sample, Q is the sampling flow rate and t_s is effective sampling time. The logarithm of the initial beta count, multiplied by a system constant substrated from the final beta count after dust collection gives the mass concentration of monitored sample.

3. EXPERIMENTAL PROCEDURE

The schematic diagram of the experimental setup is shown in fig. 4. A ZnS scintillation counter is used as a detector for beta radiatons.

A collimating system consisting of a bevelled steel aperture delimits the beam radiations incident on the crystal, thereby minimizing the amount of scattered radiation entering the detector.

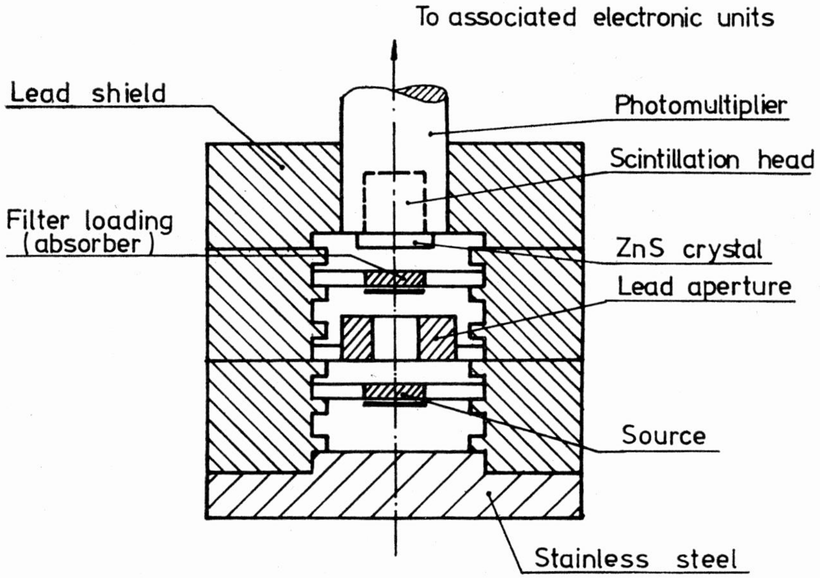


Fig. 4. Schematic diagram of the experimental arrangement

Rys. 4. Schemat części roboczej układu pomiarowego

The sources investigated are prepared in the form of thin pellets of diameter 15 mm.

The absorbers are made of various materials in form of thin discs of diameter 27 mm, whose thickness increase. In this work the absorption of beta radiations has been studied by using six absorbers of variable thickness. The absorbers are placed between the source and detector. The number of beta particles passed through the absorber is registered in a set up consising of a scintillator, photomultiplier, amplifier, discriminator and counter. This equipment is commercially available.

Beta sources of higher beta transition energies were chosen, because of their penetration ability necessary for higher dust concentrations. Some basic parameters of studied sources are presented in table 2.

Table 2

Parameters of studied sources

Isotope No.	Isotope compounds	Activity	Type of emission	Avg. energy keV
A	^{90}Sr	0.51 nCi	$\beta-$	196.1
	^{90}Sr		$\beta-$	933.5
	^{90}Y	7 nCi	$\beta-$	196.1
B	^{106}Ru	400 nCi	$\beta-$	40
	^{137}Cs	1.5 μCi	$\beta-$	510
	^{131}I	100 nCi	$\beta-$	600
C	^{89}Sr	210 nCi	$\beta-$ (γ)	1460
	^{144}Ce	260 nCi	$\beta-$	320

4. RESULTS AND DISCUSSION

Several experiments have been performed to test the validity of the exponential relationship of equation (4) and to determine experimentally the value of μ_m for different kinds of dust samples. The samples were collected on some stacks and tested in laboratory. Thicknesses of measured samples the ranged from 1 to 280 mg/cm^2.

The absorption curves of the beta particles emitted by three different sources: *A*, *B* and *C* are presented in figs 5–10. The results plotted in logarithm-natural coordinates

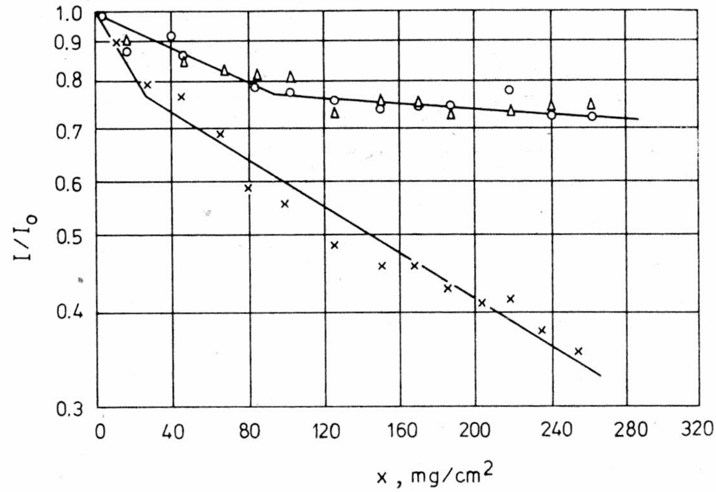


Fig. 5. Absorption curves of beta radiations for particulates emitted from A power station
× — isotope No. A, ○ — isotope No. B, △ — isotope No. C

Rys. 5. Krzywe absorpcji promieniowania beta dla pyłów emitowanych z elektrowni A

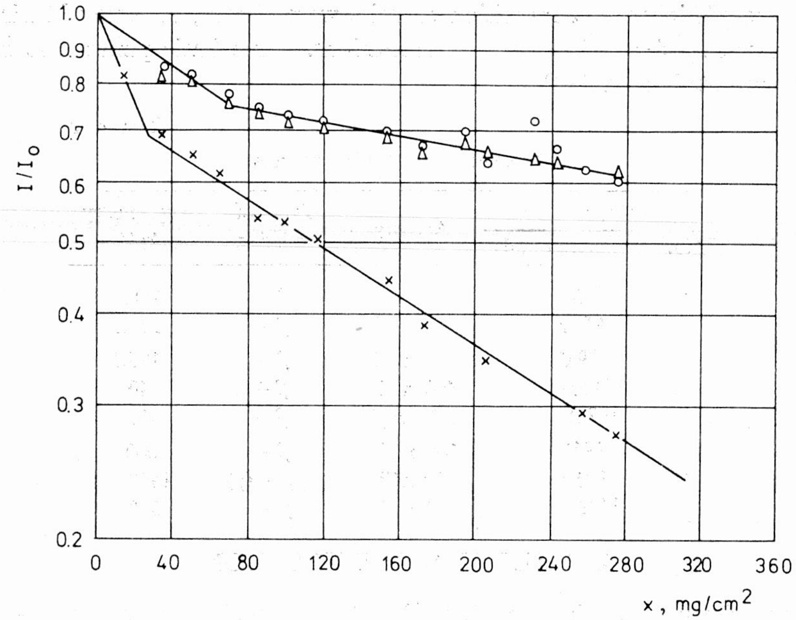


Fig. 6. Absorption curves of beta radiations for particulates emitted from B power station

× – isotope No. A, ○ – isotope No. B, △ – isotope No. C

Rys. 6. Krzywe absorpcji promieniowania beta dla pyłów emitowanych z elektrowni B

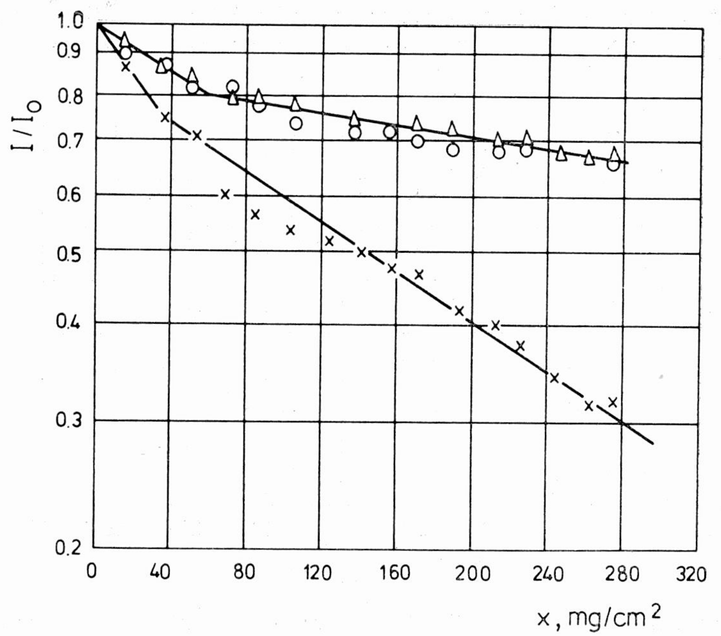


Fig. 7. Absorption curves of beta radiations for particulates emitted from C power station

Rys. 7. Krzywe absorpcji promieniowania beta dla pyłów emitowanych z elektrowni C

× – isotope No. A, ○ – isotope No. B, △ – isotope No. C

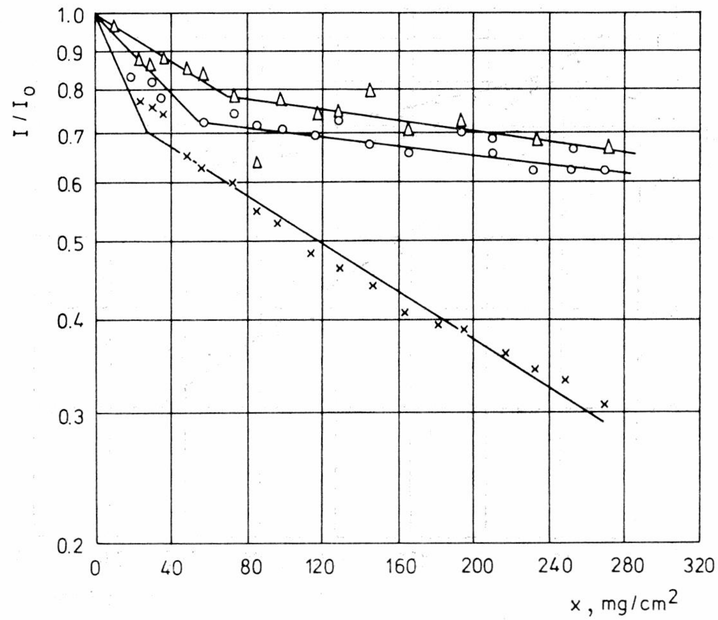


Fig. 8. Absorption curves of beta radiations for particulates emitted from the mine
× — isotope No. A, ○ — isotope No. B, △ — isotope No. C

Rys. 8. Krzywe absorpcji promieniowania beta dla pyłów emitowanych z kopalni

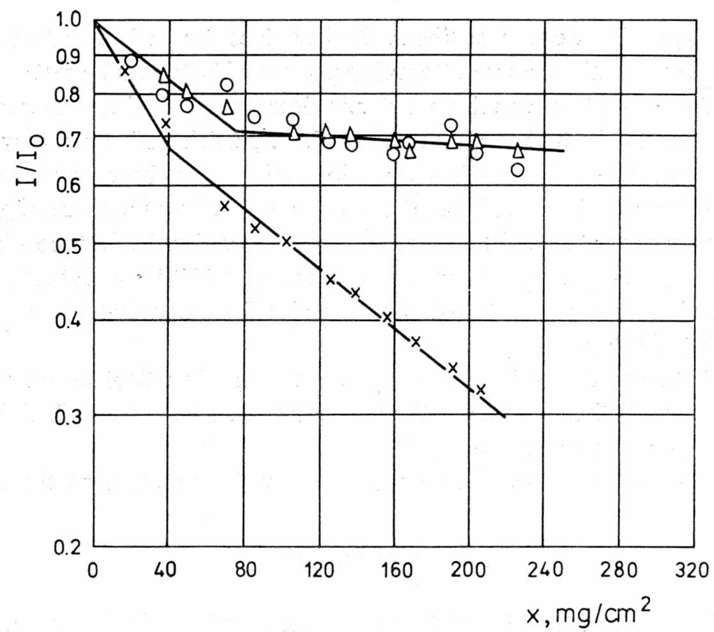


Fig. 9. Absorption curves of beta radiations for metallurgical cement
× — isotope No. A, ○ — isotope No. B, △ — isotope No. C

Rys. 9. Krzywe absorpcji promieniowania beta dla cementu hutniczego

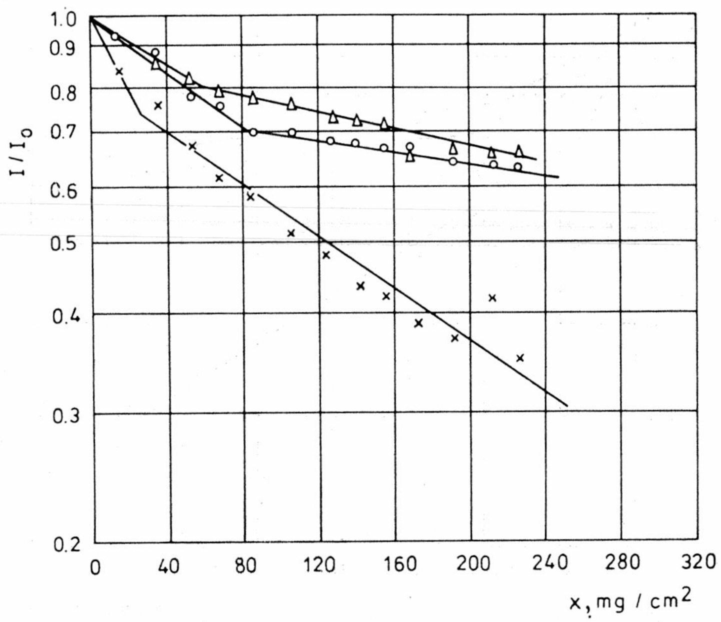


Fig. 10. Absorption curves of beta radiations for particulates of hydrated lime
× – isotope No. A, ○ – isotope No. B, △ – isotope No. C

Rys. 10. Krzywe absorpcji promieniowania beta dla wapna hydratyzowanego

show that two segments are almost linear. Broken lines for each tested sample are due to multicomponent radiation sources. Stopping powers of beta rays by tested dust samples is a function of energy of beta radiation. Rapid decrease in I values observed in smaller filter loading is due to the high energy loss of a beta particles of low energy (0.196 MeV for ^{90}Sr of isotope No. A). For lower energies ionization losses become significint.

In case of higher mass loading, beta attenuation (I/I_0) is lower because of good penetrability of higher energy beta particles, associated with ^{90}Y for the isotope No. C.

Each curve in figs 5–10 results from a different value of Z/A and beta ray energy spectrum. The stopping power of a tested dust samples for the $^{90}Sr+^{90}Y$ source is much higher than for the other ones.

Studies on beta ray absorption aimed at monitoring of particulate mass were performed with six kinds of filter loadings. Their densities are given in tab. 3. These absorbers were taken from air control devices.

The absorption of beta rays can be expressed by the equation to the equation (1):

$$\lg \frac{I}{I_0} = -\mu_m \varrho 1 \qquad (10)$$

in which ϱ is the density and l the thickness of the absorbing material. It may be assumed that the absorption coefficient is the sum of the stopping powers of all the atoms present in one gram of the absorbing material.

Table 3

Values of the density and the mass absorption coefficient of filter loadings

Particulate source	Density, mg/cm^3	Mass absorption coefficient in cm^2/g for source no. A	B	C
Plant (p.p.) A	2.0156	5.77	1.51	1.50
Plant B	2.3158	5.77	1.47	1.47
Plant C	2.0017	6.00	2.31	2.00
Coal mine	2.0775	6.00	2.31	1.93
Metallurgical cement	2.8186	4.95	1.85	1.86
Hydrated lime	2.2403	6.93	2.15	2.16

Results presented in figs. 5–10 allowed to obtain the values of μ_m and are given in tab. 3. The values of μ_m can also be found from the equation (3), because the maximum energy a beta particles (E_{max}) can be calculated from Flammersfeld's range--energy relation.

The total sensitivity of the instrument depends on the stability of the system and the statistical distribution. The sensitivity S, based only on statistical calculations using the 2σ error limit is given as follows:

$$S_{\min(2\sigma)} = \frac{2A}{\mu_m f t \sqrt{I}} \tag{11}$$

where t is the counting time, I — the detected count rate, A — the cross-section area of the collector, and f the absorbent mass. With A, μ_m, f and C fixed for a given instrumental design, the statistical sensitivity becomes a function of counting time alone, i.e.:

$$S_{\min(2\sigma)} \cdot t = K_0 . \tag{12}$$

Hence it is clear that statistical sensitivity increases with the counting time while the stability decreases.

5. CONCLUSIONS

The experimental measurements performed on six different absorbers and three types of beta ray sources support it follows that the beta attenuation dust detector rather is advantageous than the other ones.

Stopping powers of dust for beta particles can be determined in a straightforward way. There is simple relationship between the areosols concentration and stopping powers for all dust samples tested.

The data analysis indicates that I/I_0 is not a simple exponential function of particulate thickness density, therefore for every initial radiation intensity I_0 and for every individual filter loading calibration curves are different.

The sampling based on beta attenuation is the best method for continuous monitoring of suspended particles concentration in emitted gases. It may find wide application although it requires the calibration for individual source — particulates — geometry system.

REFERENCES

[1] Abib Husain S., Putman J. I., Proc. Phys. Soc. A., Vol. 70 (1957), p. 304.

[2] AISI Automatic Stack Monitor. Catalogue of Research Appliance Co., Allison Park, Pennsylvania 15101, USA.

[3] Catalogue of Kratel S. A., CH 1206 Geneve, 7 Avenue Engéne Pittard, Switzerland.

[4] Clapp C. W., Bernstein S., Elec. Eng., Vol. 69 (1950), p. 303.

[5] De Lingy C. L., Levering T., De Hoyer H., Recueil, Vol. 84 (1965), p. 503.

[6] Dresia H., Fischötter P., Felden G., VDI-Z, Vol. 106 (1964), p. 1191.

[7] Evans R. D., *The Atomic Nucleus*, Mc Graw-Hill, New York 1955.

[8] Gelman Stack Monitor. Catalogue of Gelman Instrument Co., P. O. Box 1448, Ann Arbor, Michigan 48106, USA.

[9] Gleason G. J., Taylor J. D., Tabern D. L., Nucleonics, Vol. 8 (1951), p. 1221.

[10] Hart H., *Radioactive Isotopes in Industrial Measuring Technology*, VEB Verlag Technik, Berlin 1962.

[11] Husar R. B., Atm. Env., Vol. 8 (1974), p. 183.

[12] Kuźmiński S., Szaynok A., Teisseyre M., Environm. Prot. Eng., Vol. 2 (1976), p. 21.

[13] Macias E. S., Husar R. B., *Review of Atmospheric Particulate Mass Measurement via the Beta Attenuation Technique*, Symposium on Fine Particles, Minneapolis, Minnesota, May 28–30, 1975.

[14] Nader J. S., Allen D. R., Am. Ind. Hyg. Assoc. J. ,Vol. 21 (1960), p. 300.

[15] Peterson J. H., Dovning J. R., J. Opt. Soc. Am., Vol. 41 (1951), p. 862.

[16] Saha N. K., Kaila K. L., Indian J. Phys., Vol. 32 (1958), p. 418.

[17] Shumilovskii N. N., Milttsen L. V., *Radioactive Isotopes in Instrumentation and Control*, Mac Millan Co., New York 1964.

KONTROLA ZAPYLENIA POWIETRZA ZA POMOCĄ DETEKTORA PROMIENIOWANIA β

W niniejszej pracy scharakteryzowano promieniowanie β oraz przedstawiono przyrządy do pomiaru stężenia zapylenia gazu z wykorzystaniem własności tego promieniowania. Przeprowadzono pomiary absorpcji promieniowania β o różnych energiach. Wyznaczono masowy współczynnik absorpcji dla poszczególnych rodzajów pyłów i ustalono zależność między ilością pochłanianych cząstek β a stężeniem pyłu.

We wnioskach stwierdzono, że istnieje możliwość zastosowania metody radiometrycznej do pomiaru ilości atmosferycznych aerozoli zawieszonych w otaczającym powietrzu lub usuwanych drogą filtracji.

KONTROLLE DER LUFTVERSTAUBUNG MIT HILFE EINES BETA-STRAHLEN-DETEKTORS

Im Beitrag wird die Beta-Strahlung selbst sowie ein Gerät das diese Strahlung zur Messung des Staubgehaltes in Abgasen ausnutzt eingehend besprochen. Durchgeführt wurden Absorptions-Messungen der Beta-Strahlung verschiedener Energie. Bestimmt wurde der Massen-Koeffizient der Absorption für verschiedene Staubarten; festgelegt wurde das Verhältnis zwischen den absorbierten Mengen von Beta-Partikeln und der Staubkonzentration.

Die Möglichkeit der Anwendung dieser radiometrischen Methode zur Messung der in der Luft enthaltenen Aerosolen und deren Entzug mittels Filtration wird in den Folgerungen dargelegt.

КОНТРОЛЬ ЗАПЫЛЕННОСТИ ВОЗДУХА С ПОМОЩЬЮ ПРИЕМНИКА БЕТА-ИЗЛУЧЕНИЯ

В работе охарактеризовано бета-излучение и представлены приборы для измерения запыленности газа с использованием свойств этого излучения. Проведены измерения поглощения бета--узлучения с разной энергией. Определен массовый коэффициент поглощения для отдельных видов пылей и установлена зависимость между количеством поглощаемых бета-частиц и концентрацией пыли. Отмечена возможность применения радиометрического метода для измерения количества атмосферных аэрозолей, суспендированных в окружающем воздухе или удаляемых путем фильтрования.