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ATMOSPHERIC POLLUTION
by Jan Juda and Karol Budzinski
- Poland -

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ATMOSPHERIC POLLUTION

- Poland -

[Following is a translation of the Polish-language book entitled Zanieczyszczenia Atmosfery (English version above) by Dr. Inz. Jan Juda and Mgr. Inz. Karol Budzinski, published by Wydawnictwa Naukowo-Techniczne, Warsaw, 1961, pp 1-256]

The book contains information about the sources, dispersion and investigation of atmospheric pollutants. Results of studies from foreign sources are given, and an attempt is made to analyze these data in the light of conditions prevailing in Poland.

The work is intended for the engineers who plan industrial plants and supervise the operation of machinery and industrial installations, as well as for the safety and work hygiene service employees.

Consultants:

Magister Inżynier Jacek Janosak and Mr. Feliks Sekuradski

Technical editor

E. Flacko

Technical proofreaders:

M. Daszewska and M. Reginska

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PART ONE

GENERAL INFORMATION

Chapter I

Systematic Classification of Atmospheric Pollutants

1. Introductory remarks

The problem of atmospheric and water pollution is inextricably bound with the development of humanity. However, it was not particularly grave during numerous centuries, since the amount of contamination produced by man was relatively small.

The danger of water pollution was recognized quite early because of the diseases and epidemics spread by water, but it took centuries to recognize the danger and harm inherent in a polluted atmosphere.

The problem of atmospheric pollution was dealt with by Vitruvius in his work written between year 23 and 27 B.C. Writing on the subject of planning urban settlements, he recommended: "First comes the choice of a very healthy site. Such a site will be high, neither misty nor frosty, and in a climate neither hot nor cold, but temperate; further, without marshes in the neighbourhood. For when the morning breezes blow toward the town at sunrise, if they bring with them mists from marshes and, mingled with the mist, the poisonous breath of the creatures of the marshes to be wafted into the bodies of the inhabitants, they will make the site unhealthy."

In the 13th century, the sitting of the British Parliament was transferred from London to Nottingham because of air pollution in London, and King Edward I issued a proclamation forbidding the use of coal fuel in London during the sitting of the Parliament.

The first book dealing with the harmful effect of metal dusts and vapors in the air was published in 1524 (I.6). A prize of 30 guineas or a gold medal was established in England in 1795 for the most effective method of abating fumes issuing from forges and factories (I.4).

During the last few decades, the problem of abating atmospheric pollution has assumed enormous importance, mainly for the following two reasons:

1. Increase in the number of types and sources of atmospheric pollution as a result of an explosive development of industry and transportation;

2. Concentration in industrial districts of the sources of pollution and high population densities over small areas.

This led to the necessity of dealing with the problem not only by the individual countries, but also by international organizations. It was resolved at the 1954 World Health Organization Congress in Milan that "atmospheric pollution is a complex problem which should be dealt with by all countries, including those in which this problem is a new one" (1.9).

One could risk the statement that the problems connected with atmospheric pollution at present constitute a separate science consisting of a number of specialized branches. The degree of the Master of Air Pollution is granted by five American universities (Harvard, Rutgers, California, Cincinnati and Florida). Bibliography on the subject consists of 10,000 entries, and there are several hundred scientific and industrial centers throughout the world where the problem is being studied.

2. Definition of atmospheric pollutants

The concept of pollution presupposes the existence of pure substance. Therefore, when we speak of atmospheric pollution, we must first define the composition of pure atmospheric air. The average composition of air relating to its constant components is given in Table I,1. (0.14).

The composition given in the Table relates only to the troposphere which extends to a height of 13 kilometers above the Earth's surface. A gravitational partition is evident in the higher levels of the atmosphere, but the differences in the percentage of the individual components are minimal, being of the order of 0.008%.

It should be further explained that although the composition of pure air is accepted as constant, certain perceptible changes in it are beginning to take place as a result of pollution. For instance, the average CO₂ content has increased during the last 50 years by 30 ppm (0.14). Given the mass of the atmosphere estimated at 4.5×10^{15} tons, this means an increase of the CO₂ content by 1.35×10^{11} tons.

Table I,1

Average composition of pure atmospheric air

Component	Contents in parts per million (ppm)	
	By volume	By weight
Nitrogen N ₂	780,900	755,400
Oxygen O ₂	209,500	231,500
Argon A	9,300	12,800
Carbon dioxide CO ₂	300	460
Neon Ne	28	12.5
Helium, He	5.2	0.72
Methane, CH ₄	2.2	1.2
Krypton, Kr	1.0	2.9
Nitrous oxide, N ₂ O	1.0	1.5
Hydrogen, H ₂	0.5	0.05
Xenon, Xe	0.08	0.36

The average composition of the air shown in Table I,1 is regarded as the standard with which all the components regarded as impurities are compared.

In addition to the constant components, the air contains a number of other components which are emitted into the atmosphere as a result of the natural or human activities (water, water vapor, dust, pollen, bacteria, salts, gases such as CO, SO₂, SO₃, He, HF, H₂S, O₃, NO₂, NH₃, etc.). The concentrations of these components are widely variable in time and place. As a rule, all these substances are regarded as contaminants. However, an increase in the concentration of a constant component of the air above the average value is also regarded as pollution.

Consequently, atmospheric pollution is defined as the presence of any solid, liquid or gaseous substances whose concentration in the air exceeds the average concentration of these substances in pure air.

3. Systematic classification of dusts and mists

In the discussion of the problems connected with atmospheric pollution, most numerous misunderstandings arise from the methods of defining dusts. In order to define a dust accurately, it is necessary to take into account its following characteristics:

1. Method of dispersion;

2. Degree of disintegration of the disperse phase;

3. Its form and origin.

Dusts and mists belong to two-phase systems. The component present in larger amount is called the dispersion medium, while the other component forms the disperse phase.

Both the dispersion medium and the disperse phase can be in the solid, liquid or gaseous form. Therefore, there are nine possible two-component systems. These are shown in Table 1,2 (after Ostwald (0.20)). (Note: A general bibliography is included at the end of the book).

In problems connected with atmospheric pollution, we deal only with systems No 3, 6, and 9. A three-component system: solid and liquid in gas occurs quite frequently in the atmosphere. In the technical literature, this system is usually referred to as aerosol.

The next basis for the classification of two-component systems is the degree of disintegration of the disperse phase. In order to avoid confusion, it has been accepted after J. Giborowski (0.9) to use the terms granule and droplet respectively for the solid and liquid elements of the disperse phase.

Three degrees of disintegration are distinguished in the classification of colloids: mechanical, colloidal and molecular.

Before a systematic classification of dusts and mists is set up, it is necessary to establish the upper limit of granule or droplet size below which a two-phase system can be regarded as a dust or a mist. However, the establishment of a rigid limit is very difficult, particularly with regard to liquids. The generally accepted limit is the size of a particle whose rate of fall in still air is constant. However, the rate of fall depends not only on the particle size, but also on its specific gravity, shape and surface properties. For this reason, there are substantial differences in the upper size limit, which is generally accepted to lie between 60 μ (0.14) and 1,000 μ (1.3). Haldau (0.16) proposes the following division: 1) $> 500 \mu$ -- coarse particulates; 2) 500 - 100 μ -- medium dust; 3) 100 - 5 μ -- fine dust; 4) 5 μ -- very fine dust. This division has been partly taken into account in the classification of dusts adopted in the present work.

The basic criterion in dividing two-component systems into those mechanically and colloiddally disintegrated is the behavior of the granules (droplets) in still air. The essential information is

Table I,2

Division of two-component systems depending on the state of the disperse phase and the dispersing medium

No	Disperse phase	Dispersing medium	Name	Examples
1.	Solid	Solid	--	Ground coal or ore with combustible rock. muds, crystals with occluded water.
2.	Liquid	Solid	mud	
3.	Gas	Solid	Dust, solid foam	
4.	Solid	Liquid	Colloidal suspension	Suspensions in sedimentation processes.
5.	Liquid	Liquid	Colloidal emulsion	
6.	Gas	Liquid	Foam	
7.	Solid	Gas	Dust	Fog, condensing vapor, clouds.
8.	Liquid	Gas	Mist	
9.	Gas	Gas	Mixture of gases	Combustion fumes, industrial gases.

whether the granules (droplets) settle down at a uniform rate, or whether they exhibit the Brownian motion. However, the assignment of a rigid particle size limit in this case is even more difficult than in the previous one. The Brownian motion in the air can be exhibited by particles or droplets as large as 5μ , while it is certainly exhibited by all particles 0.1μ in diameter. W. Ostwald (0.20)

proposes the granule (droplet) diameter of 0.5μ as the dividing line between mechanical and colloidal dispersions, Corres (I,1) proposes a particle size of 0.2μ , Buckup and Schmidt, 2μ , and the French sources (O.22), a diameter of 5μ . J. L. Eichborn (I,2) suggests that two-component systems composed of particles (droplets) $< 5 \mu$ in diameter be called aerosols, those having diameters of $5 - 50 \mu$ coarse aerosols, and that the term suspension be applied to systems composed of still larger particles.

V. M. Alekseyeva (O.1) defines a dust as being a two-phase system having particles larger than 0.1μ in diameter, and an aerosol as a solid-gas or liquid-gas system composed of granules or droplets smaller than 0.1μ .

The properties of dusts and their behavior in the air also depend on their origin or form. This gave rise to numerous additional definitions aiming at more precise description of the properties of dusts.

N. A. Fuks (O.11) proposes a general division of aerosols into dispersion and condensation types. Dispersion aerosols are formed as a result of the disintegration of particles larger than 500μ and their dispersion in a gaseous medium, while condensation aerosols are formed as a result of the condensation or solidification of vapors. The particles of dispersion aerosols are irregular in shape, while those of condensation aerosols are spherical. Fuks divided all aerosols into three groups regardless of their particle size: 1) dust — a dispersion aerosol with solid disperse phase; 2) smoke — a condensation aerosol with a solid disperse phase; 3) mist — a dispersion or condensation aerosol with a liquid disperse phase.

The combination of the above characteristics of two-phase systems has resulted in a number of descriptions, such as aerosol, industrial aerosol, transportation aerosol, fly cokes, fly ash, house dust, smoke, mist, cloud, fog, etc. However, these are differently defined by the various authors which, together with the colloquial meaning of some of these words, leads to frequent misunderstandings. Furthermore, there are many terms in the foreign literature which have no equivalents in Polish.

We shall define a dust as a solid-gas two-component system if the degree of disintegration of the solid component is so great that its particles will settle at a uniform rate after a brief period of acceleration as a result of flow resistance, or be subject to the Brownian motion in still air and under NTP (760 mm Hg and 20°C) if subject only to the force of gravity.

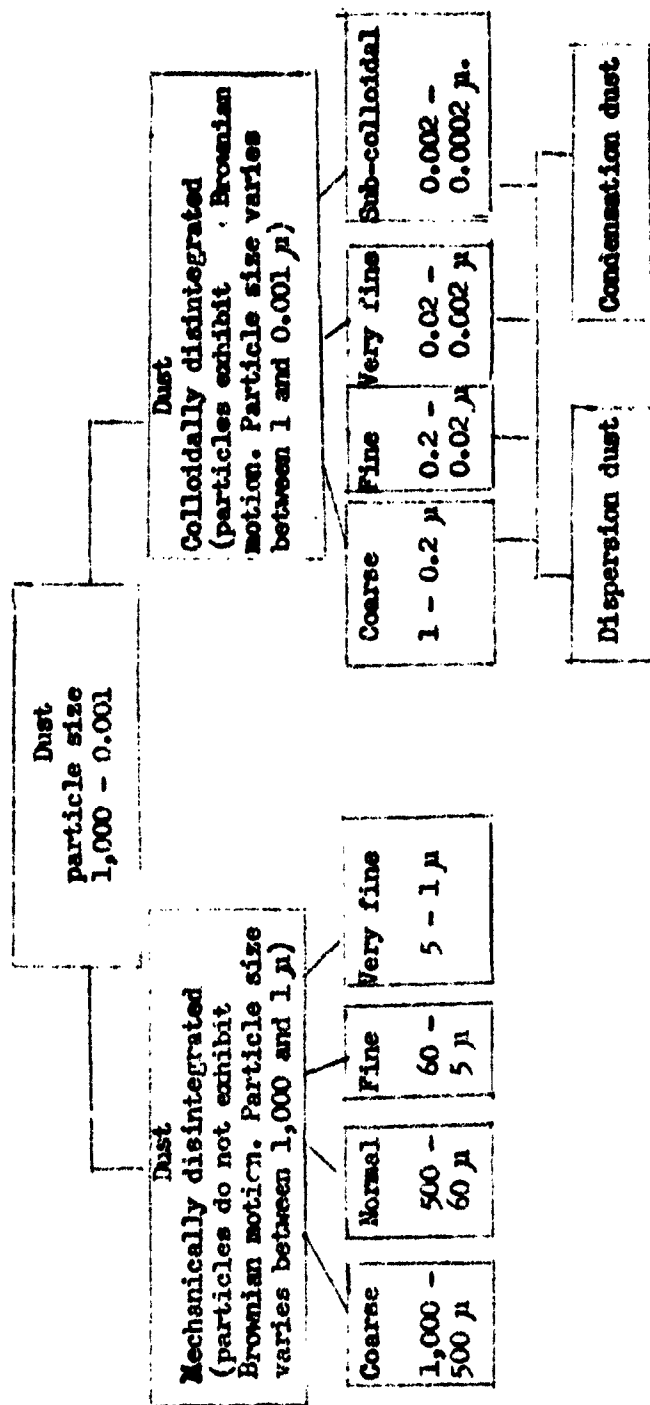


Fig. 1,1. A schematic representation of the classification of dusts

Table 1,3

The names of two-phase systems used in Russian, English, French and German literature

Name according to the adopted classification	Name in the foreign language	Definition	Granule (droplet) size range
Mechanically disintegrated dust	pyl. dust poussière Staub	A two-phase system with a solid disperse phase, most frequently of mechanical disintegration and dispersion.	Particle size mainly 1 - 500 μ . Up to 50 μ according to L. Silverman (0.14); > 10 μ according to Gibbs (0.14); > 5 μ according to Green and Lane (0.12); > 1 μ according to W. L. Faith (0.12); > 0.5 μ acc. to Katz (0.14); 0.1 μ acc. to Alekseyeva (0.1); > 10 μ acc. to Kurakov (1.6).
Mechanically disintegrated dust	— spray fly ash —	A two-phase system with a solid disperse phase. Term usually applied to coke, coal and ash particles carried with combustion gases.	> 10 μ
Dispersion or condensation colloidal dust	dym smoke fumée de combustion Rauch	Mainly a two-phase system derived from the combustion of fuels, having a solid disperse phase. L. Silverman (0.14) uses this definition also to describe three-component systems with solid and liquid disperse phases derived from other chemical reactions besides	Particle size mainly < 1 μ . This size is accepted also by W. L. Faith (0.10); < 0.5 μ according to L. Drinker and Hatch (0.8) and Silverman (0.14); < 0.1 μ according to Gibbs (0.14); < 5 μ according to Green and Lane (0.12).

Table I,3 (continued)

Name according to the adopted classification	Name in the foreign language	Definition	Granule (droplet size range
Colloidal condensation dust	fume fumee metallurgique Rauch-dampf Dust	Mainly a two-phase condensation system derived from chemical and metallurgical processes and not from combustion in boilers and internal combustion engines. In some cases, a three-component aerosol.	Particle size mainly $< 1 \mu$ according to Katz (0.14). Particle size can be up to 100μ when referring to metallurgical processes.
Mist (mechanically disintegrated)	tuman mist bruine "bel	A two-phase system with a liquid disperse phase.	Droplet size $500 - 40 \mu$. In English and French literature (0.22), droplet size greater than 40μ .
Mist	fog brouillard brume —	A two-phase system with a liquid disperse phase.	Droplet size 40μ . In French literature (0.22) brouillard corresponds to particle size between 5 and 40μ , while the term brume is used for droplet sizes $< 5 \mu$.
Inversion mist	— smog, haze smog Rauchnebel	A three-component system with a solid and a liquid in the disperse phase.	Particle size mainly $< 5 \mu$, droplet size $< 40 \mu$. The original English word "smog" is used in French. The word "haze" is used rather infrequently.

Table I,4

Particle size range of aerosols

Name according to the adopted classification	Type of aerosol	Particle or droplet size in μ .
Mists and fogs	Rain drops	5000-500
	Mist H ₂ O	500-40
	Fog H ₂ O	40-1
	H ₂ SO ₄ mist	10-1
	SO ₃ mist	3-0.5
Mechanical dusts	Foundry sand	2000-200
	Chemical fertilisers	800-30
	Flotation tailings	400-20
	Coal dust	400-10
	Sifted foundry sand	200-4
	Ore before flotation	200-4
	Cement	150-10
	Fly-ash	80-3
	Pigments	8-1
	Pollen	60-20
	Spores	30-10
	Bacteria	15-1
Colloidal dispersion dusts	Fuel oil combustion products	1-0.03
	Rosin combustion prod.	1-0.01
	Tobacco combustion products	0.15-0.01
	Coal combustion products (soot)	0.2-0.01
Colloidal condensation dusts	Oxidation of bases	2-0.1
	NH ₄ Cl fumes	2-0.1
	Zinc oxides	0.3-0.03

The present work makes use of the classification of dusts introduced by J. Juda (0.13) and shown in Fig. I,1.

The fact that the particles exhibit the Brownian motion has been taken as the basis for dividing dusts into mechanically or colloidally disintegrated, and a diameter of $1\ \mu$ has been arbitrarily chosen as the limiting particle size. The additional division into dispersion and condensation dusts has been introduced only for colloidal dusts since, as a rule, condensation dusts are not present in the particle size range of mechanically disintegrated particulates.

The definition of mist or fog is similar to that of dust, with the difference that it is a liquid-gas, two-component system.

In order to facilitate the reader's use of the foreign literature, and to introduce a degree of the unity into the data obtained by the present authors from foreign sources, Table I,3 presents the terms for various types of dusts and mists. Among those used in the foreign literature, the terms "fume", "fog" and "smog" have no equivalents in Polish. The first two can be included in the proposed systematisation fairly easily. The term "smog" arose in England and was adopted in the United States specifically to describe phenomena arising in London and Los Angeles where a potent fog containing a high concentration of solid pollutants and toxic gases, especially the sulfur compounds, is formed as a result of inversion (see Chapter V).

In some cases, where the description given is general in nature, continued use will be made of the term "smoke" in the general sense of colloidal or condensation dispersion dust (soot) formed in the process of fuel combustion. The dispersion medium in this case consists of the gaseous products of combustion.

As an illustration of the size range of the individual types of two-phase systems encountered in science and technology, Table I, 4 gives their limiting granule (droplet) sizes according to M. Katz (0.14).

4. Characteristic parameters of atmospheric pollutants

The basic parameter characterizing a given impurity is its concentration S , i.e., the ratio of the amount of impurity to that of the air:

$$S = \frac{\text{amount of component considered as an impurity}}{\text{amount of air}}$$

The units in which the pollutant concentrations are expressed will be those used to express the amounts of the given component per unit amount of pure air.

In the case of dusts, the pollutant concentration is expressed as

$$S_p = \frac{\text{amount of the disperse phase}}{\text{volume of the dispersing medium (air)}}$$

Depending on the measuring instrument used and the aim of the measurement, the dust concentration can be expressed as:

1. The number of particles of the disperse phase per unit volume of air (unit symbol $2/\text{cm}^3$);
2. The weight of the disperse phase particles per unit volume of air (unit symbols g/Nm^3 , g/m^3 , mg/m^3 , $\mu\text{g}/\text{m}^3$).

Since the dust concentration in the air varies sharply with time, the index of dust concentration over long periods of time is frequently measured in terms of dust fallout O_p , which is defined as follows:

O_p is the amount of dust settling on unit area in unit time, e.g.: g/m^2 per day, kg/a per month, or T/km^2 per year.

The relationship between these units is shown in Table I,5.

Table I,5

Relationship between dust sedimentation units O_p

① Jednostka	G/m^2 i dzień ②	kg/a i mies. ③	T/km^2 i rok ④
G/m^2 i dzień ②	1	3	$3,6 \cdot 10^3$
kg/a i mies. ③	0,333	1	$1,2 \cdot 10^3$
T/km^2 i rok ④	$0,278 \cdot 10^{-3}$	$0,833 \cdot 10^{-3}$	1

Legend: 1. Unit; 2. Day; 3. Month; 4. Year.

The concentration of gaseous pollutants is usually expressed as the ratio of the amount of the component considered to be a pollutant to the volume of air. In view of the rather small volumes of pollutants usually involved, the concentration of gaseous pollutants is expressed as

$$S_g = \frac{\text{volume of pollutant in cm}^3 \text{ or mm}^3}{\text{volume of air in m}^3}$$

Therefore, the units are either cm^3/m^3 or mm^3/m^3 . Since the ratio of cm^3 to m^3 is one millionth, and that of mm^3 to m^3 one milliard, use is made in foreign literature of the abbreviations ppm (parts per million) and ppmm (parts per milliard). The concentration of gaseous pollutants can be expressed in a manner similar to that used in the case of solid pollutants:

$$S_g = \frac{\text{Weight of pollutant in } \text{m}^3 \text{ or } \text{dm}^3}{\text{volume of air in } \text{m}^3 \text{ or } \text{dm}^3}$$

The symbols then have the form: mg/m^3 , $\mu\text{g}/\text{m}^3$, or mg/dm^3 . Taking into account the densities of the individual gases, we obtain the relationships between the concentrations expressed in different units, as shown in Table I,6.

Table I,6

Relationship between gaseous pollutant units

Type of gas (name and formula)	Specific gravity kg/m^3	Concentration $1 \text{ cm}^3/\text{m}^3 - 1 \text{ ppm}$ corresponds to the number of mg/m^3	Concentration of $1 \text{ mg}/\text{m}^3$ corresponds to the number of $\text{cm}^3/\text{m}^3 - 1 \text{ ppm}$
Ammonia NH_3	0.7714	0.77	1.30
Hydrogen Chloride HCl	1.6391	1.64	0.61
Nitric oxide NO	1.448	1.45	0.68
Sulfur dioxide SO_2	2.927	2.93	0.34
Carbon dioxide CO_2	1.9768	1.98	0.50
Hydrogen fluoride HF	0.987	0.99	1.02
Nitrous oxide NO	1.226	1.23	0.81
Carbon monoxide CO	1.25	1.25	0.8

Inlet-concentration U is the amount of pollutants formed in the course of technological processes which is carried from the source to the purification installations.

U is the amount of pollutants carried from the source of formation, in kg/hr , ton/hr , kg/ton of production, percent of production, or m^3/hr , or m^3/ton of production.

* also conveyance or transport.

Emission E is the amount of pollutants emitted into the atmosphere after passage through the purification installation.

E is the amount of pollutants emitted into the atmosphere in kg/hr, ton/hr and kg/ton of production, percent of production or m³/hr, m³/ ton of production.

5. Characteristic air pollutants

The number of pollutants which can be present in the air is extremely large. The Standard Specifications dealing with the maximum permissible concentrations of gaseous pollutants in places of work comprise 261 positions, while the dust and mist pollutants occupy 164 positions. Obviously, all the pollutants generated in places of work can be emitted into the atmosphere.

For technical and organisational reasons, and because of the limited range and sensitivity of the measuring instruments, it is impossible to conduct systematic measurements of the concentrations of all the pollutants. Therefore, it was necessary to limit the scope of measurements to those pollutants which are commonly present in industrial regions, and which are encountered in sufficiently great concentrations to enable them to be measured accurately. These pollutants received the name of characteristic air pollutants.

Among the characteristic pollutants we include dusts, and the oxides of carbon and sulfur, the oxides of nitrogen and 3,4-benzpyrene having been added in recent years. Constant and systematic measurements of these pollutants are being done throughout the world. Of course, in the individual cases these measurements are extended to cover other pollutants, especially in the neighborhood of plants emitting particularly toxic substances such as CS_2 .

Emission of dusts into the atmosphere is inextricably tied with industrial processes. For this reason, both the concentration and sedimentation of dusts are very characteristic parameters of atmospheric pollution. The chemical and mineralogical composition of powders is determined in addition to the measurement of their concentration.

The oxides of carbon are among the most common air contaminants.

In accordance with the preceding definition, carbon dioxide CO_2 is considered to be a pollutant when its concentration exceeds the value of $300 \text{ cm}^3/\text{m}^3$ of air. CO_2 is produced in all combustion processes, and the amount of CO_2 produced in 1951 as a result of fuel combustion to generate energy is estimated at 7×10^9 tons. The concentration of CO_2 in industrial districts is frequently greater than $600 \text{ cm}^3/\text{m}^3$.

Carbon dioxide is not toxic, and its concentration in the air is not controlled by any regulations (apart from the general hygienic considerations), but the results of the measurement of its concentration in the air contain information about the general state of atmospheric pollution. This is due to the following reasons:

1. In all industrial processes, emission of CO_2 is accompanied by the emission of other pollutants, usually in known proportions;

2. Carbon dioxide is heavier than air, and is therefore more difficult to disperse in the atmosphere;

3. Quantitatively, CO_2 holds the first place among the contaminants emitted into the atmosphere;

4. The concentrations of CO_2 in the air are so great, that it is possible to measure them with considerable accuracy.

For these reasons, the CO_2 content in the air can be regarded as a relative measure of the degree of air pollution.

Carbon monoxide CO is the product of incomplete combustion, and accompanies all the combustion processes to a greater or lesser degree. It is strongly toxic, but in view of its specific gravity of 1.25 kg/m^3 (a relative density of 0.9669) it rapidly disperses in the atmosphere. The concentration of CO in industrial centers and large cities may exceed $55 \text{ cm}^3/\text{m}^3$.

As a rule, all fuels contain sulfur or its compounds which yield SO_2 in the course of combustion (sulfurous acid anhydride, a gas having a specific gravity of 2.9263 kg/m^3 , and a relative density of 2.2635). It is very toxic, and disperses slowly in the atmosphere. Sulfur dioxide can become oxidized in the air to sulfur trioxide SO_3 (sulfuric acid anhydride), which yields sulfuric acid on reacting with atmospheric moisture. In the air, sulfuric acid forms a mist whose droplets combine with droplets of water and settle on the surface of solid particles. The concentration of sulfuric acid in industrial areas may exceed $10 \text{ cm}^3/\text{m}^3$.

At high temperatures present in combustion processes, atmospheric nitrogen is oxidized to nitrous oxide: $\text{N}_2 + \text{O}_2 = 2\text{NO}$. At lower temperatures, nitrous oxide converts to nitric oxide in accordance with the equation: $2\text{NO} + \text{O}_2 = 2\text{NO}_2$, and is usually emitted into the atmosphere in this form. The concentration of NO_2 in combustion fumes may reach from 100 to $1,500 \text{ mg/cm}^3$.

Nitric oxide is strongly toxic, and is considered to be one of the reasons for the Los Angeles smog. For this reason, it is recommended in the United States to consider it as a characteristic pollutant (0.14).

Small amounts of aromatic hydrocarbons, and especially 3,4-benz pyrene, are produced in the process of combustion. The latter is in the form of colloidal crystals which are usually adsorbed on

other dusts. This compound has been regarded in recent years as one of carcinogens. Although there is still no exact evidence to show that the concentrations of 3,4-benzpyrene presently encountered in the atmosphere can cause lung cancer in humans, there is a high degree of probability that it is so. For this reason, the systematic measurements also include 3,4-benzpyrene. Its concentrations in industrial districts may exceed 0.40 $\mu\text{g}/\text{m}^3$.

In addition to research into the pollution of the atmosphere with dusts and gases, systematic measurements of radioactivity in the atmosphere have recently been instituted, including the total level of radioactivity, as well as pollution with radioactive dusts.

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Chapter II

Sources of Atmospheric Pollutants

1. Systematic classification of the sources of atmospheric pollutants

The sources of atmospheric pollutants are extremely numerous and varied. Generally, they can be divided into natural sources inherent in the activity of nature, and artificial sources resulting from the activity of man.

The classification of the sources of pollutants is given in Fig. II,1. Although the amounts of pollutants from the natural sources are substantial, they are not very significant under the conditions prevailing in Poland and, therefore, they will be discussed only in general terms.

2. Natural sources of atmospheric contaminants

The main sources of natural air pollutants are the eruptions of volcanoes, forest and prairie fires, and the decomposition of organic matter.

Dusts originating from natural sources are divided into three groups: cosmic, inorganic and organic. The source of cosmic dusts lies in numerous comets which, upon entering into the solar system, partly evaporate as a result of increased temperature, and then solidify forming condensation dusts. The amount of cosmic dust settling on the Earth is variously estimated to be between 10^3 tons (0.15) and 3.7×10^6 tons (0.10) per year. These amounts are so small in comparison with other sources of pollutants, that their influence on pollution can be ignored.

Natural inorganic dusts are formed as a result of atmospheric activity, eruption of volcanoes, forest and prairie fires, etc. Temperature differences between night and day, which in the desert regions can amount to 80°C , and the action of precipitation cause the crumbling of the Earth's surface to the point of very fine dusts. These dusts are borne upwards by the winds and carried over long distances from their places of origin. For instance, the settling of the Sahara dust causes considerable damage in Sicily, and is observed as far away as the Azores. According to W. Rupp (c.14) the amount of

dust produced as the result of atmospheric action in the USA alone is 30×10^6 tons yearly. It follows from the data for the USA that the total pollution of air by natural inorganic dusts may be even greater than that caused by artificial dusts.

The formation of natural dusts represents a danger not only because of atmospheric pollution, but it can also cause deterioration of large areas of tillable land whose upper layers are blown by the winds into the atmosphere. However, measures aimed at preventing these losses enter the scope of land improvement planning (planting of protective woodland belts, irrigation, etc.).

Exceptionally large amounts of dust are formed in volcanic eruptions. As a result of the eruption of Krakatau in 1883, a surface area equal to $327,000 \text{ km}^2$ was covered with a layer of dust 60 mm thick. Fine dust from this eruption floated in the atmosphere for a number of years following the event. Also of volcanic origin was the substantial dust sedimentation recorded in 1909 in Central and Southern Europe. The amount settling over Italy was estimated at 141×10^3 tons, while that settling over Austria was estimated at 375×10^3 tons. How fast and far the volcanic dust can spread is illustrated by an occurrence described by G. H. Bull and D. G. James (II,4). On 3 April 1956 an aerial patrol reported a dust cloud 15 kilometers above south-west England. It was shown that the dust originated in a volcanic eruption in Kamchatka on 30 March 1956.

The amounts of dust formed in major volcanic eruptions are estimated as follows: Tambora (1825)— 150×10^9 tons, Cosseguina in Nicaragua (1835)— 50×10^9 tons, Krakatau (1883)— 18×10^9 tons, Katami in Alaska (1912)— 20×10^9 tons (0.10). While the dust clouds resulting from the eruptions of Vesuvius reached a height of only 1,000 m, the cloud formed during the eruption of Krakatau rose to a height of 50 kilometers.

Equally large amounts of dust are formed by forest fires. After a forest fire around Lake Michigan, dust fallout from this fire was observed in Africa.

Sea storms are also a source of dust pollutants. After a violent storm off the shores of England on 22 December 1894 (0.10), lands situated between 60 and 70 miles from the coastline were covered with a visible layer of salt. The presence of salt particles in the air is observed up to 1,000 kilometers from the sea coast, but their number does not exceed one or two per cubic centimeter of air.

Part of the airborne dust is of organic origin. By analogy with sea plankton, W. Feet proposes to call it aeroplankton (0.10). This consists of living organisms (bacteria), as well as organic

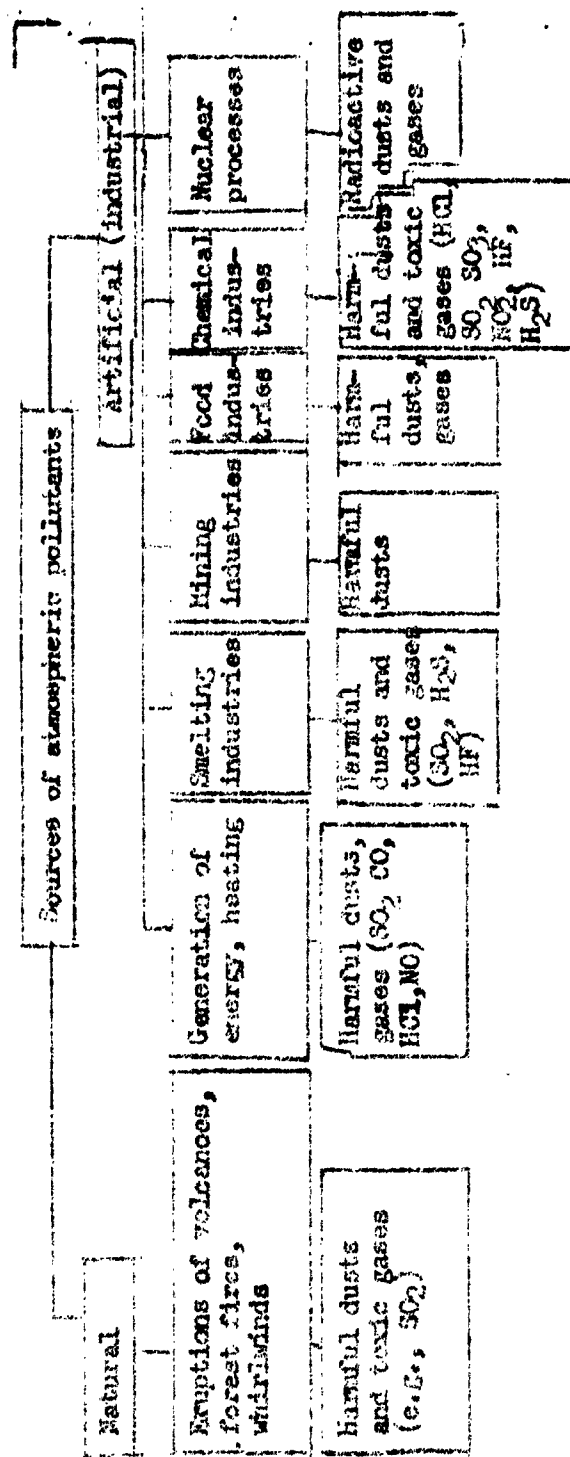


Fig. II, 1. A schematic classification of the sources of atmospheric pollutants

dust consisting of pollen and spores.

Particularly large concentrations of bacteria are observed in large cities. Thus in Paris the air contains 4,790 bacteria per cubic meter, as against 345 bacteria per cubic meter in rural districts.

Spores are lifted into the air very easily, and they remain there for long periods of time. Their presence is detected at altitudes up to 6,000 meters, and they can be borne by winds over distances of several hundred kilometers. W. A. Rupp (O.14) estimates the amount of vegetable dusts in the USA at 10⁶ tons annually. In some areas the pollution of air by pollen dusts is so great that transportation difficulties are encountered on this account. In the forest districts of British Columbia electric locomotives and motor vehicles are damaged because of it.

It is considerably more difficult to estimate the amount of gaseous pollutants emitted by natural sources.

Volcanic eruptions are accompanied by the evolution of SO₂, HCl, HF and H₂S. Electric discharges in the atmosphere cause the formation of NO₂ and ozone (O₃). CO₂ is evolved in forest and prairie fires, and by animal organisms. Man uses about 10 m³ of air daily, evolving 0.4 m³ of CO₂. Given the total world population of 3 x 10⁹, this yields 8.7 x 10⁸ tons of CO₂ per year.

3. Sources of artificial atmospheric pollutants

3.1. Combustion of fuels

The following main types of pollutants are formed in the course of solid fuel combustion: dust, CO₂, CO, SO₂, and oxides of nitrogen. Other pollutants may be present in small amounts.

In addition to the combustible components (carbon, hydrogen and sulfur), solid fuels contain incombustible mineral components which are defined as the ash content in the description of fuels.

Depending on the conditions of combustion, the mineral components of solid fuel can form either clinker or fly ash. In the case of incomplete combustion, the dust may contain coal particles. Mechanically disintegrated dusts can be further partly sub-divided to form colloidal smokes.

As a result of high temperatures generated in combustion chambers, the mineral components of solid fuels are partly vaporized and sublimated. The resultant products are carried up by flue gases, and condense when the temperatures drop to form fumes. Of similar

character is the soot which is formed in the course of decomposition of high molecular weight hydrocarbons and the subsequent condensation of carbon.

The amount of dust carried into the atmosphere with the flue gases as a consequence of the combustion of solid fuels depends on the following factors:

1. The type of fuel — its particle size, ash content, fusibility, volatile matter content, etc.;
2. Conditions of combustion — the type of stoker, volume of the combustion chamber, excess of air, the means of removing clinker, etc.;
3. The effectiveness of dust filters.

In order to describe and characterize dusts emitted into the atmosphere, it is necessary, first of all, to determine the amount and characteristics of the dust removed from the flue gases. The choice of the filtering device is determined by the particle size characteristics of the dust to be removed, namely, the weight percentage of the various size fractions of dust particles. The powdered fuel burners now commonly used in energy generation increase the heat efficiency and boiler output, but the dust concentration of the filter inlet in these burners is several times higher than that of mechanical or fixed stokers. Table II,1 (II,20) shows the inlet dust concentration in the various types of burner. Furthermore, dust containing a higher proportion of fine particle fraction is produced in pulverized coal burners.

As is seen from Fig. II,2, which is based on the VDI data, (0.21) the stoker burners produce about 15% of particles less than 10μ in diameter, while the dust generated in the pulverized coal burners contains about 50% of this fraction, and the amount can go as high as 80%. Naturally, this places greater and more exacting demands on the dust removal systems.

Knowing the value of U and the effectiveness of the filtration equipment η , the emission of dust can be found from the following relationship:

$$E = U (1 - \eta)$$

The filtration technology has made such rapid strides in recent years, that a reduction of dust emission from large thermal generating plants to a minimum is quite feasible and actually attainable. On the basis of studies carried out in 1947 by the Air Pollution and Smoke Prevention Association of America (SPAA), the

Table II,1

Amount of dust carried in the flue-gases from various types of burner

Type of burner	Amount of dust carried by the flue-gases, as percentage of the ash content of the fuel
Fixed stoker	10-20%
Mechanical stoker	20-30%
Powdered fuel burners with fluid slag removal	55-70%
Powdered fuel burners with solid slag removal	80-90%

$$E = U(1 - \eta)$$

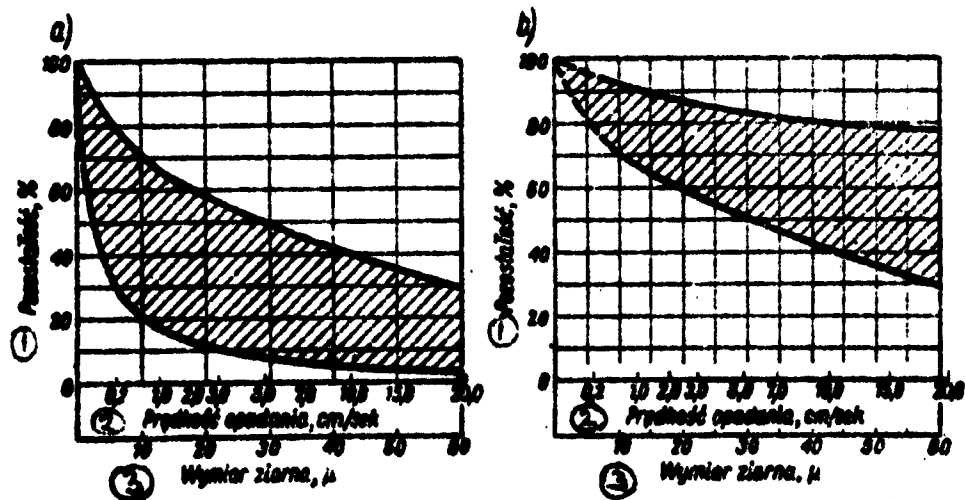


Fig. II,2. Particulate analysis spectra of dusts: a) from stoker burners; b) from coal dust burners.

Legend: 1. Residue, in %; 2. Sedimentation rate, in cm/sec.; 3. Particle size, in μ.

maximum permissible dust emission values for power generating stations have been proposed in 1950 (II.15). These are shown in Table II,2. They correspond to dust concentrations in flue gases emitted into the atmosphere from 0.5 to 0.15 g/m³, or from 4 to 9 g/kWh of generated electric power. This means a nearly ten-fold reduction of the formerly permissible emission which was set at 1.73 g/m³ by the previously binding regulations.

According to the data of L. Dietrich (II.9) compiled on the basis of studies carried out in West Germany in 1952, energy generation produced 372×10^9 Nm³ of flue gases carrying 7.3×10^5 tons of dust annually. Dust emission amounted to 1.43×10^6 tons per year, which means that the average dust concentration in flue gases emitted into the atmosphere was 3.9 g/Nm³, or about 24 grams per kWh of power generated, and the mean efficiency of the filtration equipment was about 82%.

However, it follows from the reports presented at the Premier Congrès National pour la prévention de la pollution atmosphérique held in Paris in November 1960, that whereas the filtration equipment efficiency was 96% in 1950, the equipment manufactured in 1960 was 99% effective (II.29).

Table II,2

Degree of air pollution by dust generated by American power stations

Generation of steam in tons per hour*	Amount of dust emitted into the atmosphere	
	in kg/hr	in kg/ton of steam
4,5	10	2,2
27	60	2,2
68	130	1,9
91	150	1,65
136	190	1,4
227	250	1,1
363	320	0,9
907	725	0,8
1360	1090	0,8
1815	1450	0,8

* by all boilers discharging into one stack.

As a result of such a significant increase in the effectiveness of filtration equipment, the average emission of dust by thermal

power generating stations in France in 1959 amounted to a mere 6.8 g/kWh of power generated (II,28), which is within the limits proposed by the SPAA.

However, only the filtration equipment installed in large thermal power generating stations is so impressively effective. The emission of dust accompanying the combustion of solid fuel in other branches of industry is considerably greater. W. L. Faith (0.9) lists dust emission depending on the type of burner used (Table II,3). The figures quoted are in agreement with those given in a preceding Table since the effectiveness of the filtration equipment on domestic hearths and railways equals zero, and emission is equal to generation.

Table II,3

Dust emission from various types of combustion equipment

Combustion equipment	Fuel	Emission per kilogram of fuel	Dust concentration in g/m ³
Domestic hearths	Coal	26	2.6
Industrial furnaces	"	12	1.2
Railways	"	31	3.1
Garbage incineration	garbage	4.3—4.5	0.43—0.45
Open air combustion	refuse	11	1.1

Using the available data as the basis, we can estimate the amount of dust emission in Poland as a result of the combustion of solid fuels. The estimate will be based on the figures included in Rocznik Statystyczny (Statistical Year Book) for 1960. The balance sheet for hard and brown coal consumption in Poland is given in Table II,4.

The total emission of dust can be estimated either using the values given in Table II,3, or operating on the basis of the average ash content in Polish coals, together with the estimated average dust generation and the effectiveness of filtration equipment. The results of calculations performed by the first method are given in Table II,5. The results of calculations performed according to the second approach on the basis of an average ash content are given in Table II,6.

The calculations given in Table II,6 have been made on the assumption that the average efficiency of industrial dust filters is 60%. Obviously, this value is debatable in view of the absence of any extensive and systematic measurements. However, the results of

Table II,4
The consumption of hard coal, brown coal, and coal
briquettes in Poland 1959

Type and use	Million tons	
	Coal	Briquettes
Hard coal	83,912	-
Processing: In coke ovens	13,724	-
In gas works	1,264	-
In briquetting works	654	-
In smoldering state	356	-
Fuel: for heat and power generation	18,689	-
Used by the coal industry	3,060	-
Railroads	9,369	193
Domestic use	10,807	477
Issued as additional remuneration	5,676	1
Brown coal	3,484	-
Processed in briquette factories	608	-
Fuel: For heat and power generation	2,019	-
Used by the coal industry	216	-
Railways	-	2
Domestic use	274	1,472
Additional remuneration	5	33

Table II,5
Estimated dust emission resulting from combustion of
hard coal, brown coal, briquettes and coke 1959

Mode of combustion	Annual consumption in tons	Emission in kg/ton	Total Emission in tons/year
Industrial furnaces	22.9 . 10 ⁶	12	3.5 . 10 ⁵
Domestic hearths and minor industries	19.5 . 10 ⁶	26	5.0 . 10 ⁵
Railways	9.6 . 10 ⁶	31	3.0 . 10 ⁵
		Total	11.5 . 10 ⁵

Table II,6

Estimated inlet concentration and emission of dusts
from various types of solid fuel in Poland in 1959

① Paliwo	② Miejsce użycia	③ Zróżn. Ilość paliwa t/rok	④ Zawar- tość popiołu w pali- wie p %	⑤ Unos pyłu % p	⑥ Unos pyłu t/rok	⑦ η %	⑧ Emisja pyłu t/rok
⑧ Węgiel kamień- ny i bru- natny	⑨ energetyka przemysł węgl- owy koleje paleniska domo- we	18,7 · 10 ⁶	20	65	1,83 · 10 ⁶	60	97 · 10 ⁴
		3,1 · 10 ⁶	12	30	0,11 · 10 ⁶	50	5,5 · 10 ⁴
		9,6 · 10 ⁶	10	30	0,29 · 10 ⁶	0	29 · 10 ⁴
		17,2 · 10 ⁶	10	20	0,345 · 10 ⁶	0	34,5 · 10 ⁴
⑩ Węgiel brunat- ny i bry- kiety	⑪ energetyka przemysł węgl- owy paleniska domo- we	2,0 · 10 ⁶	20	70	0,28 · 10 ⁶	60	11,2 · 10 ⁴
		0,4 · 10 ⁶	20	30	0,012 · 10 ⁶	50	0,6 · 10 ⁴
		1,82 · 10 ⁶	20	20	0,073 · 10 ⁶	0	7,3 · 10 ⁴
⑫ Koks	⑬ ogrzewnictwo i przemysł drobny	1,81 · 10 ⁶	10	30	0,055 · 10 ⁶	0	5,5 · 10 ⁴
⑭ Razem		34,43 · 10 ⁶			3,995 · 10 ⁶		1,8 · 10 ⁶

Legend: 1. Fuel; 2. Where used; 3. Annual fuel consumption, in tons; 4. Ash content of the fuel p, in %; 5. Dust concentration at filter inlet, in % p; 6. Dust concentration filter inlet, in tons per year; 7. Dust emission, in tons per year; 8. Hard and brown coal; 9. Power generation, coal industry, railways, domestic hearths; 10. Brown coal and briquettes; 11. Power generation, coal mining industry, domestic hearths; 12. Coke; 13. Space-heating and minor industries; 14. Total.

the measurements of grit fall-out in industrial areas presented be-
low suggest that the average efficiency of the filtering equipment
in industry accepted above is on the high side. On the other hand,

it can be stated with full confidence that the emission of dust in Poland caused by the combustion of solid fuel is greater than 11×10^5 tons per year, since the values accepted on the basis of the American experience are too low for our conditions.

The burning of solid fuel is also one of the most substantial sources of gas and fume pollution. Table II,7 gives the average composition of flue-gases according to Wilke (II.37).

Table II,7

Average chemical composition of flue-gas

① Składnik	② Stężenie	③ Jednostka	④
N ₂	78-80	% objętości	⑤
O ₂	7-15	% objętości	
CO ₂	6-14	% objętości	
CO	0-1	% objętości	
SO ₂	500-2000	mg/m ³	
SO ₃	20-250	mg/m ³	
H ₂ S	0-5	mg/m ³	
NH ₃	ślady	-	
HCHO	ślady	-	
H ₂ F	ślady	-	
HCl	ślady	-	
Cl ₂	ślady	-	

Legend: 1. Component; 2. Concentration; 3. Unit; 4. Trace; 5. Percent by volume.

In calculating the amount of carbon oxides emitted, it can be assumed that between 90 and 98% of the carbon contained in the fuel is oxidized to CO₂, the remainder being converted into CO. Between 75 and 80 percent of the sulfur present in solid fuel is oxidized to sulfur oxides, mainly SO₂. This results in an SO₂ content in flue-gas of about 600 cm³/m³, or 1720 mg/m³. Sulfur trioxide SO₃ in flue-gas amounts to between one and two percent of the SO₂ content.

According to American data (II.45), (II.3) some oxides of nitrogen are formed at the high temperatures encountered in furnaces. These are emitted into the atmosphere, mainly in the form of NO₂. The NO₂ content in flue-gases depends on the conditions of combustion, and varies between 100 and 1,500 cm³/m³; the amount produced increasing with the temperature of the furnace. Flue-gases from power generating and industrial sources contain, on the average, between 300 and 500 mg/m³ of NO₂, or between three and five kilograms of NO₂ per ton of

coal burned.

It can be accepted with a degree of accuracy that all of the gaseous pollutants formed in the process of combustion are emitted into the atmosphere.

In order to facilitate calculations, Table II,8 lists the amounts of CO₂ and CO emitted into the atmosphere per ton burned depending on the carbon content of the fuel, on the assumption that 95% of carbon is oxidized to CO₂. Table II,9 gives the amounts of SO₂ emitted per ton of coal burned as a function of the sulfur content of the fuel.

The average emission of SO₂ per ton of coal burned is about 16 kilograms in France (II.28), 27 kilograms in England (II.42), and between 10 and 22 kilograms in West Germany (II.30). According to Voigt (II.38), emission of SO₂ by power generating stations go as high as 60 kilograms per ton.

Table II,9

Emission of CO₂ and CO as a function of the carbon content of coal:

Zawartość węgla w paliwie ①	90%	95%	98%	99%	99.5%	99.8%	99.9%	99.95%	99.98%
Emission CO, Nm ³ /kg	0.89	0.98	1.06	1.15	1.24	1.33	1.42	1.51	1.6
Emission CO, kg/kg	1.74	1.92	2.09	2.27	2.44	2.62	2.79	2.96	3.14
Emission CO Nm ³ /kg	0.047	0.051	0.056	0.061	0.064	0.07	0.075	0.08	0.084
Emission CO kg/kg	0.0585	0.0642	0.67	0.076	0.082	0.0875	0.0935	0.099	0.105

Legend: 1. Carbon content in coal; 2. Emission.

The total emission of SO₂ was estimated at 2.5 x 10⁶ tons in 1958 in West Germany (II.32), and 5.2 x 10⁶ tons in 1953 in England (II.42), while in Paris alone the emission is 9.3 x 10⁴ tons per year (II.41).

Regardless of the type of fuel, combustion products always contain some aromatic hydrocarbons including 3,4-benzopyrene, whose structural formula is shown in Fig. II,3. Its concentrations in combustion products are minimal, but it receives a great deal of attention because of its exceptionally harmful properties.

In addition to solid fuel, the combustion of liquid and gaseous fuels also represents a source of pollution. Under the conditions

Table II,9

Emission of SO_2 as a function of the sulfur content of coal

Zawartość siarki w paliwie % ①	0,2	0,4	0,6	0,8	1,0	1,2	1,4	1,6
Emisja SO_2 w kg/t paliwa ②	4	8	12	16	20	24	28	32
Zawartość siarki w paliwie % ①	1,8	2,0	2,4	2,8	3	4	5	6
Emisja SO_2 w kg/t paliwa ②	36	40	48	56	60	80	100	120

Legend: 1. Sulfur content of fuel, in %; 2. Emission of SO_2 , in kilograms per ton of fuel.

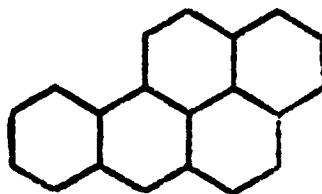


Fig. II,3. Structural formula of 3,4-benzopyrene

prevailing in Poland, it can be assumed that the entire amount of liquid fuel consumed is burned by motor vehicles. [See Note].

([Note:] Air pollution caused by motor vehicles will be discussed later in the present chapter).

Among gaseous fuels used in Poland, we shall distinguish lighting gas, natural gas, and coke-oven gas. Since the lighting and natural gases are usually processed to remove sulfur, the only contaminant emitted into the atmosphere in a complete combustion of these gases is CO_2 . Gaseous pollutants are emitted as a result of the burning of coke-oven gas. According to English data (II.42), about 25 kilograms of SO_2 are emitted by burning 1,000 m^3 of coke-oven gas.

Table II,10 gives the total amount of gaseous pollutants emitted as a result of burning solid and gaseous fuels in 1959. The values have been calculated on the basis of the average carbon and sulfur contents of fuels consumed in Poland. It follows from the Table

Table II,10

Emission of gaseous pollutants resulting from the combustion of solid fuel in 1959

① Paliwo	② Zużycie t/rok (m ³ /rok)	③ Średnia zawartość czystego węglia C %	④ Średnia zawartość siarki S %	⑤ Emisja t/rok		
				CO ₂	CO	SO ₂
⑥ Węgiel kamienny i brykiety	42,7 · 10 ⁶	75	1,8	114,5 · 10 ⁶	3,75 · 10 ⁶	1,54 · 10 ⁶
⑦ Węgiel brunatny i brykiety	3,6 · 10 ⁶	50	0,8	7,12 · 10 ⁶	0,21 · 10 ⁶	0,21 · 10 ⁶
⑧ Koks	10,1 · 10 ⁶	80	1,2	28,1 · 10 ⁶	0,94 · 10 ⁶	0,24 · 10 ⁶
⑨ Gaz kokso- walczy	(4 223 · 10 ⁶)	—	—	—	—	0,1 · 10 ⁶
⑩ Razem	56,4 · 10 ⁶			149,72 · 10 ⁶	4,9 · 10 ⁶	1,94 · 10 ⁶

Legend: 1. Fuel; 2. Annual consumption, in tons/year (or m³/year); 3. Average ^{pure} carbon content; 4. Average sulfur content; 5. Emission, in tons/year; 6. Hard coal and briquettes; 7. Brown coal and briquettes; 8. Coke; 9. Coke-over gas; 10. Total.

that emission of SO₂ in Poland is estimated at about 34 kilograms per ton of fuel.

These values are compared in Table II,11 with the 1953 emission of dust and SO₂ in England. The figures are based on the report presented to the British House of Commons in 1954 by the Committee on Air Pollution (II.32).

3.2. Building materials industry

Cement manufacture is one of the most dust-producing industrial processes. Dust is generated in the following manufacturing steps.

Table II,11
Emission of grit and SO₂ resulting from the combustion
of fuels in England

① Rodzaj zużycia	② Paliwa			③ Emisja 10 ⁶ t	
	10 ⁶ t		10 ⁶ m ³		
	④ stał	⑤ płynne	⑥ gaz kok- sowniczy	⑦ pył	SO ₂
Węgiel ⑧					
⑨ Paleniska domowe	36,8	—	—	1,0	0,9
⑩ Stacje elektryczne	36,7	—	—	0,3	1,0
⑪ Koleje	13,8	—	—	0,4	0,4
⑫ Przemysł	64,6	—	2,06	1,1	1,8
⑬ Koksownie	—	—	3,62	—	0,1
⑭ Gazownie	6,2	—	—	—	0,2
Koks ⑮					
⑯ Gazownie i przemysł	14,7	—	—	—	0,4
Paliwa płynne ⑰	—	9,0	—	—	0,4
⑱ Razem	172,8	9,0	5,68	2,8	5,2

Legend: 1. Type and use; 2. Fuel; 3. Emission; 4. Solid;
5. Liquid; 6. Coko-oven gas; 7. Grit; 8. Coal; 9. Domestic hearths;
10. Power generating stations; 11. Railways; 12. Industry; 13. Coko-
ovens; 14. Gas works; 15. Coke; 16. Gas works and industry; 17. Li-
quid fuels; 18. Total.

1. Disintegration and drying processes: the grinding of
limestone, marls, clinker, and pulverized coal for combustion. Dis-
persion dust is produced.

2. Transportation, storage and packaging processes (dust).

3. Calcining processes (dusts and fumes).

Reduction of dust emission from cement 1 stores is very
difficult in view of the number of sources involved. The difficulty
is compounded by the fact that dust emitted from cement kilns con-
sists mainly of fractions with particle size smaller than 10 μ .
Table II,12 gives the 0 - 10 μ fraction content of dusts from vari-
ous kilns according to E. Ruhlend (II.26). As can be seen from the
table, the percentage of the < 10 μ fraction in the grade effluent
gas (prior to entering the arrester device) varies between 28 and
99.5. This creates additional demands on the arresting equipment.

Table II,12

Particulate analysis of dusts from various cement kilns

① Typ pieca	② Zawartość ziarna o wymiarach 0-10 μ %
Szybowy ③	15-28
Leopolda ④	26-45
Obrotowy mokry ⑤	39-60
Obrotowy suchy ⑥	32-60
Fluidyzacja ⑦	93-99,5

Legend: 1. Type of kiln; 2. Fraction between 0 and 10 μ ; 3. Shaft; 4. Leopold; 5. Wet rotory; 6. Dry rotory; 7. Fluidized bed.

Table II,13

Chemical composition of the raw material and the emitted dust

① Składnik	② Surowiec %	③ Pył emitowany %
Strata ④ promien.	35,43	23,95
SiO ₂	11,39	15,90
Al ₂ O ₃	5,31	3,78
Fe ₂ O ₃	1,81	2,58
CaO	43,52	34,40
MgO	0,98	0,78
SO ₂	0,72	7,74
K ₂ O	1,25	11,06
Na ₂ O	0,09	0,41

Legend: 1. Component; 2. In raw material, in %; 3. In emitted dust, in %; 4. Loss.

On the other hand, dust carried away from cement kilns constitutes a valuable raw material, and its chemical composition differs little from that of the kiln charge. Table II,13 shows the chemical composition of the charge and the dust carried away from the kiln on

the basis of H. Ihlefeldt's data (II.18).

In view of the considerable value of the reclaimed dust, the investment in arrester equipment is quickly amortized, and it is, therefore, profitable to install relatively expensive arrester assemblies.

The truth of this statement is best illustrated by the results of studies carried out in West Germany and France. Studies carried out by the Cement Industry Research Institute in West Germany (II.26) in 1948 have yielded the results compiled in Table II,14. It follows from this data that dust transport from cement kilns may amount to 50% of production, while dust emission amounts to no more than 0.36 - 8.8% of production. According to the data of L. Dietrich (II.9), the total dust emission from German cement kilns in 1952 was only 150×10^3 tons,

Table II,14

Amounts of dusts emitted from cement kilns

① Typ pieca	② Ilość pyłu w gazie surowym kg/t pro- dukcji	③ Stężenie za- pylenia gazu surowego G/m ³	④ Stężenie za- pylenia gazu wylotowego G/m ³	⑤ Straty pyłu w % produkcji
Szybowy ⑥	4-80	1-5	0,16-2,1	0,06-1,2
Leopolda ⑦	10-50	3-9	0,29-2,9	0,36-1,8
Piec obrotowy szlamowy z kładuchami ⑧	45-140	6,5-18,0	0,4-6,0	0,28-6,2
Piec obrotowy z wtryskiem szlamu ⑨	200-500	24-62	1,0-5,1	0,8-6,5
Piec obrotowy suchy ⑩	90-270	10-30	2,7-10,5	2,4-8,8

Legend: 1. Type of kiln; 2. Dust concentration at filter inlet, in kg/ton of production; 3. Dust concentration at filter inlet, in g/m³; 4. Dust concentration in emitted gas, in g/m³; 5. Dust loss, as percentage of production; 6. Shaft; 7. Leopold; 8. Slurry rotory, chain type; 9. Rotory kiln with slurry injection; 10. Dry rotory kiln.

amounting to 1% of production. In this case, the average efficiency of the arresting equipment was equal to 92.5%. In France, the total emission of dust from cement factories in 1959 was about 100×10^3 tons, amounting to a mere 0.72% of a total production of 14×10^3 tons,

Production of cement in Poland in 1959 amounted to 5.3×10^6 tons. The total amount of dust generated in all stages of production gives, at 30% of production, an annual total of 1.59×10^6 tons. The amount of dust emitted must be considered high due to poor efficiency of arrester devices. Accepting a cautious estimate of the arrester efficiency at 80%, we obtain a dust emission total equal to 4% of production, or 212×10^3 tons/year. It should be pointed out that the emitted dust may contain up to 7% SO_3 .

In addition to dust, cement factories emit flue gases amounting to between 3 and 4.5 Nm^3 per kilogram of production. The average volumetric composition of these gases is as follows (II.12):

CO_2	from 6 to 30%
O_2	" 2 " 15%
N_2	up to 70%

In addition to the above main components of cement factory flue-gases, traces of CO , SO_2 and H_2S are found, but these are due only to an incorrect management of the production processes, and thus can be ignored in further considerations.

On the basis of the VDI data (0.21), it can be accepted that the emission of CO_2 amounts to between 0.45 and 0.65 Nm^3 per kilogram of production. Under the conditions prevailing in Poland, this means that cement works emit $2.65 \times 10^9 \text{ Nm}^3$ of CO_2 .

3.3. The metallurgical industry

Large amounts of residual dusts are formed in the course of metallurgical processes, and the preparation and processing of ores and fluxes. However, modern foundries do not represent a serious source of pollutants because of the modern dust arrester devices used.

Both dusts and fumes are formed in blast furnace processes. Mechanical and colloidal dusts are formed in the upper part of the blast furnace shaft as a result of mutual attrition between particles, while fumes are formed in the hearth.

The quantity of grit formed in blast furnaces amounts to between 6 and 10% of the charge. Therefore, the particulate matter concentration varies between 20 and 50 grams/m^3 (up to 200 grams/m^3 in exceptional cases) at an average generation of between 3,000 and 4,000 m^3 of gas per ton of pig iron. The average composition of the blast furnace grit is as follows: 12% SiO_2 , 5% Al_2O_3 , 15% CaO , 50% FeO and Fe_2O_3 , 5% CO_2 , 5% C, and 8% of other components.

Thus blast furnace grit represents a valuable raw material,

and its recovery is very profitable. On the other hand, blast furnace gas contains about 24% CO and 2% H₂, and is used as fuel for internal combustion piston and turbine engines, for steam generation, etc. The utilisation of blast furnace gas has caused its permissible particulate matter content to be established at 20 mg/m³ many years ago. Its use in turbine engines poses still more stringent particulate matter content requirements, limiting the maximum permissible concentration to between 2 and 5 mg/m³, or 0.08 kg/ton of pig iron. The attainment of such low dust emission values from blast furnaces is possible only with the use of arrester devices with an efficiency of 99.5%.

A certain amount of dust is emitted into the atmosphere either in the course of emptying dust containers, or through malfunctioning of the arrester equipment. Therefore, emission into the atmosphere might be estimated at more than 0.08 kg/ton of iron. According to L. Dietrich (II.9), emission of grit from blast furnaces in 1952 in West Germany was 0.103×10^6 tons for a total production of iron amounting to 12.6×10^6 tons, which corresponds to about 0.8 kilograms/ton of production.

In the USA, the regulations concerning maximum permissible grit emission from blast furnaces are based on the weight of charge:

$$Z = \frac{G}{100} \left(0.06 + \frac{198}{G + 450} \right) \text{ kg/hr}$$

where G is the weight of the blast furnace charge, in kg/hr.

This denotes an emission of 0.6 - 1.3 kg/hr, or 0.3 - 0.65 kilograms of dust per ton of iron.

As a rule, modern smelters have agglomeration facilities, which are a source of dust emission. According to K. Guthmann (II.14), dust emission from agglomerators should not exceed 0.6% of production. Assuming that the agglomerator production constitutes about 65% of the iron production, we can calculate the total amount of dust emission from agglomerators and blast furnaces: $0.08\% + 0.6 \times 0.65\% = 0.47\%$ of iron production. Of course, this is only attainable if the agglomerator equipment is fully sealed and effective arrester devices are employed.

In the Martin steel making process, the amount of grit generated depends on the type of charge. Mainly fumes are formed in a liquid charge, while spray and fumes are formed by a solid charge. It can be accepted that between four and six kilograms of dust are formed per ton of product in the case of a solid charge.

The following gas and dust emission rates can be taken in the

manufacture of steel by various processes (R. J. Sarjant, (II.31)):

	gas, in Nm ³ /ton	dust, in kg/ton
Open hearth	2,600	2
Bessemer converter	740	9
Electric furnace	200	4.5
Crucible	1400-2,250	11.3

The average dust concentration in untreated gases varies between two and three grams per m³, while the dust content of exhaust gas should not exceed 0.5 - 1.5 g/m³. It is particularly difficult to abate grit emission from open-hearth furnaces and Bessemer converters using oxygen. The amount of dust formed in such cases shows a strong increase, and dust concentrations in untreated waste gas go up to 35 g/m³, while more than 90% of dust consists of the <1 μ fraction.

Given efficiently functioning dust recovery equipment, dust emission from steel mills should not be greater than 0.1 - 0.3% of production.

Measurements were carried out in 1959 of dust emission from the Dunkirk metallurgical complex consisting of six blast furnaces with a capacity of 2,000 tons per day, six open-hearth furnaces with a capacity of 125 tons per day, converters, and agglomeration facilities. The total dust emission from the entire complex did not exceed five tons per day out of a total dust generation of 2,000 tons per day (II.17).

Among gaseous pollutants produced in blast furnaces, one should mention, first of all, SO₂ and CO. The sulfur content per ton of blast furnace charge is as follows:

Ore and fluxes	0.4 kg/ton
Coke	<u>5.8 kg/ton</u>
Total	6.2 kg/ton

Sulfur introduced with the charge is broken down as follows:

Pig iron	0.3 kg/ton
Blast furnace slag	5.3 kg/ton
Blast furnace gas	<u>0.6 kg/ton</u>
Total	6.2 kg/ton

Thus we can take it that $0.6 \times \frac{32}{16} = 1.2$ kg SO₂ per ton of charge, or 2.4 kg SO₂ per ton of product¹⁶ emitted. In addition to SO₂, blast furnace can emit up to 30 kg of product.

Therefore, on the basis of the average world data, we can estimate the emission of pollutants by the iron and steel industry as follows:

1. Blast furnace (dust)	0.008 - 0.08% of product
2. Agglomeration (dust)	0.4 - 0.6% "
3. Steel works (dust)	0.3% "
4. Blast furnace (CO)	3% "
5. Blast furnace (SO ₂)	0.24% "

Given the 1959 total production in Poland of 4.4×10^6 tons of pig iron and 5.2×10^6 tons of steel, we can estimate pollutant emission as follows:

1. Blast furnaces	$4.4 \times 10^6 \times 0.0008 = 0.00352 \times 10^6 \text{ tons} = 3.52 \times 10^3 \text{ tons};$
2. Agglomerators	$4.4 \times 10^6 \times 0.65 \times 0.006 = 0.0171 \times 10^6 \text{ tons} = 17.1 \times 10^3 \text{ tons};$
3. Steel mills	$6.2 \times 10^6 \times 0.003 = 0.0186 \times 10^6 \text{ tons} = 18.6 \times 10^3 \text{ tons}.$

It follows from investigations carried out in the Gornoslaski Industrial District (Gornoslaski Okreg Przemyslowy) under the sponsorship of the Polish Academy of Sciences (II.46) that the above figures represent an ideal aim which can be approximated if the effectiveness of dust recovering equipment and the management of blast furnace gas are improved. Under the conditions prevailing in this Industrial District, the following amounts of dust were emitted during 1957 and 1958: 2.12% of production from blast furnaces and 0.88% of production from agglomerators. Emission from steel mills can be accepted to lie within the previously stated limits. Thus we can accept the following figures for dust emission in Poland:

1. Blast furnaces	$4.4 \times 10^6 \times 0.0212 = 0.093 \times 10^6 \text{ tons} = 93 \times 10^3 \text{ tons};$
2. Agglomerators	$4.4 \times 10^6 \times 0.65 \times 0.0088 = 0.025 \times 10^6 = 25 \times 10^3 \text{ tons}.$

When the steel mills are included, the total emission can be estimated at 136.5×10^3 tons per year. Emission of CO and SO₂ can be estimated as follows:

Emission of CO	$4.4 \times 10^6 \times 0.03 = 0.132 \times 10^6 = 130 \times 10^3;$
Emission of SO ₂	$4.4 \times 10^6 \times 0.0024 = 0.0106 \times 10^6 = 10.6 \times 10^3.$

The smelting of non-ferrous metals represents another source of atmospheric pollution. Although these pollutants do not play a substantial role in the country as a whole, they do have a decisive

local significance, all the more since the particulants and gases emitted by these industries are exceptionally toxic. Prevention of pollutant emissions from non-ferrous metal smelters is complicated by the fact that these pollutants are mainly in the form of fumes with particle size $< 1 \mu$.

The following pollutants can be emitted by the non-ferrous metal industries: lead, zinc, copper, cadmium, manganese, chromium and their compounds, arsenic, magnesium, chlorine, sulfur oxides, nitrogen oxides, carbon oxides, etc. The quantitative estimation of this emission is very difficult, since it is dependent both on the process, and on the type of arrester equipment used.

According to German sources, particulate matter concentration in the gases emitted in the course of zinc and lead manufacturing processes varies between 9 and 40 g/m³.

3.4. The mining industry

Large amounts of dust are formed in the course of cutting, transporting and grading coal. The amount of dust formed in hard and brown coal mines is estimated at between four and six percent of production. In Poland, this would indicate emission of some 4 to 6 x 10⁶ tons of dust annually.

According to West German data (II.9), the mining of 120 x 10⁶ tons of hard coal in 1952 was accompanied by the generation of 7,150 x 10³ tons of dust, while the losses amounted to only 27 x 10⁶ tons. In brown coal mines, the production of 83 x 10⁶ tons resulted in the formation of 3.75 x 10⁶ tons of dust, and a loss of 161.2 x 10³ tons.

Since only insignificant amounts of coal dust are emitted into the atmosphere, coal mines do not constitute a significant source of atmospheric pollution despite the large amounts of dust generated. However, the mining industry constitutes an area where the dust control and abatement represent one of the basic technological, hygienic, and economic problems.

3.5. The chemical industry

One of the major sources of air pollution is the chemical industry, in which the generation of particulate matter has been increasing with great rapidity in recent years in connection with an ever broadening introduction of the fluid bed method. In addition to particulate matter, the chemical plants emit large amounts of strongly toxic gases and mists, such as SO₂, SO₃, H₂SO₄, H₂S, CS₂F, Cl, HCl, NH₃, etc.

In view of the large variety of technological processes used

Table II,15

Emission of pollutants in the San Francisco area, in tons per day

①	Źródło	Rodzaj zanieczyszczenia						
		⑤	Organiczne					④
			⑥	⑦	⑧	⑨		
		Pyl	Węglowodory nasycone	Węglowodory nienasycone	aldehydy	alkohole i estry	NO _x	SO _x
⑩ A Spalanie	spalanie śmieci ⑪	73	169	123	74	82	3	3
	spalanie paliw płynnych ⑫	12	1	—	1	2	86	177
	spalanie paliw gazowych ⑬	3	1	—	1	18	80	2
	⑭ Razem A	88	171	123	76	102	169	182
⑮ B Przemysł metalurgiczny	stalownie ⑯	22	—	—	—	—	—	2
	huty żelaza ⑰	12	1	—	—	—	—	1
	huty metali nieżelaznych ⑱	5	—	—	—	—	—	97
	piece do wypalania różnych ⑲	11	—	—	—	—	—	2
	⑲ Razem B	14	13	3	—	3	—	2
⑳ C Przemysł chemiczny	rafinerie ⑳	23	90	8	2	—	35	150
	chemiczne różne ㉑	62	51	7	—	28	8	68
	spożywczy ㉒	3	10	—	—	2	10	5
	barwniki ㉓	3	78	12	—	34	2	11
	㉔ Razem C	91	229	27	2	64	55	234
㉕ Razem A+B+C		243	414	153	78	169	224	520

Legend: 1. Source; 2. Type of pollutant; 3. Organic; 4. Inorganic; 5. Particulate; 6. Saturated hydrocarbons; 7. Unsaturated hydrocarbons; 8. Aldehydes; 9. Alcohols and esters; 10. Burning; 11. Garbage incineration; 12. Combustion of liquid fuels; 13. Combustion of gaseous fuels; 14. Total; 15. Metallurgical industry; 16. Steel mills; 17. Iron foundries; 18. Non-ferrous metal foundries; 19. Kilns, various; 20. Chemical industry; 21. Refineries; 22. Miscellaneous chemical; 23. Food industry; 24. Dyestuffs; 25. Grand total.

in the chemical industry, it is very difficult to make even an approximate estimate of the amount of pollutants emitted into the atmosphere. However, emission from chemical plants may constitute the main source of atmospheric pollution in some areas. As an illustration, Table II.15 shows the figures for pollutant emission from the plants of the individual industries around San Francisco. The Table shows that the chemical industry emitted about 26.5% of the total amount of particulate matter, 30% of organic pollutants, 29% of nitrogen oxides, and 47% of sulfur oxides.

The influence which can be exerted by emission from chemical plants on the local pollution conditions, is illustrated by some results of research carried out in the USSR. For instance, according to Yu. G. Fel'dmann (II.13), the daily emission from a rayon factory was: 1,200 kg of methanol, 800 kg methylene chloride, and 250 kg of ethyl alcohol. According to E. V. Yeflimova (II.12), paint, titanium, manganese, etc. plants emit up to 15,000 kilograms of HCl daily. According to R. S. Gildenskiold, synthetic fiber factory emits 40,000 kilograms of CS₂ daily.

It is very difficult to limit particulate matter emission in the chemical industry, since the pollutants are usually in a colloidal form. In sulfuric acid manufacture by the contact method, 90% of the mist generated consists of particles less than 1 μ , while the fraction below 0.2 μ amounts to 80%.

3.6. Motor vehicles

In view of a substantial development of motorization in some industrial and urban centers, air pollution by engine exhaust gases constitutes one of the major items in the total pollution picture. In places such as Los Angeles (1.2×10^6 motor vehicles) or Paris (2.674×10^6 motor vehicles), the control of exhaust gas pollution assumes the proportion of a major technical problem.

A car engine emits, on the average, between 25 and 30 m³ of exhaust gases per litre of fuel, and an average 50 horsepower car produces about 300 m³ of fumes per hour. A typical analysis of the gasoline engine exhaust gas compiled by R. L. Chass et al. (II.6) is given in Table II.16. On this basis, we can calculate the emission of pollutants by a 50 horsepower engine as follows: 300 g of hydrocarbons, 120 g of acetylene, 180 g of nitrogen oxides, and 15 m³ of CO. In addition, high-compression engines emit up to 0.5% of sulfur compounds and up to 200 mg of tar products. The large high-compression Citroen 65 CV produces 3,580 m³ of CO per hour.

In the course of studying various types of cars, V. N. Alekseyeva and V. A. Khrustol'yeva (II.1) have found an average of

Table II,17

Content of CO and Pb in air depending on the
Volume of traffic of motor vehicles

1 Skł- dnik	2 jed- nostka	3 Napięcie ruchu pojazdów na min		
		55-70	11-17	1-5
CO	ppm	9-16	2-3	0-1
Pb	G/m ³	3,61-4,74	1,31-1,61	0,2-0,5

Legend: 1. Component; 2. Unit; 3. Volume of
traffic of motor vehicles per minute

Table II,16

Average analysis of exhaust gases from the car engine

① Składnik	② Jed- nostka	③ Charakter pracy silnika			
		④ jałowy	⑤ przyspie- szenie	⑥ praca	⑦ opóźnianie
Węglowodory ⑧	ppm	800	400	375	3500
Acetyleny ⑨	ppm	710	170	178	1096
Aldehydy ⑩	ppm	15	27	34	199
Tlenki azotu ⑪	ppm	23	1100	900	6
Tlenek węgla ⑫	% obj. ⑬	5,0	4,3	3,5	4,0
Dwutlenek ⑭ węgla	% obj. ⑬	10,2	12,1	12,4	6,0
Objętość spalin ⑮		8	60	35	8
Temperatura ⑯ spalin	°C	150-205	540-595	315-370	205-480
Czas pracy ⑰	%	19	19	37	25

Legend: 1. Component; 2. Unit; 3. Type of running; 4. Idling; 5. Acceleration; 6. Steady; 7. Deceleration; 8. Hydrocarbons; 9. Acetylenes; 10. Aldehydes; 11. Nitrogen oxides; 12. CO; 13. CO₂; 14. Volume of exhaust gases; 15. Temperature of exhaust; 16. Duration of work; 17. By volume.

15 g of hydrocarbons and 4.5 g of CO per m³ of exhaust gases. According to H. W. Thoensen (II.36), car exhaust fumes may contain up to 13% CO and up to 1,000 mg/m³ of sulfur compounds.

In addition to gaseous pollutants, engine-exhaust gases always contain some colloidal particulate matter. According to Faith (0.78), between 0.22 and 3.2 mg of colloidal particulate matter are produced per gram of gasoline burned. This particulate matter may contain up to 30% of lead compounds if ethyl gasoline is used (II.8). According to K. Nagibshenko (II.24), one kilogram of gasoline burned in a car engine yields 0.9 g of Pb.

Engine-exhaust fumes also contain a certain amount of 3,4-benzopyrene, and it is considered that in large urban centers the car is one of the main sources of this pollutant.

Studies have been carried out in the USA to determine the CO and Pb content in the air as a function of the volume of motor traffic. These studies were done away from the cities, along main access highways where air pollution could be ascribed only to engine-exhaust

fumes. The results of these studies are presented in Table II,17 (II.5). They show a strict correlation between the pollutant concentration and the volume of traffic.

In Poland, where there were 212×10^3 cars and 630×10^3 motorcycles in 1959, atmospheric pollution due to motor vehicles does not constitute a serious problem as yet. Nevertheless, it should be taken into account in large cities and industrial centers. Given a total annual consumption of liquid fuel in Poland amounting to 2.6×10^6 tons, about 8×10^5 tons of CO and 0.5×10^5 tons of SO₂ are produced each year.

3.7. Other man-made sources of pollution

In addition to the pollution sources listed above, there are many other minor sources which are difficult to classify. However, it should be stressed that there are no technological processes which do not generate some particulates. For instance, losses due to residual dusts in textile factories are estimated at 3 - 5% of production, while similar losses in tobacco factories amount to about 2%.

Dispersion dusts are formed in all the cases where friction is involved. The wear of rails and tires in the Berlin subway in 1930 amounted to 210 tons. Asphalt pavements show an annual rate of wear amounting to 0.5 - 1 mm, and there is considerable wear of the rubber tires in motor vehicles.

Other sources of dust pollution result from the storage and transportation of powder-like materials. In industrial districts, slag heaps are a constant and serious source of pollution.

3.8. Radioactive dusts

Radioactive dusts are formed in both the peaceful and the military applications of nuclear energy. A. B. Bergsted (II.44) points out the following sources of radioactive dusts:

1. Uranium mining and processing;
2. Chemical processing of fission products obtained from reactors;
3. Nuclear reactors;
4. Nuclear explosions.

The amounts of dust generated in uranium mines, and in the course of ore and fission product processing are of the same order as those

generated in other mines and technological processes. The arrester devices and means of personnel protection must assure a reduction of dust emission to the permissible levels.

Dusts introduced into a reactor together with gases, or those generated in the reactor itself as a result of evaporation and corrosion, can acquire artificial radioactivity.

Radioactive gases and dusts are generated in nuclear explosions, and their amount depends on the yield of the bomb and the type of explosion. We distinguish high atmospheric explosions in which the ball of fire does not touch the surface, and low atmospheric explosions in which it does. In the course of high atmospheric explosions (about 600 meters above ground level), the amount of dust sucked up from the ground is relatively small. In such cases, the radioactive cloud consists, in addition to gases, mainly of dusts resulting from an uncontrolled fission chain reaction of U^{235} or Pu^{239} (where about 200 different isotopes are produced), and of the structural materials of the bomb. Large amounts of dust are formed in ground level explosions, and the cloud contains mainly the Si^{31} , Al^{28} and Na^{24} isotopes in addition to the fission products. The amounts of dust generated in explosions are not given in unclassified literature, where only the total radioactivity of the vapors, dusts and gases formed in the blast are quoted. One minute after the explosion of a bomb containing one kilogram of explosive charge, the total radioactivity is equal to that of 800,000 tons of radium. This decreases to an equivalent of 600 tons of radium, and is still at eight tons after one week (II.44).

During extensive nuclear tests carried out between 1956 and 1958, the radioactivity of the air in Central Europe reached a value of 2×10^{-11} curies/ m^3 .

3.9. A summary

Table II,18 gives estimated values of the total annual emission of dust, CO and SO_2 from the major artificial sources in Poland. In reality, values higher than those tabulated should be reckoned with. Furthermore, the compilation does not take into account a number of sources where the estimate of emission is difficult to make, as in the chemical industry and numerous small industrial plants.

4. Concentration of Atmospheric Pollutants

Pollutant concentration in the air varies with time and place. Temporary pollutant concentrations depend on a number of parameters, such as the time of year, atmospheric conditions, the situation of the measuring station, etc. Also of some significance is the seasonal increase in the pollutant activity, such as emission from domestic hearths during the winter. Therefore, the determination of average

Table II,18

Estimated emission by the
major pollutant sources in
Poland

① Zródło za- nieczyszczeń	② Emisja 10 ⁴ t/rocznie		
	③ Pył	CO	SO ₂
Spalanie pa- liw stałych			
③ i gazowych	11,5-18,0	49,0	19,4
Spalanie pa- liw płynnych			
④ (samochody)	0,002	8,0	0,5
⑤ Cemento- wanie	2,12	—	—
⑥ Hutnictwo	1,37	1,3	0,13
⑦ Razem	21,5	58,3	20,0

Legend: 1. Source of
pollutant; 2. Emission, in
10⁵ tons/year; 3. Combustion
of solid and gaseous fuels;
4. Combustion of liquid fuels
(cars); 5. Cement plants; 6.
Metallurgical industry; 7.
Total; 8. Particulate matter.

concentration values demand long periods of observation, one year being
the minimum comparison unit.

Dust concentration in cities and industrial centers varies be-
tween 0.1 and 10 mg/m³. Table II,19 gives a comparison of the results
of dust concentration measurements in major American cities and in
Paris.

More absolute and less variable are the measurements of
dustfall. Generally, an annual value of between 200 and 360 tons/km²
is considered permissible in industrial areas. Table II,20 gives the
results of grit settling measurements carried out in major industrial
centers. Justifiable anxiety is caused by the results, contained in
the Table, of measurements carried out by the "Energopomiar" and "Go-
project" organizations in Polish industrial centers. As can be seen

Table II,19

Dust concentration in
the air (annual average)
in 1958

① Ośrodek	② Stężenie mg/m ³
Los Angeles	0,265
Detroit	0,344
New York	0,244
Cincinnati	0,176
San Francisco	0,104
③ Waszyngton	0,130
④ Paryż ¹⁾	0,162
1) W 1950 r.	

Legend: 1. Center; 2. Concentra-
tion; 3. Washington; 4. Paris.

from the Table, Poland holds world records in dust pollution of the industrial centers.

A comparison of the results for Bochum and Goldenberg (Table II,20), where the measurements were carried out before and after the installation of dust arrester equipment shows that it is possible to achieve a substantial reduction in atmospheric pollution by making use of all the opportunities.

Table II,20

Dustfall in major industrial centers

① Odrodek	② Opad pyłu t/km²rok
Leningrad	288
③ Woroszyłowski	360
④ Charków	460
⑤ Londyn	360
Birmingham	480
Liverpool	960
Baltimore	540
Detroit	325
New York	320
Bochum 1950	575
Bochum 1952	336
Goldenberg 1940	2000
Goldenberg 1952	350
Łódź	1000-4000
Katowice	1300-3000
Zabrze	3600
Wałbrzych	900-1500

Legend: 1. Center; 2. Dustfall, in tons/km²/year; 3. Voroshilovsk; 4. Kharkov; 5. London.

To illustrate the order of magnitude of gas pollution, we shall quote characteristic results obtained on the basis of continuous measurements in large urban and industrial centers.

The CO₂ content in the air above urban and industrial centers may exceed 600 cm³/m³. The average CO₂ concentration in Paris in 1959 (II.41) was 349 cm³/m³, while the maximum concentration of 579 cm³/m³ occurred in February. This shows a constant increase in the CO₂ content in recent years (the maximum concentration in 1957 was only 495 cm³/m³).

In Lisbon (II.39), the average CO₂ concentration in 1959 was 369 cm³/m³.

The CO concentration in industrial centers may exceed 55 cm³/m³. The average CO concentration in Paris was, in 1959, 14.8 cm³/m³, the maximum being 20 cm³/m³, which means a 50% increase over 1956. In the motor traffic tunnels in Paris, the CO concentration goes up to 50 cm³/m³. During smog periods in Los Angeles, the CO concentration frequently exceeds 100 cm³/m³.

The SO₂ concentration in urban districts may exceed 10 cm³/m³. In Paris, the SO₂ concentration in 1959 varied between 0.016 and 0.695 cm³/m³ (0.048 - 2.03 mg/m³). The corresponding figures were 0.065 - 0.4 mg/m³ for Lisbon (II.39), 0.15 - 0.5 mg/m³ for Milan 0.12 - 0.68 mg/m³ for Geneva (II.11), and 0.2 - 1.31 mg/m³ for London.

Studies carried out in the vicinity of the Warsaw power generating stations in 1957 and 1958 gave values of between 0.004 and 1.31 mg/m³. Relatively large SO₂ concentrations were detected in Krakow in the course of measurements carried out between 1953 and 1955. The average SO₂ concentration in the Gornoslaski Industrial District varied between 0.15 and 1.99 mg/m³, with single readings as high as 11 mg/m³ (sic!) (II.10).

Some very interesting conclusions can be drawn from the graphs of mean dust concentrations for the individual months of the year and days of the week. These graphs, constructed on the basis of measurements carried out in Paris in 1959, are shown in Figures II.4 and II.5 (II.41). It follows from these graphs that the maximum concentration of air pollutants is observed in February. The maximum annual concentration is explained by the fact that the heaviest emission from domestic hearths occurs in February which is the coldest month in Paris. The pronounced drop in pollutant concentration on Sundays is explained by lighter motor traffic.

Another interesting conclusion can be drawn from these graphs. This follows from a remarkable agreement in the seasonal and daily changes in the concentrations of CO₂, SO₂, and dusts. This fact makes it possible to use the CO₂ concentration as the general index of air pollution.

It follows from the recent studies (II.23) that one gram of dust in urban and industrial districts contains about 23 µg of 3,4-benzpyrene. The maximum concentration of 3,4-benzpyrene per 100 m³ of air is estimated at 34 µg in London and 36 µg in Liege (II.11). The average 3,4-benzpyrene concentration in English towns is estimated at between 1 and 5 µg/100 m³, while the corresponding figure for Los Angeles is 3 µg/100 m³ (II.23). The 3,4-benzpyrene concentration increases strongly as a result of photochemical reactions, and the levels of this pollutant increase sharply during periods of strong inso-

lation.

Relatively large amounts of hydrocarbons C_nH_m are emitted in areas with heavy motor traffic. For instance, the following hydrocarbon concentrations have been measured in American cities: $5.9 \mu\text{g}/\text{m}^3$ in Boston, $2 - 10 \mu\text{g}/\text{m}^3$ in Cincinnati, $2 - 5 \mu\text{g}/\text{m}^3$ in Los Angeles, and $0.3 - 5.2 \mu\text{g}/\text{m}^3$ in San Francisco.

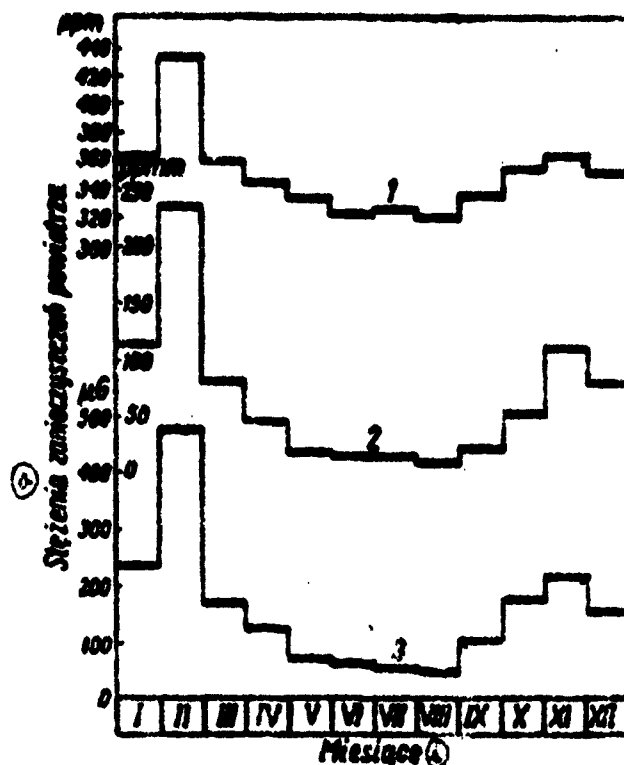


Fig. 11.4. Average monthly pollutant concentrations in Paris
1. CO_2 ; 2. SO_2 ; 3. Dust concentration.

Legend: a. Atmospheric pollutant concentration; b. Months

High concentrations of other pollutants may arise in the individual industrial centers. For instance, concentrations of $0.05 - 0.08 \text{ mg}/\text{m}^3$ of H_2S and $0.35 - 0.37 \text{ mg}/\text{m}^3$ of CS_2 have been measured in Lodz (11.35).

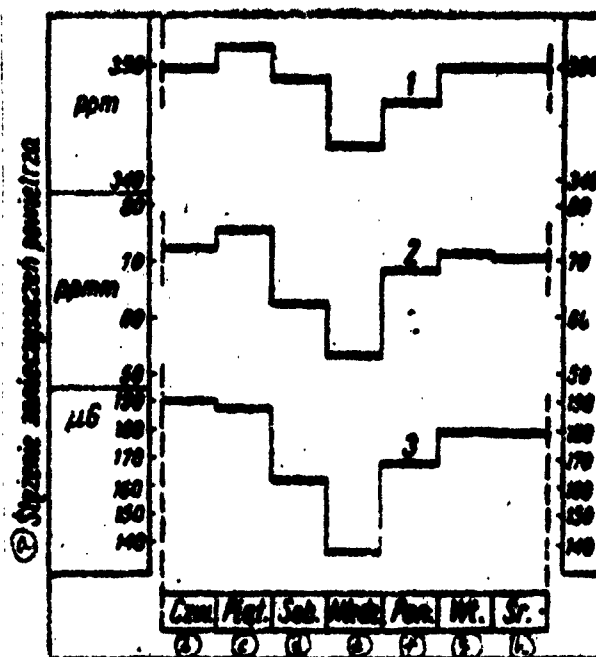


Fig. II,5. Average daily pollutant concentrations in Paris.
1. CO₂; 2. SO₂; 3. Dust concentration.

Legend: a. Atmospheric pollutant concentration; b. Thursday;
c. Friday; d. Saturday; e. Sunday; f. Monday; g. Tuesday; h. Wednesday.

5. Air Pollution Legislation

Since the numbers and activity of artificial emission sources and the resultant pollutant concentrations are constantly increasing, especially so in urban and industrial centers, it has become necessary to introduce legislation enforcing preventive measures.

The legal sanctions applied to those responsible for polluting the air can be derived from the paragraphs concerning statutory nuisances by legal persons present in all civil codes. On the basis of statutory nuisance provisions, the owners of homes located near a Berlin power generating station have won in 1936, a substantial suit for damages arising out of dust spoilage of their properties.

At the present time, there are in force in the various countries precise legal regulations concerning pollution abatement. This legislation may define the following:

1. Maximum permissible emissions by the individual sources;
2. The type and width of protective zones surrounding emission sources;
3. Maximum permissible pollutant concentrations.

The first precise legislation concerning the abatement of pollutant emission was issued in England in 1880 under the name of Alkali, etc. Works Regulation Act. These regulations have been constantly revised and supplemented, and the last edition dates from 1950. In addition, the Clean Air Act, which embodies the regulations of the Electricity Commission of 1932, was passed in 1956 (II.42), (II.43).

This legislation accurately defines the type of industrial plant whose construction or start-up requires a prior approval of the appropriate authority, and sets out protective and smokeless zones, as well as the maximum permissible levels of some pollutants.

The maximum permissible emission of grit from power generating stations has been set at 0.92 g/m^3 , and the concentration of particles larger than 25μ in diameter must not exceed 0.35 g/m^3 . At the same time, the smoke emitted from the stack must not be darker than No 2 standard on the Ringelmann scale.

The Horizet act was passed in France in 1932. It limits the maximum permissible grit emission from industrial plants to 1.5 g/m^3 , and the total permissible emission from any one source to 300 kg/hr (II.2).

Interim regulations were drawn up in Holland in 1947, which relate the maximum permissible emission of grit to the height of the stack according to the equation:

$$E = \left(\frac{h}{50}\right)^2 \text{ G/Nm}^3$$

where h is the height of the stack.

At the same time, emission of particles larger than 50μ must not exceed the following value:

$$E_{>50} = 0.025 \left(\frac{h}{50}\right)^2 \text{ G/Nm}^3$$

In accordance with the formula, the maximum permissible emission from a chimney 50 meters high is 1 g/m^3 , while that from a chimney 100 meters high is 4 g/m^3 .

These regulations concern energy generating

Table II, 21
Maximum permissible concentrations of air pollutants in the USSR

① Nazwa substancji	② Dopuszczalne stężenie mg/m ³	
	③ jednorazowe	④ średnia w ciągu 24 godz
④ Alkoleina	0,3	0,1
⑤ Octan amylu	0,1	—
⑥ Arsen i jego związki	—	0,003
⑦ Benzen	2,4	0,8
⑧ Benzyna	5,0	1,5
⑨ Octan butylu	0,1	—
⑩ Siarczek węgla CS ₂	0,03	0,01
⑪ Tlenek węgla CO	6,0	2,0
⑫ Chlor	0,1	0,03
⑬ Chlorobutadien	0,25	0,08
⑭ Dwuchlorooctan	3,0	1,0
⑮ Pył (nie toksyczny)	0,5	0,15
⑯ Octan etylu	0,1	—
⑰ Fluor i jego związki	0,03	0,01
⑱ Formaldehyd	0,035	0,012
⑲ Chlorowódor HCl	0,05	0,015
⑳ Siarkowódor H ₂ S	0,03	0,01
㉑ Ołów i jego związki	—	0,0007
㉒ Ceteroetylen ołowiu	—	0,0017
㉓ Mangan i jego związki	0,03	0,01
㉔ Rtęć	—	0,003
㉕ Alkohol metylowy	1,5	0,5
㉖ Octan metylu	0,07	—
㉗ Tlenki azotu NO, NO ₂	0,30	0,10
㉘ Fenol	0,3	0,1
㉙ Pęciotlenek fosforu	0,15	0,05
㉚ Sadza	0,15	0,05
㉛ Kwas siarkowy H ₂ SO ₄	0,3	0,1
㉜ Tlenek siarkowy SO ₂	0,5	0,15
㉝ Octan winylu	0,2	—

Legend: 1. Substance; 2. Permissible concentration, in mg/m³; 3. Single discharge; 4. Acetolein; 5. Amyl acetate; 6. Arsenic and compounds; 7. Benzene; 8. Gasoline; 9. Butyl acetate; 10. CS₂; 11. CO; 12. Chlorine; 13. Chlorobutadiene; 14. Dichloroacetate; 15. Non-toxic particulates; 16. Ethyl acetate; 17. Fluorine and compounds; 18. Formaldehyde; 19. HCl; 20. H₂S; 21. Lead and compounds; 22. Tetraethyl lead; 23. Manganese and compounds; 24. Mercury; 25. Methanol; 26. Methyl acetate; 27. NO and NO₂; 28. Phenol; 29. Phosphorus pentoxide; 30. Soot; 31. H₂SO₄; 32. SO₂; 33. Vinyl acetate; 34. Diurnal average.

plants which burn up to 100 kilograms of fuel per hour. The maximum permissible emission may be set at a lower value for plants burning higher amounts of fuel.

In the USA, pollution control regulations vary from state to state, and even from city to city. The previously quoted SPAA recommendations are binding for power generating plants. In New York, the maximum permissible grit emission has been set at 1.18 g/km^3 , while the content of particles larger than 17μ may not exceed 42% (II.27). The maximum permissible SO_2 emission in the USA is set at 0.2% by volume (about 5.72 g/km^3) (II.27).

In the USSR, the binding work safety regulations spell out the widths of protective zones which must separate residential districts from industrial areas. The widths of these belts depend on the chimney height and fuel consumption rates. The start-up of a new plant requires the prior approval of the sanitary inspector.

In 1958, the USSR introduced the world's first norms for the maximum permissible pollutant concentrations. So far, these norms comprise 30 positions (Table II, 21). As can be seen from this Table, the norms regulate both the maximum single discharges and the diurnal average grit emissions.

In Poland, a decree is now in preparation concerning atmospheric pollution abatement, which sets out the maximum permissible emission levels and the widths of protective zones around industrial objectives.

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Chapter III

Damage Caused by Atmospheric Pollution

1. Introductory remarks

Air pollution has various, but mainly harmful effects. Analysing the harmful action of air pollution, G. W. Szelechowski (O.I.S) lists the following:

1. Atmospheric pollution in urban centers has increased to such a degree, that it may be the cause of many illnesses of their populations;
2. As a result of dust pollution, most of ultraviolet radiation does not reach the surface of the Earth;
3. Dust pollution causes an increase in the amount of heavy positive ions, thereby lowering the wholesomeness of the air;
4. The frequency of fog is higher in industrial regions;
5. The wear and tear of machinery and equipment is much higher as a result of grit pollution in the air;
6. Dust pollution in the air reduces the amount of sunlight available, thereby increasing the amount of electricity needed for lightings;
7. Atmospheric pollution harms vegetation and accelerates the decay of buildings and installations.

In view of the fact that the scope of damage caused by pollution is so broad, an accurate financial estimate of the losses is very difficult. Nevertheless, attempts have been made over a number of years to estimate the damage caused by pollution in the individual regions and countries as a concomitant of pollution measurements. It should be noted that the results arrived at show an astonishing degree of agreement.

Generally speaking, there are three groups of losses:

1. Material losses;

2. Indirect losses;
3. Direct losses.

2. Material losses

In the course of industrial processes, large quantities of grit, fumes, and gases are emitted, amounting to between one and six percent of production.

Table III,1

Quantity and value of particulates emitted by industrial undertakings in West Germany in 1952

①	Źródło	② Emisja 10 ³ t/rok	③ Straty 10 ⁶ DM/rok
④	Kopalnie węgla kamiennego	27,0	1100
⑤	Kopalnie węgla brunatnego	161,0	2860
⑥	Wielkie piece	103,0	9300
⑦	Stalownie	48,0	3800
⑧	Produkcja miedzi	0,8	1010
⑨	Produkcja cynku	7,7	7160
⑩	Produkcja ołowiu	4,1	1350
⑪	Produkcja cementu	150,0	1560
⑫	Silownie	1430,0	—
⑬	Razem	1911,6	30390

Legend: 1. Source; 2. Emission, in 10³ tons/year; 3. Losses, in 10³ DM/year; 4. Hard coal mining; 5. Brown coal mining; 6. Blast furnaces; 7. Steel mills; 8. Copper production; 9. Zinc production; 10. Lead production; 11. Cement production; 12. Power generating stations; 13. Total.

L. Dietrich (II.9) has calculated the amount of dusts emitted into the atmosphere in West Germany in 1952 (Table III,1). The Table shows that the annual material losses amounted to 30×10^6 DM, or 7×10^9 dollars. The amounts of dust given in Table III,1 are more or less equivalent to those emitted in Poland in 1959, and it therefore seems that our material losses should be of the same order.

As a result of the development of the recovered dust processing industry, even the dusts from heat generating stations have a value on the world market (about \$1 per ton in the USA).

Work aiming at the utilization of dust recovered from energy generating stations as a building material are conducted in Poland under the direction of W. Sklamowski (III.4).

Also, intensive research has been in progress over the last few years on the means of recovering rare elements such as germanium and gallium from power station dust. Work done on this problem indicates that the recovery of rare elements can be profitable.

The strongly increasing pollution of the air with sulfur compounds has led to the situation where it may be necessary in future to install equipment for de-sulfurizing the flue gases (at present, the construction of such installations is in the experimental stage. It appears that the sulfur thus recovered may supply the entire world demand for this commodity, and this method of production may be profitable.

3. Indirect losses due to pollution

Indirect losses caused by pollutants in the air can be divided as follows:

1. The scattering and absorption of sunlight;
2. Increased frequency of fogs;
3. Changes in the properties of soils.

Dusts and liquid droplets in the air absorb and scatter most of the ultraviolet radiation. Although the ultraviolet radiation constitutes only about 1% of the total solar radiation, it nevertheless has a great biological significance. Decreased ultraviolet radiation causes an increase in the numbers of bacteria in the air, and hinders the development of vegetation. The loss of ultraviolet rays in Berlin in 1930 was estimated at 14%. In London, the loss in the winter is about 97%, and in the industrial districts of Leningrad it is estimated at 40% (0.18).

Pollutants suspended in the atmosphere also absorb a part of the visible light, which in turn causes an increased consumption of electricity for the lighting of towns and communities. The loss of sunlight amounts to 40% in Leningrad, 38% in London, 21.5% in New York, and 50% in Leeds. The increase in electric power consumption resulting from the loss of daylight in Leningrad is estimated at 28% (0.18).

R. G. Veryard (III.13) has even proposed the hypothesis that air pollution has changed the conditions of solar radiation enough

to exert a tangible influence on the progressive change of the Earth's climate.

Atmospheric pollutants are also among the main causes of fog formation. Whereas the relative humidity of air devoid of condensation nuclei may go up to 400% without fog formation, such formation can take place in polluted air at relative humidity levels below 100%. In addition to water vapor, other sources of fog formation are the hydrocarbons, SO_2 and NO_2 contained in the air. These are considered to be the chief causes of smog formation (III.6). Saturated vapor pressure of these gases is 10^{-5} times lower than the saturated vapor pressure of water vapor. As a result of photochemical reactions, they condense on condensation nuclei to form a mist having a droplet size of the order of 0.01μ . Under adverse meteorological conditions, this may lead to smogs described as "disastrous". The first particularly dangerous concentration of smog was recorded in the Meuse valley in Belgium in 1930. Further occurrences were recorded in Donorre (USA) in 1948, and in London in 1952.

The losses caused by a five-day smog in London in December 1952 have been estimated at $\pounds 10 \times 10^6$ (0.13). The losses caused by smog on 31 January 1959 amounted to $\pounds 50 \times 10^6$. Vast losses were suffered at that time by airline companies. Whereas the total losses by the BEA due to meteorological conditions during the three preceeding months amounted to $\pounds 200,000$, its losses on 31 January 1959 were $\pounds 20,000$, those of Air France were $\pounds 4,500$, and the cost of closing down the London Airport was $\pounds 8,000$. It can be generally accepted that the incidence rate of fogs in urban and industrial centers is between two and three times greater than in unpolluted areas having similar meteorological conditions.

The productivity of trees is lowered as a result of the selective absorption and scattering of sunlight due to pollution. According to M. Bossavy (III.3), the average annual increase in the height of fir trees in the region of Maurienne is between 25 and 30% greater than in unpolluted environments. In the vicinity of Brandenburg, one pear tree yields about 24.5 kilograms of fruit, while a pear tree of the same variety near Berlin yields only 17 kg. of fruit (0.10).

Apart from the direct destruction of vegetation, the dust and condensed acid fallout causes fundamental changes in the properties of soils and significantly lowers their productivity.

4. Direct losses due to pollutants

The main losses caused directly by atmospheric pollution can be divided into the following groups:

1. Wear of machinery and mechanisms;
2. Corrosion of metals;
3. Decay of buildings;
4. Spoiling of apparel;
5. Destruction of vegetation.

Airborne dusts are the main cause of the wear of machines and mechanical parts. For instance, the wear of cylinders in an internal combustion engine increases by about 10 - 15% when the air filter is removed (III.1).

According to Baston (III.2), airborne dusts and sulfur compounds have a decisive effect on the corrosion of metal parts. The wear of rails and metal sleepers around Essen is estimated at 8,000 tons annually. In San Louis, the annual expenditure on the maintenance painting of metal structures amounts to 2.5×10^6 per year (III.16).

In 1959, a survey was carried out in Paris to estimate the damage to buildings caused by atmospheric pollution. The data of L. G. Richard (III.11) show that whereas the life span of galvanised roofing in unpolluted areas is about 50 years, such roofs in Paris are completely destroyed in about 30 years as a result of corrosion. This adds up to a loss of the order of 12.56×10^6 new francs, or about 2.5×10^6 per annum. Losses ensuing from the damage to plastering and facades in Paris amount to 35×10^6 francs (about 7×10^6).

Considerable losses are also caused by dust settling on high-voltage power lines, where it lowers the effectiveness of insulators by absorbing moisture and acids. This frequently causes short circuits and power failures.

Air pollution is considered among the main causes of the spoilage of clothing. In England, they have even introduced a special scale of textile soiling (III.10). The unit on this scale is the SAD (soiling additional density) defined as

$$1 \text{ SAD} = \lg J_0/J_s$$

Where J_0 is the light density of the scattered clean material

J_s is the light density of the scattered soiled material

To evaluate the degree of airborne dirt from the view point of

textile soiling, the "munk" unit has been introduced, which is defined as the drop of the value of J_s by 0.1 when 0.1 m³ of air is sucked through 1 mm² of white filter paper. In industrial areas, the munk value was found to increase from 700 to 2,000.

5. A general estimate of losses caused by atmospheric pollution

An estimate of the total financial loss caused by atmospheric pollution must of necessity be more or less vague.

In Great Britain, the Committee on Air Pollution under the chairmanship of H. Beaver (II.42) tabled in 1954 a report to the Parliament which gives the following estimate of losses caused in 1953 by atmospheric pollution:

1. Laundering and cleaning	£ 25 x 10 ⁶
2. Renovation and painting of dwellings	" 30 x 10 ⁶
3. Cleaning and wear of other buildings	" 20 x 10 ⁶
4. Corrosion of metals	" 25 x 10 ⁶
5. Damage to clothing and footwear	" 52.5 x 10 ⁶
6. Agricultural losses	" 10 x 10 ⁶
Total	£ 162.5 x 10 ⁶

Direct losses, such as lowered productivity of workers, sickness benefits, etc., are difficult to estimate. If the work productivity fell only by one percent, the total losses would be according to a conservative estimate £ 115 x 10⁶ per year i.e., £ 10 per inhabitant of industrial areas, or £ 5 per inhabitant of England. In addition, further losses of £ 25 - 50 x 10⁶ per year due to incomplete combustion of fuels should be taken into account.

E. Smith (III.12) makes a calculation from which it follows that it would be possible to reduce the losses due to air pollution by £ 100 - 150 x 10⁶ per year by investing a lump sum of £ 600 x 10⁶. The investment would be broken down as follows (all items ± 25%):

1. Mechanical burners for small units	45
2. Dust removal	100
3. Higher stacks	50
4. Smokeless domestic hearths	175
5. Production of smokeless fuels	155
Total	£ 525,000,000

It is startling to realize that this investment would be amortized in about five years.

Similar calculations have been made in other countries. In

the USA, the losses per inhabitant in 1952 were estimated at about \$ 41 in Pittsburgh and \$ 20 in New York. The total losses for the whole country are estimated at $\$ 1.5 \times 10^9$, or \$ 10 per inhabitant per year (0.12), (0.14).

Annual losses caused by atmospheric pollution are estimated at 1 - 1.5×10^9 DM (9 or 20 - 30 DM per inhabitant) in West Germany, and 4×10^9 Belgian francs in Belgium.

It would be very interesting to make similar calculations of the losses sustained in Poland as a result of atmospheric pollution. An accurate calculation is extremely difficult because of the lack of the pertinent data, but an estimate can be made on the basis of analogy with the English, American, or German data.

At $\pounds 250 \times 10^6$ per year, the total losses due to atmospheric pollution in England correspond to a total emission of 2.8×10^6 tons of dust and 5.2×10^6 tons of SO_2 per year. Emission of dust in West Germany in 1952 was estimated at 1.9 million tons, while the losses amounted to 1.5×10^9 DM per year.

Assuming that particulate matter is a characteristic pollutant, and that the amounts of other pollutants are proportional to it, we obtain a loss figure of $\pounds 90$ (or \$ 270) per ton of dust in England. In Germany, the corresponding figure is 780 DM (or 140) per ton of dust. The losses in industrial districts are much higher. In Los Angeles, a dust emission of 81×10^3 tons/year corresponds to a loss of $\$ 32 \times 10^6$, or about \$ 400 per ton of dust.

Taking into account the lower concentration of industry and population density in Poland, we can assume that the losses caused by emission of one ton of dust amount to 4 - 5×10^6 zlotys. Therefore, for a total emission of 1.9×10^6 tons, we have an annual loss figure of 8 - 10×10^9 zlotys.

The proof that considerable importance attaches to the problem of air pollution is seen in the expenditure for research in this field in the USA. In New York, the 1953 expenditure on pollution control amounted to \$ 375×10^3 , while the corresponding figure for Los Angeles rose to \$ 3×10^6 in 1959.

6. The effect of pollutants on humans

Atmospheric impurities may be the cause of numerous diseases in the inhabitants of industrial and urban centers. For this reason, the effect of the individual types of pollutants on the human organism is a subject of interest to many branches of medicine. However,

the attainment of positive results in the field of pollution abatement is possible only in a close cooperation between medicine and technology, where the technologist must know all the parameters influencing the degree of harmfulness of pollutants, and the orders of magnitude of these parameters.

The harmfulness and the maximum permissible concentration of air pollutants can be determined on the basis of the following: 1), biological research on humans; 2), biological research on experimental animals; 3), statistical research.

Biological research on humans depends on determining the minimum concentrations of a given pollutant in the air whose presence in the human organism can be detected by testing the human blood, urine, or hair. The starting point in this kind of research is the assumption that atmospheric pollutants should never attain a concentration level which would cause their presence in the human organism. Such research makes it possible to take into account all the factors influencing the degree of absorption by the human organism of airborne contaminants. This would be very difficult to attain by any other means. However, the method of biological research on humans has its faults, some of which are listed below:

1. It is impossible to detect the presence in the human organism of a number of pollutants present in the air, including Cl, HCl, SO₂, NO₃, NO₂, etc.;
2. The degree of pollutant absorption depends, to some extent on the characteristics of the individuals examined.

Nevertheless, biological research on humans supplies some valuable clues for the establishment of the maximum permissible pollutant concentrations, as well as for determining the degree of air pollution. According to E. C. Vigliani (III.14), the atmospheric CO concentration of the order of several cm³/m³ causes a tangible increase in the CO concentration in the blood. In France, and particularly in Paris, systematic measurements are made of the levels of CO in the blood of traffic policemen and drivers. The method developed for this purpose permits the measurement of the CO content in the blood with an accuracy to 0.01 ml per 10 ml of blood.

Biological research on animals depends on determining pollutant concentrations which induce pathological changes in the animals. Using the established conversion coefficients, it is possible to determine, by analogy, the pollutant concentrations which can cause disease symptoms in man.

The results obtained in these types of research permit in

essence only the determination of the degree of harmfulness of some selected types of pollutant, without giving an overall picture of direct and indirect effects of simultaneous presence in the air of many types of pollutants. An accurate determination of such interaction is very difficult, and some clues in this respect can be obtained from statistical research which depends on the statistical analysis of the general state of health of large numbers of population in industrial areas compared with similar population groups inhabiting regions relatively free of pollution.

It is seen from statistical analyses that atmospheric pollutants may be the cause of numerous disorders in people, causing death in the extreme cases.

It is also necessary to take into account the fact that air pollution is harmful not only through direct action on the human organism, but also indirectly through the partial screening of sunlight, ionization of the air, increased incidence of fogs, etc.

Numerous statistical studies indicate that in urban and industrial areas there is a higher incidence of such diseases as rickets in children, pulmonary diseases, especially tuberculosis, silicosis, bronchitis and lung cancer, as well as diseases of the eyes and circulatory system. Table III.2 shows some examples of the increased incidence of some diseases attributed to atmospheric pollution according to N. Lupu and K. Velikan (III.8), A. Kalyushnyy (III.7), and K. P. Faerber (III.5). It should be added that the studies in question embraced from 70,000 and 240,000 people, and the increased incidence of diseases can only be attributed to atmospheric pollution.

According to J. Delacroix (II.11), the mortality due to lung cancer in Belgium increased by 300% between 1950 and 1958, and now lung cancer is the second largest cause of death after heart diseases.

The following numbers of deaths have been recorded as due to some notorious smog disasters: 60 in the Meuse valley (1930), 20 in Donora (1948), and 4,000 in London (1952).

In Los Angeles, three degrees of alarm have been established, to be issued according to the pollutant concentration in the air. The limits are determined by the following concentrations:

①	Stopied alarmu	② Septenic	CO	NO ₂	SO ₂	O ₃
I		cm ³ /m ³	100	3	3	0.5
II		cm ³ /m ³	200	5	5	1.0
III		cm ³ /m ³	300	10	10	1.5

Legend: 1. Degree of alarm; 2. Concentration.

Table III,2

Increase in the incidence of diseases in districts with strongly polluted atmosphere (the comparison district was taken as 100%)

Type of disease	Increased incidence in comparison with the control district
Rickets in children	200 - 250%
Tuberculosis	300 - 350%
Silicosis	500 - 550%
Bronchitis	300 - 370%
Sight defects in children	400%

In the case of the first-degree alarm, limitations on the volume of motor traffic and industrial production are imposed; in the case of the third-degree alarm, a state of emergency is declared. Pollutant concentrations arising in the third-degree alarm are considered likely to cause serious diseases or death.

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PART TWO

DISPERSION OF POLLUTANTS IN THE ATMOSPHERE

Chapter IV

Aerosol Mechanics

1. Introductory remarks

Aerosol mechanics is concerned with the description of the behavior of solids (dust particles) dispersed in a medium under the influence of the external forces, and the resistance forces of the medium. The interaction forces between the particles are sufficiently small in comparison with the aforementioned forces to be negligible. In view of this assumption, the task of aerosol mechanics reduces to the theoretical and experimental description of the movement of the individual particles in the surrounding medium under the influence of various forces. If the effect of the mutual interaction between the particles cannot be ignored, it is compensated for by the introduction of suitable corrections.

Theoretical consideration of the movement of solid particles in a gaseous medium is also applicable to the movement of water droplets in a gaseous medium if these droplets are sufficiently small.

2. Uniform motion of particulates

The most elementary phenomenon in the aerosol mechanics is the uniform motion of the particle under a constant force of acting in a constant direction. A body moving in a gaseous or a liquid body encounters a resistance whose direction is opposite to that of the direction of motion of the particle, and its magnitude is dependent upon the shape and dimensions of that body, velocity, and the properties of the medium in which it is moving. Resistance to uniform motion is calculated from the following formula:

$$R = \frac{C_{\gamma} F u^2}{2g} = \frac{C_{\alpha} F u^2}{2} \quad (\text{IV}, 1)$$

where R is the force of resistance;
 C is the resistance coefficient;
 γ_0 is the specific gravity of the medium;
 F is the surface area of the projection of the body on a surface perpendicular to the direction of its motion;
 u is the velocity of the body with respect to the medium;
 g is the acceleration due to gravity;
 ρ is the density of the medium.

Resistance coefficient C depends on the conditions of motion of the body, and on its shape. The motion of a spherical body is one which has received most theoretical study and experimental verification.

The form of the expression for resistance coefficient C depends on the value of the Reynolds number

$$Re = \frac{ud}{\nu}$$

(where d is the particle diameter, and ν is the viscosity of the medium). If the particle diameter d is considerably larger than the free path of the medium molecules, then resistance coefficient C is

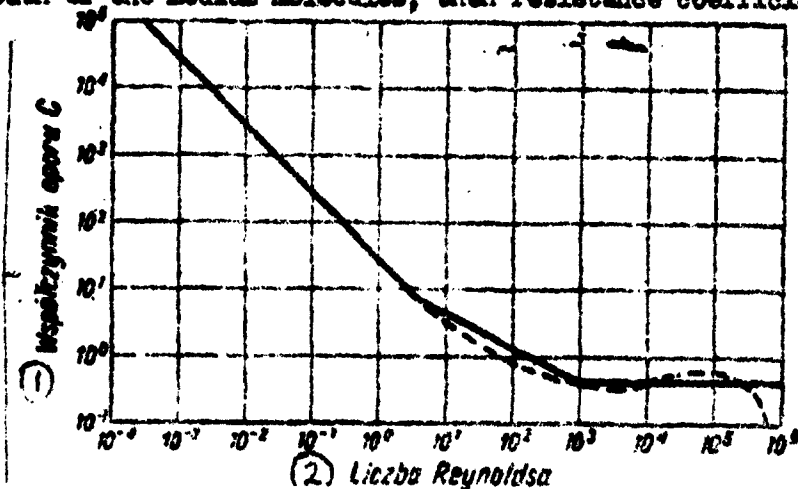


Fig. IV,1. Relationship between the resistance coefficient and the Reynolds number.

Legend: 1. Resistance coefficient C ; 2. Reynolds number.

a function of the Reynolds number. Therefore, the value of C depends on the dimensions of the dust particle in motion.

Fig. IV,1 shows the relationship $C = f(Re)$ according to Lapple

and Sheppard for the range of Reynolds numbers $10^{-4} < Re < 10^6$. The curve may be divided into three sections, each of which corresponds to a different type of motion and to a different form of the relationship $C = f(Re)$.

At higher values of the Reynolds number ($Re \gg 10^3$), the value of C is more or less constant, and equals about 0.44. This is the range of turbulent motion, and the force of resistance varies according to Newton's law:

$$R = 0.44 \frac{\pi d^2}{4} \gamma \frac{u^2}{2g} \quad (IV,2)$$

In the laminar motion range, i.e., in the range of $Re < 3$, the force of resistance may be expressed by the Stokes law:

$$R = 3\pi\mu du \quad (IV,3)$$

Therefore, in the case of laminar motion, the resistance acting on a moving particle is directly proportional to its diameter d , its velocity u , and the dynamic viscosity of the medium μ .

The resistance coefficient C is inversely proportional to the Reynolds number

$$C = \frac{24}{Re} \quad (IV,4)$$

The above range of applicability of the Stokes law ($Re \leq 3$) has been set by Lapple and Sheppard. Rayleigh sets the range of the Stokes law applicability at $Re < 2$, while Arnold gives $Re < 1.2$.

The Stokes formula has been derived on the basis of ignoring completely the dynamic (hydrodynamic or aerodynamic) forces, and can, therefore, be applied only to motion at low velocities u . The dynamic forces have been partially taken into account in the relationship derived by Oseen, which is in agreement with experimental results over a wider range of Reynolds numbers than is the case with the Stokes law. Resistance coefficient C according to Oseen is expressed by the formula:

$$C = \frac{24}{Re} \left(1 + \frac{3}{16} Re \right) = \frac{24}{Re} + 4.5 \quad (IV,5)$$

In the range intermediate between the laminar and the turbulent motions, the dependence of coefficient C on Re is more complicated.

According to Lapple and Sheppard, the following equation can be applied in the case of intermediate motion:

$$C = \frac{14}{\sqrt{Re}} \quad (IV,6)$$

In this case, the force of resistance is expressed by the formula

$$R = 1,67 \pi \sqrt{\frac{\gamma_0}{g}} \mu d^2 u^2 \quad (IV,7)$$

Frequent use is made of the relationship derived by Allen which is applicable over the range $2 < Re < 500$

$$C = \frac{18,5}{Re^{0,4}} \quad (IV,8)$$

and, correspondingly,

$$R = 2,3 \pi \left(\frac{\gamma_0}{g}\right)^{0,4} \mu^{0,6} d^{1,4} u^{1,4} \quad (IV,9)$$

In addition, empirical formulae are frequently used in determining resistance coefficients.

Baturin (IV.1) gives a formula valid for the range $0 < Re < 800$

$$C = \frac{24}{Re} (1 + 0,15 Re^{0,7}) \quad (IV,10)$$

According to Gustavsson (IV.2), resistance coefficient can be calculated from the formula

$$C = \frac{24}{Re} (1 + 0,13 Re^{0,7}) \quad (IV,11)$$

If the particle diameter d is considerably smaller than the mean free path l of the medium molecules ($d \ll l$), i.e., in the case of very small particle diameters or at very low pressures, the particle motion is molecular in character. It does not influence the velocity distribution of the molecules of the medium, and it does not cause macroscopic round-flow in the medium. Resistance of the medium is due to the fact that a larger number of gas molecules collides with the front part of the particle than with the back. If

the particle mass is significantly greater than that of the gas molecules, i.e., at $d > 10^7$ cm ($d > 10^{-3}$ μ), the formula for resistance coefficient C can be written in the following form:

$$C = \frac{12\mu g}{A\lambda u} \quad (\text{IV},12)$$

where μ is the dynamic viscosity of the medium;

A is the function of the coefficient α which determines the character of rebound of the gas molecules from the surface of the dust particle.

After substituting the value of C from equation (IV,12) in (IV,1), we obtain the following relationship for the resistance force of the medium:

$$R = \frac{6\eta F u \gamma}{A\lambda} \quad (\text{IV},13)$$

The values of A are as follows: in the case of mirror rebound, $A = 1.175$; in the case of scatter rebound, but with the preservation of the absolute velocity, $A = 1.091$; in the case of rebound with scatter and full accommodation, $A = 1.131$.

3. Shape coefficient

The Stokes law can be applied also to the laminar motion of dust particles other than spherical in shape, if the so-called shape coefficient is taken into account.

Relationships for the shape coefficient for dust particles having the shape of an ellipsoid of revolution have been derived from theoretical considerations.

Resistance of the medium is expressed by the following relationship:

$$R = 6\pi\mu a u \alpha'$$

where a is the radius of the ellipsoid in the plane of rotation;
 α' is the shape coefficient for ellipsoid of revolution, which is expressed by one of the following two formulas:

1. In the case of motion of an elongated ellipsoid of revolution along the longer axis

$$\kappa'_c = \frac{4}{3}(\beta^2 - 1) \frac{1}{\frac{2\beta^2 - 1}{\sqrt{\beta^2 - 1}} \ln(\beta + \sqrt{\beta^2 - 1}) - \beta} \quad (\text{IV}, 14)$$

2. In the case of movement of an elongated ellipsoid of revolution across the longer axis

$$\kappa'_s = \frac{8}{3}(\beta^2 - 1) \frac{1}{\frac{2\beta^2 - 3}{\sqrt{\beta^2 - 1}} \ln(\beta + \sqrt{\beta^2 - 1}) + \beta} \quad (\text{IV}, 15)$$

3. In the case of movement of a flattened ellipsoid of revolution along the shorter axis

$$\kappa'_c = \frac{4}{3}(\beta^2 - 1) \frac{1}{\frac{\beta(\beta^2 - 2)}{\sqrt{\beta^2 - 1}} \text{arc tg } \sqrt{\beta^2 - 1} + \beta} \quad (\text{IV}, 16)$$

4. In the case of movement of a flattened ellipsoid across the shorter axis

$$\kappa'_s = \frac{8}{3}(\beta^2 - 1) \frac{1}{\frac{\beta(3\beta^2 - 2)}{\sqrt{\beta^2 - 1}} \text{arc tg } \sqrt{\beta^2 - 1} - \beta} \quad (\text{IV}, 17)$$

is the ratio of the longer to the shorter axis.

The values of the shape coefficient κ' calculated from the foregoing relationships are compiled in Table IV, 1.

As a result of Brownian motion of granules having the shape of an ellipsoid of revolution, the angle between the longer axis and the direction of movement is constantly changing. The mean value of resistance in all the positions of the longer axis with respect to the direction of movement is obtained from

$$R = 6\pi\mu au \left(\frac{1}{3}\kappa'_c + \frac{2}{3}\kappa'_s \right) \quad (\text{IV}, 18)$$

Substituting $\beta \rightarrow \infty$ in equations (IV, 16) and (IV, 17), we obtain the following expression for the value of resistance to the motion of an infinitely thin circular platelet with a radius a :

1. In the case of motion perpendicular to the surface of the platelet

$$R = 16\pi\mu au \quad (\text{IV}, 19)$$

2. In the case of motion parallel to the surface of the platelet

$$R = \frac{32}{3} \mu a u \quad (IV,20)$$

Table IV,1

Values of the shape coefficient

β	① Elipsoidal wydłużona			② Elipsoidal spłaszczona		
	④ wzdłuż osi obrotu	⑤ w poprzek osi obrotu	⑤ średnia statystyczna	④ wzdłuż osi obrotu	⑤ w poprzek osi obrotu	⑤ średnia statystyczna
2	1,20	1,38	1,32	0,90	0,79	0,82
3	1,40	1,73	1,62	0,88	0,72	0,77
4	1,60	2,06	1,91	0,87	0,68	0,74
6	1,97	2,68	2,44	0,86	0,64	0,72
8	2,31	3,26	2,94	0,85	0,62	0,70
10	2,65	3,81	3,42	0,85	0,61	0,69
20	4,16	6,38	5,64	0,85	0,59	0,68

Legend: 1. Elongated ellipsoid; 2. Flattened ellipsoid; 3. Along the axis of rotation; 4. Across the axis of rotation; 5. Statistical mean.

After the Oseen correction is introduced, equation (IV,20) gives results very close to those obtained experimentally

$$R = 16 \mu a u \left(1 + \frac{Re}{2\pi} \right) \quad (IV,21)$$

In a similar manner, we can obtain from formulas (IV,14) and (IV,15) expressions for the resistance to motion of acicular particles $2L$ in length and with a length to diameter ratio equal to β :

1. In the case of motion along the axis of the needle

$$R = \frac{4\pi \mu u L}{\ln 2\beta} \quad (IV,22)$$

2. In the case of motion across the axis of the needle

$$R = \frac{8\pi\mu u L}{\ln 2\beta} \quad (\text{IV},23)$$

On the basis of the above relationships, we can calculate the resistance to motion and the rate of settling for particles having shapes other than spherical.

4. The settling velocity of dust particles

A granule falling freely in the gravitational field moves in a uniform motion until the moment at which the forces acting on the particle: resistance of the medium R, gravity P, and the buoyancy of the medium W become balanced.

Since the resistance force R depends on the type of motion, the rate of free settling is also dependent on the motion, and thus the form of mathematical expressions describing the settling velocity depends on the type of motion.

Equating the forces of resistance and gravity, and solving the resultant equations with respect to the settling velocity of dust particles u_p , we obtain the following relationships:

1. For laminar motion (according to the Stokes Law)

$$u_p = \frac{1}{18} \frac{(\gamma - \gamma_0)}{\mu} d^2 \quad (\text{IV},24)$$

2. For transitional motion on the basis of the Lapple and Sheppard equation

$$u_p = \frac{20(\gamma - \gamma_0)^{1/2}}{\left(\frac{\gamma_0}{g} \cdot \mu\right)^{1/3}} d = 20 d \sqrt{\frac{(\gamma - \gamma_0)^2 g}{\gamma_0 \mu}} \quad (\text{IV},25)$$

3. For turbulent motion

$$u_p = \sqrt{\frac{3(\gamma - \gamma_0) g d}{\gamma_0}} \quad (\text{IV},26)$$

The velocity of small particles (with diameters of the order of the free path of gas molecules, or about 10^{-5} cm) is calculated

making use of the Cunningham correction

$$u_c = u_p \left(1 + K \frac{l}{r} \right) \quad (\text{IV}, 27)$$

where K is a constant ($K \approx 0.8$ to 0.86);
 l is the average free path of gas molecules (under atmospheric pressure $l = 10^{-5}$ cm);
 r is the radius of the falling particle;
 u_p is the settling velocity in laminar motion calculated from formula (IV, 24).

The maximum diameter of the particle below which the Cunningham correction must be taken into account is given by various authors to lie between 0.5 and 1 μ .

Approximate formulas for the settling velocity based on experimental data are also encountered. One of the more frequently met is the Gums formula applicable over the range $3 < Re < 300$:

$$\frac{1}{u_p} = 1,835 \frac{\mu}{(y - y_0)} \frac{l}{d^2} + 0,1514 \sqrt{\frac{y_0}{g(y - y_0)}} \frac{1}{d} \quad (\text{IV}, 28)$$

and over the range $300 < Re < 2,500$:

$$\frac{1}{u_p} = 1,835 \frac{\mu}{g(y - y_0)} \frac{l}{d^2} + 0,1463 \sqrt{\frac{y_0}{g(y - y_0)}} \frac{1}{d} \quad (\text{IV}, 29)$$

If the specific gravity of the falling particle and the viscosity of the medium are known, then the relationship between the settling velocity and the particle diameter can be determined accurately. Fig. IV, 2 shows a graph of the settling velocity of quartz particles in air.

Similar assumptions can be made with regard to the determination of the average particle diameters corresponding to the conditions of change in the type of motion. Frequently, arbitrary particle sizes are determined by assuming that their specific gravity is equal to that of water, and that they are settling in air. In this case, the turbulent motion arising at $Re > 10^3$ corresponds to granules larger than 2 mm, the upper limit of laminar motion corresponds to a particle diameter of about 100 μ (which depends not only on the specific gravity, but also on the value of Re accepted as the limit of laminar motion), while the particles having dimensions between those quoted move with the transitional type of motion. It should be remembered

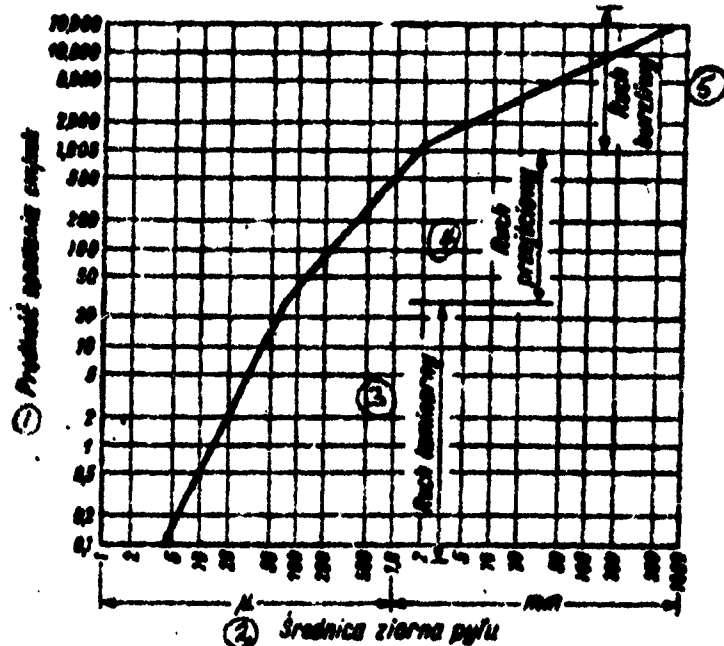


Fig. IV,2. Relationship between the settling velocity and the particle size for quartz

Legend: 1. Settling velocity, in cm/sec; 2. Particle diameter; 3. Laminar motion; 4. Transitional motion; 5. Turbulent motion.

that the average particle sizes given are approximate, and depend both on the specific gravity of the material and on the viscosity of the medium, as well as on the assumed size range for which a given type of motion occurs.

In particulate technology, the rate of settling of dust particles in air at 20°C and 760 mm Hg constitutes the basis of the size classification of particulate matter. The relationship between the rate of settling of granules in air at given parameters for arbitrarily spherical particles of various specific gravities is shown in Fig. IV,3.

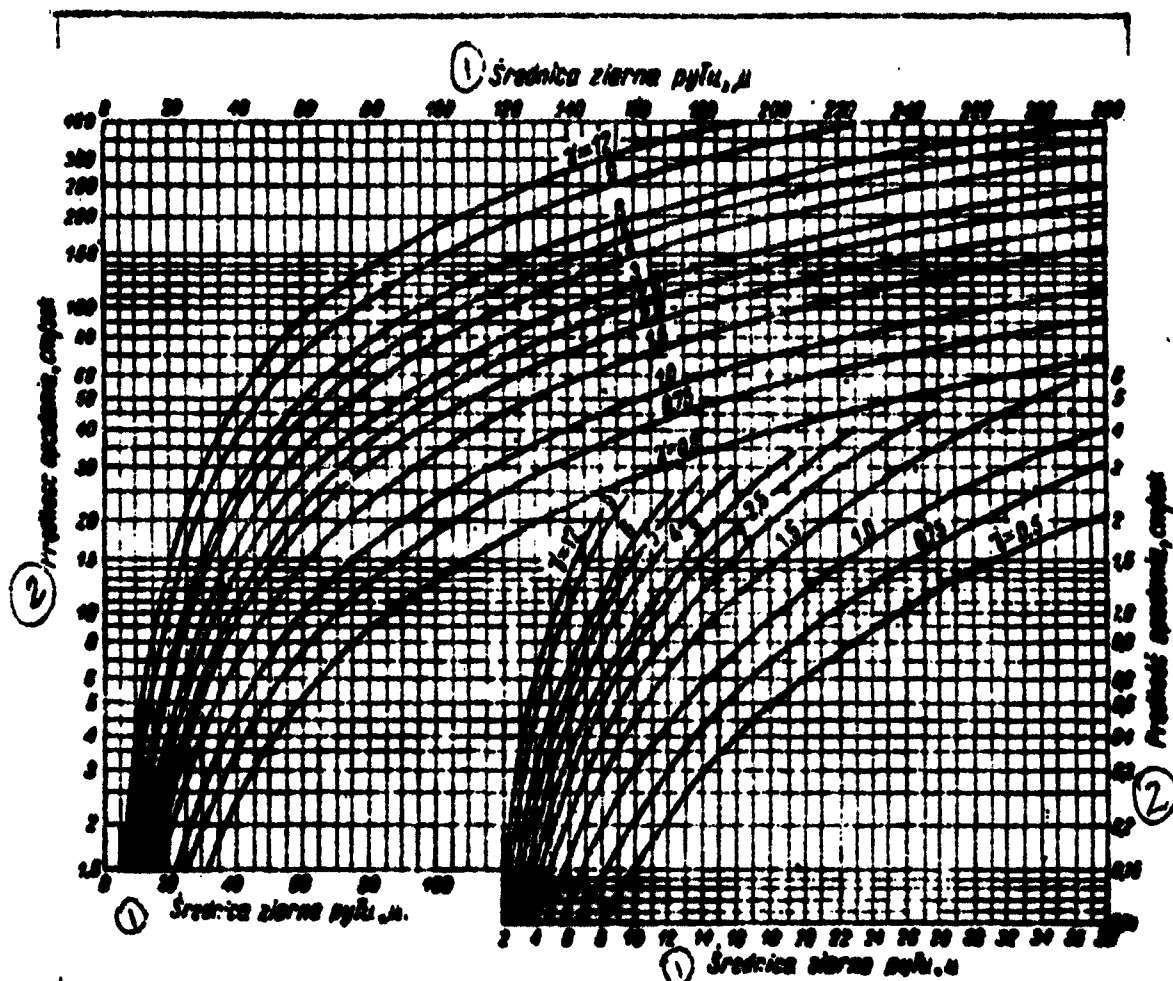


Fig. IV,3. The rate of settling of dust particles in quiescent air at 20°C and 760 mm Hg as a function of the particle size and specific gravity of the dust

Legend: 1. Particle diameter; 2. Settling velocity.

5. Brownian motion

Experiments show that very small solid particles (e.g., dust particles) suspended in a liquid or a gas execute irregular zig-zag movements. This motion was discovered by the English botanist Brown, and is named after him. It is caused by collisions between particles and the gas or liquid molecules, in which the energy absorbed is so great, that it causes a perceptible change in the direction of movement of the particles.

The theory of Brownian movement has been the subject of research by many physicists, including Smoluchowski. Einstein derived a formula for the mean square of displacement of a dust particle subject to Brownian movement in a time t

$$\overline{x^2} = 2Dt \quad (\text{IV},30)$$

where D is the diffusion coefficient, expressed by equation

$$D = \frac{kT}{f} \quad (\text{IV},31)$$

where k is the Boltzmann constant ($k = 1.38 \times 10^{-16}$ erg/°C)

T is the absolute temperature;

f is the friction coefficient of the medium.

The friction coefficient for spherical particles in the course of Brownian movement in a liquid can be derived from the Stokes law

$$f = 3\pi d\mu \quad (\text{IV},32)$$

whence we obtain the relationship:

$$D = \frac{kT}{3\pi d\mu} \quad (\text{IV},33)$$

The Einstein equations have been derived using the following assumptions:

1. The movement of the individual particles is mutually independent;
2. The mean energy of movement by the particle along any axis has the same value of $1/2kT$, in accordance with the principles of static mechanics;
3. The movements of the particle in the consecutive intervals of time $0 - t$, $t - 2t$, $2t - 3t$, etc., are mutually independent.

It follows from formulas (IV,30) and (IV,33) that the velocity of Brownian movement increases with a decrease in the particle size, in contrast with the movement caused by the force of gravity. Table IV,2 shows the rates of settling and velocities of molecular movement

Table IV,2

Rate of settling and the velocity of Brownian movement

① Średnica ziarna μ	② Prędkość opadania cm/sek	③ Prędkość ruchów Browna cm/sek	① Średnica ziarna μ	② Prędkość opadania cm/sek	③ Prędkość ruchów Browna cm/sek
0,002	$12 \cdot 10^{-3}$	$6,3 \cdot 10^{-3}$	0,2	$12 \cdot 10^{-1}$	$6,3 \cdot 10^{-4}$
0,01	$3 \cdot 10^{-3}$	$2,8 \cdot 10^{-3}$	1,00	$3 \cdot 10^{-1}$	$2,8 \cdot 10^{-4}$
0,02	$12 \cdot 10^{-3}$	$2,0 \cdot 10^{-3}$	2,00	$12 \cdot 10^{-1}$	$2,0 \cdot 10^{-4}$
0,10	$3 \cdot 10^{-1}$	$8,9 \cdot 10^{-4}$			

Legend: 1. Particle diameter, in μ ; 2. Rate of settling, in cm/sec; 3. Velocity of Brownian movement, in cm/sec.

of silver dust particles depending on the particle size (after Gibbs, (0.8)). Both velocities are more or less equal in the case of particles 0.2 μ in diameter.

The influence of Brownian movement is perceptible in the case of particles less than about 1 μ in diameter, and is partly taken into account in the Cunningham correction.

Table IV,3 gives formulas for the rate of settling of dust particles in air. The particle sizes are calculated on the assumption that their specific gravity is equal to that of water.

Table IV,3

Behavior of dust particles in air

Średnica ziarna d (1) μ	Liczba Reynoldsa Re (2) Re	Rodzaj ruchu (3)	Prędkość opadania (4)
$d > 2000$	$Re > 10^5$	burzliwy (5)	$u_p = \sqrt{\frac{3(\gamma - \gamma_0)}{\gamma_0} g d}$
$d < 2000$	$3 < Re < 10^5$	przejściowy (6)	$u_p = \frac{20(\gamma - \gamma_0)^{2/3}}{(C_0/g\mu)^{1/3}} d$
$1 < d < 115$	$Re < 3$	laminarny (7)	prawo Stokesa (8) $u_p = \frac{1}{18} \frac{(\gamma - \gamma_0)}{\mu} d^2$
$0,1 < d < 1$		laminarny (7)	poprawka Cunninghama (9) $u_p = \frac{1}{18} \frac{(\gamma - \gamma_0)}{\mu} d^2 \left(1 + k \frac{1}{r}\right)$ $k = 0,8 - 0,86$
$d < 0,1$		laminarny (7)	ruchy Browna (10) $A = \sqrt{\frac{BT}{N} \frac{1}{3\pi\mu r}}$

Legend: 1. Particle diameter, in μ ; 2. Reynolds number, Re ; 3. Type of movement; 4. Rate of settling; 5. Turbulent; 6. Transitional; 7. Laminar; 8. Stokes law; 9. Cunningham correction; 10. Brownian movement.

6. The general conditions of movement of solid particles

In section 2 of the present chapter we have considered the simplest case of particle movement when the particle is being acted upon only by the forces of gravity, buoyancy, and resistance of the medium. In reality, this case occurs very rarely, and usually the movement of a particle is a result of a combination of many forces.

If a particle is acted upon by forces $P_1, P_2, P_3 \dots P_n$, movement is caused which is opposed by the force of resistance R . After some time, an equilibrium of all the forces will be established, which can be written in the vector form

$$\overline{P}_1 + \overline{P}_2 + \overline{P}_3 + \dots + \overline{P}_{n-1} + \overline{P}_n = \overline{R} \quad (\text{IV}, 34)$$

Velocity of the particle can be calculated from formula (IV, 34). Direction of movement of the particle will be in accordance with the resultant force P .

Among the forces which act on a dust particle in addition to those stated above, we can mention:

1. Mass inertia forces arising out of acceleration of the particle, e.g., centrifugal acceleration, Coriolis force, etc.

In general, the mass inertia forces P_m acting on dust particles are calculated from the formula

$$P_m = m \frac{dv}{dx} = \frac{\pi d^3}{6} (\gamma - \gamma_0) \frac{dv}{g dx} \quad (\text{IV}, 35)$$

In the case of centrifugal acceleration caused by rotational movement, the value of P_m is expressed by the following formula:

$$P_m = \frac{\pi d^3}{6} (\gamma - \gamma_0) \frac{1}{g} \omega^2 r = \frac{\pi d^3}{6} (\gamma - \gamma_0) \frac{1}{g} \left(\frac{n}{30} \right)^2 r \quad (\text{IV}, 36)$$

where ω is the angular velocity of rotation;
 r is the radius (distance from the axis of rotation);
 n is the number of revolutions per minute.

2. Electrostatic forces P_e caused by the interaction of the electrostatic field and the charge on the dust particle

$$P_e = n e_0 E_x \quad (\text{IV}, 37)$$

where n is the number of elementary charges on the dust particle;
 e_0 is the elementary charge;
 E_x is the intensity of electrostatic field.

3. Heat diffusion forces, arising as a result of the existence of a temperature gradient in the gas in the direction of movement

$$P_t = C \frac{d}{p} \frac{1}{T} \frac{dT}{dx} \quad (\text{IV}, 38)$$

where C is a constant;
 p is the gas pressure;
 d is the average particle diameter;
 T is the absolute temperature of the gas;
 $\frac{dT}{dx}$ is the temperature gradient of the gas in the direction of movement.

4. Macroscopic diffusion forces P_D , to be described in chapter V.

If the medium in which the dust particle is suspended is quiescent, but moves with a velocity v with respect to an immobile system of reference, then because of the force of resistance, the particle will also have a velocity component v_1 with respect to this system of reference.

In the study of the behavior of dust particles in the atmosphere we find that in most cases inertia, electrostatic, and heat diffusion forces are negligibly small in comparison with the force of gravity, atmospheric diffusion, and the resistance of the moving medium. Depending on the actual conditions, any of these factors may have a decisive effect on the behavior of dust particles.

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Chapter V

The Influence of Meteorological Conditions on the Dispersion of Pollutants

1. Introductory remarks

Meteorological phenomena are one of the decisive factors influencing the distribution and concentration of pollutants in the atmosphere. The variability of meteorological conditions causes variations in the basic parameters of atmospheric pollution, i.e., the pollutant concentration and dustfall at a given point. From the viewpoint of the science of pollution, the knowledge of the local atmospheric conditions in the region under consideration is of paramount importance. It can be taken that the area of perceptible effect by a source of pollutant emission lies within the radius of several tens of kilometers.

Following are the most important factors influencing the character and range of pollutant dispersal: 1), wind velocity; 2), vertical temperature gradient; 3), vertical wind velocity gradient; 4), fluctuations in wind velocity; 5), prevalent direction of the wind, and fluctuations in it; 6), the Richardson number and the phenomenon of atmospheric diffusion; 7), meteorological precipitation.

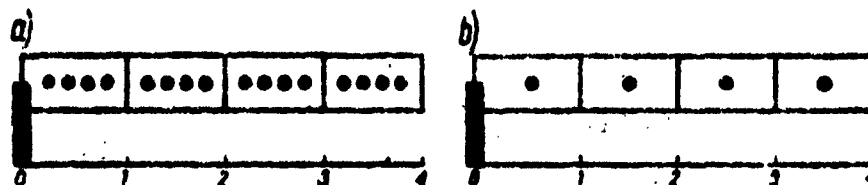
The above factors will be discussed in the body of the present chapter.

2. The influence of wind velocity on the dispersion of pollutants

Horizontal displacement of air masses affects the dispersion in two ways. Firstly, the average wind velocity is also the speed at which the pollutants are dispersed in the atmosphere. Secondly, assuming that emission from a given source is constant and invariable in time, an increase in the wind velocity causes a decrease in the pollutant concentration at a given point.

On the basis of an analysis of the formulas to be given in chapter VI, we shall see that in most problems the pollutant concentration or dustfall are inversely proportional to the average wind velocity $\bar{w}$. A rough schematic representation of this phenomenon is

shown in Fig. V, I.



Distance from source of emission Distance from source of emission

Fig. V, I. A schematic representation of the effect of wind velocity on pollutant concentration; emission — four units per second; a) wind velocity $v_w = 1$ m/sec; b) wind velocity $v_w = 4$ m/sec.

3. Vertical temperature gradient

In order to define the adiabatic temperature gradient, we shall assume that a parcel of air has been displaced in the vertical direction over a distance dz , and the rate of displacement was so slow, that the parcel of air was under the same pressure as the surrounding air in all its positions. The change in the pressure of the parcel of air can be obtained from the barometric equation

$$g dz = - R T' \frac{dp}{p} \quad (V,1)$$

$$\frac{dp}{p} = - \frac{g}{R T'} dz \quad (V,2)$$

where T' is the temperature of the surrounding air.

Assuming that the change in the parcel of air gas is adiabatic, we can determine the change in its pressure from the adiabatic equation

$$\frac{dT}{T} = \frac{R}{C_p} \frac{dp}{p} \quad (V,3)$$

$$\frac{dp}{p} = \frac{C_p}{R} \frac{dT}{T} \quad (V,4)$$

Comparing equations (V,1) and (V,4), we obtain

$$- \frac{dT}{dz} = \frac{g T}{C_p T'} \quad (V,5)$$

If we assume a small displacement of the parcel of air so that the ratio of T to T' is approximately equal to unity, equation (V,5) can be written in the following form:

$$-\frac{dT}{dz} = \frac{g}{C_p} = \Gamma \quad (V,6)$$

The quantity Γ is the so-called adiabatic vertical gradient of air temperature; Γ equals $1^\circ\text{C}/100 \text{ m}$. The foregoing considerations apply to dry air. If the air is humid, equation (V,6) can be written as follows:

$$-\frac{dT}{dz} = \varphi' \frac{g}{C_p} = \Gamma' \quad (V,7)$$

where φ' is a function dependent on temperature and pressure.

If the atmosphere had the adiabatic temperature gradient, the air density above the Earth's surface would be the same at all altitudes.

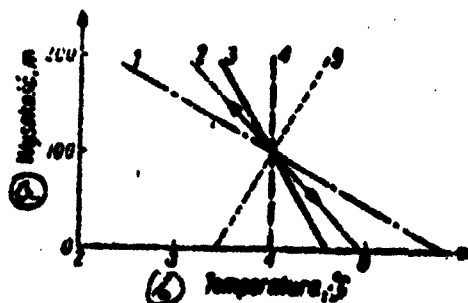
Under the actual conditions, heat exchange between the Earth's surface and the atmosphere causes the temperature gradient in the lower layers of the atmosphere to deviate substantially from adiabatic. The actual temperature gradient can assume both greater and smaller values than $\Gamma = 1^\circ\text{C}/100 \text{ m}$, including negative values (inversion).

The average vertical temperature gradient in the atmosphere is $\varphi = 0.6^\circ\text{C}/100 \text{ m}$. In Fig. V,2, such a variation of temperature with altitude is represented by line 3.

The vertical temperature gradient exerts a decisive influence on the stability of the atmospheric layer adjoining the earth. Figs V,3, V,4, and V,5 depict the behavior of a parcel of air at different values of the vertical temperature gradient.

Fig. V,2. Graphs showing the relationship between temperature and altitude to different values of the vertical temperature gradient; 1. Super-adiabatic gradient; 2. Adiabatic gradient; 3. Average gradient; 4. Isothermic gradient; 5. Inversion.

Legend: a. Altitude; b. Temperature.



If the adiabatic temperature gradient is present in the air (Fig. V,3), then after being displaced from its original position up or down, a parcel of air will have the same temperature and specific gravity as that of the surrounding air (assuming an adiabatic change in the parcel itself). The force of aerostatic buoyancy which could cause a further displacement of the parcel of air does not arise, and so the parcel is in a state of neutral equilibrium.

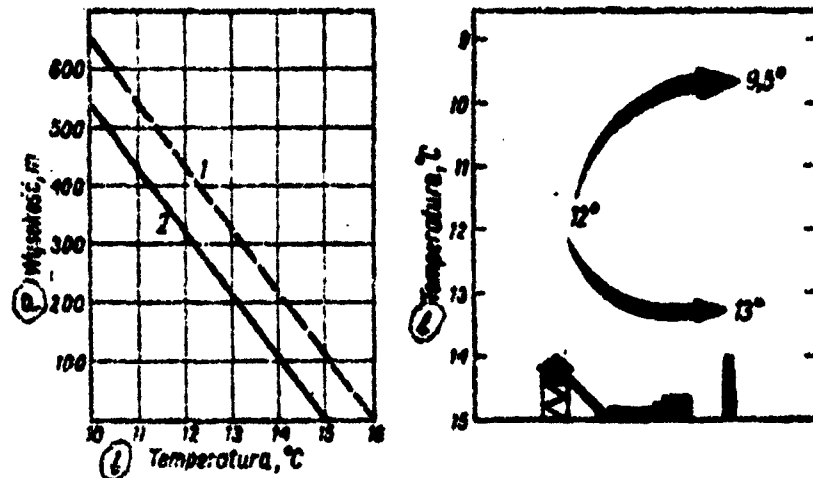


Fig. V,3. Behavior of a parcel of air in the case of adiabatic temperature gradient. 1. Adiabatic gradient; 2. Actual gradient.

Legend: a. Altitude; b. Temperature.

If the temperature gradient is greater than adiabatic (i.e., superadiabatic), the parcels of air are in unstable equilibrium (Fig. V,4). A parcel of air displaced upwards from its original position will always be at a temperature higher than that of the surrounding air, and its density will be less. As a result, aerostatic forces will arise causing a continued upward displacement of the parcel. If the parcel is displaced downward from its original position, then its temperature will be always lower than that of the surrounding air, and it will continue to fall. Thus, an exceptional instability of the atmosphere occurs in the case of a super-adiabatic temperature gradient.

If the temperature gradient is smaller than adiabatic (Fig. V,5), a parcel of air displaced from its original position is acted upon by forces tending to restore it to its original position. Although a stable equilibrium of a parcel of air occurs always

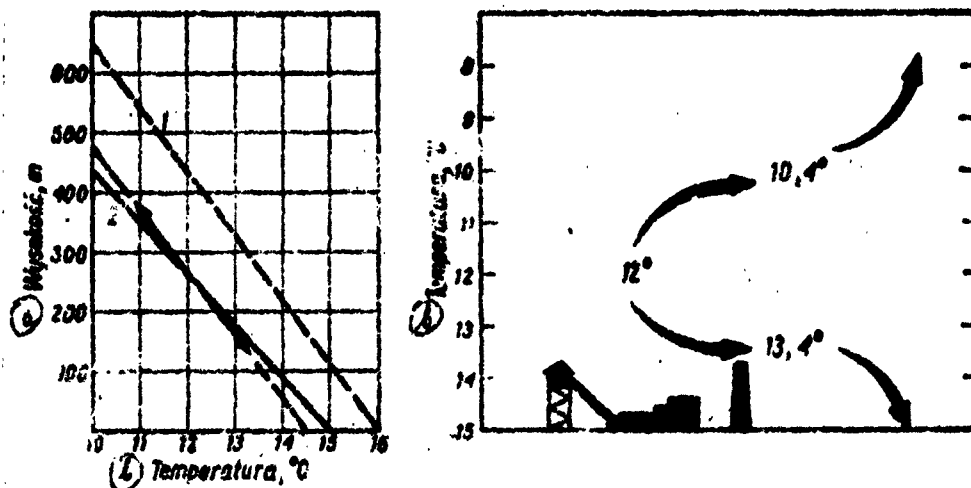


Fig. V.4. Behavior of a parcel of air in the case of a super-adiabatic temperature gradient. 1. Adiabatic gradient; 2. Actual gradient.

Legend: a. Altitude; b. Temperature.

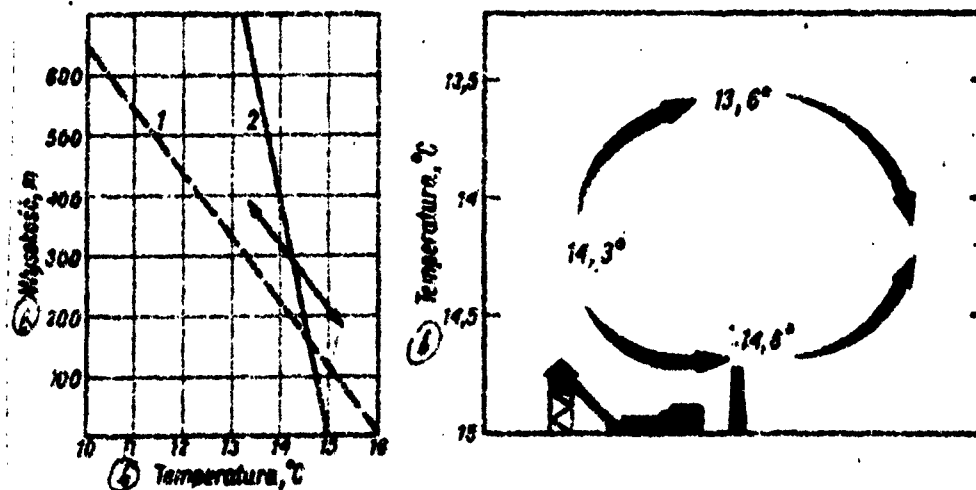


Fig. V.5. Behavior of a parcel of air under the conditions of inversion 1. Adiabatic temperature gradient; 2. Actual temperature gradient (inversion).

Legend: a. Altitude; b. Temperature.

when $\phi < \Gamma$, it is only in the case of inversion, i.e., when $\phi < 0$, that the stability of the individual levels of the atmosphere is so great that there is virtually no mixing.

Mathematical expression of the equilibrium of a parcel of air may take the following form. Equation for the equilibrium of forces acting upon the parcel in the horizontal direction has the form

$$\gamma' - \gamma = \frac{\gamma}{g} \frac{d^2 z}{dt^2} \quad (V,8)$$

where γ is the density of the air comprising the parcel of air under consideration;
 γ' is the density of the surrounding air;
 z is the altitude;
 t is time;
 g is gravity.

If we assume that the pressure inside the parcel of air, and that of the surrounding air are equal, then (V,8) can be written in the form

$$\frac{T - T'}{T} g = \frac{d^2 z}{dt^2} \quad (V,9)$$

Let the temperature of the parcel of air and its environment in the initial position be T_0 . After displacement of the parcel of air over a distance z , its temperature will be $T = T_0 = \Gamma z$, while the temperature of the surrounding air will be $T' = T_0 - \phi z$. Taking these relationships into account, we obtain from equation (V,9)

$$\frac{\phi - \Gamma}{T} z g = \frac{d^2 z}{dt^2} \quad (V,10)$$

It follows from equation (V,10) that acceleration $\frac{d^2 z}{dt^2}$ acting on the parcel of air displaced from the position of equilibrium increases with an increase in the distance z of its displacement from the original position, with a decrease of the surrounding temperature T' , and with an increase in the difference between the adiabatic and the actual temperature gradients $\phi - \Gamma$. If the atmospheric equilibrium is stable, i.e., $\phi < \Gamma$, then the acceleration acting on the parcel of air is negative, i.e., it is in the direction opposite to that of its initial displacement. If the equilibrium is unstable (super-adiabatic gradient) $\phi > \Gamma$, then the acceleration has a positive sign, that is, it is in the direction of the original displacement.

The knowledge of the vertical temperature gradient is of

prime importance to the study of pollution, particularly in the lower layers of the atmosphere. As has been mentioned above, it can vary within wide limits as a result of heat exchange with the ground.

Attention should be paid to the regularity of the formation of typical temperature gradients and their variability on the diurnal as well as the annual scale. During the day, the ground layer of air is heated by the Earth's surface which becomes heated by solar radiation, so that there is a tendency to form the super-adiabatic temperature gradient. Conversely, during the night the ground layers of air lose heat to the cooler ground surface, creating the conditions favoring inversion. This regularity is seen particularly clearly during good weather, that is, during cloudless days and nights. Fig. V,6 shows a schematic representation of the possibility of changes in the vertical temperature gradient in the lower layers of the atmosphere.

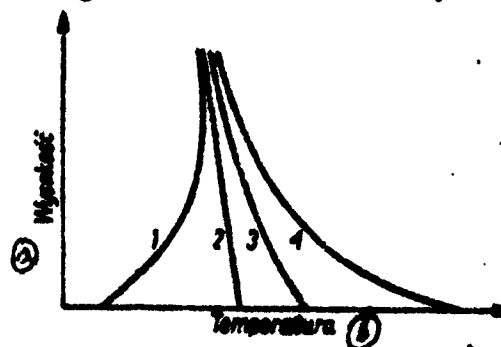


Fig. V,6. Graph of possible changes in the vertical temperature gradient in the ground layers of the atmosphere on cloudless days and nights. 1. Inversion; 2. Average gradient; 3. Adiabatic gradient; 4. Super-adiabatic gradient.

Legend: a. Altitude; b. Temperature.

Obviously, the temperature gradient may change with altitude, causing conditions which may or may not favor the dispersion of pollutants in the atmosphere. Several characteristic curves showing the relationship between the vertical temperature gradient and the altitude are given in Fig. V,7.

Fig. V,8 shows a schematic representation of pollutant dispersion depending on the vertical temperature gradient. Evidently, case e) is the most disadvantageous, where the inversion layer is formed at the level of the smoke stack. Emission cannot penetrate this layer to escape into the upper parts of the atmosphere, and the whole mass of pollutant is concentrated in the ground layer.

The frequency and duration of the occurrence of the typical

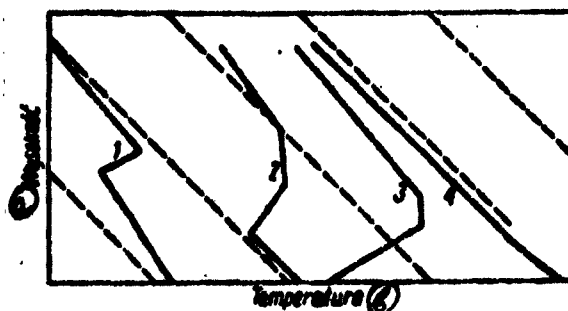


Fig. V.7. Characteristic examples of the change of temperature with altitude. 1. Inversion layer at a finite altitude, with flow of warm air; 2. Flow of a cold air mass at a moderate wind velocity in layers adjoining the ground; 3. Inversion in the ground layer of air on a clear night; 4. Change of temperature with altitude on a sunny summer afternoon. The dotted lines represent temperature changes for the adiabatic temperature gradient.

Legend: a. Altitude; b. Temperature.

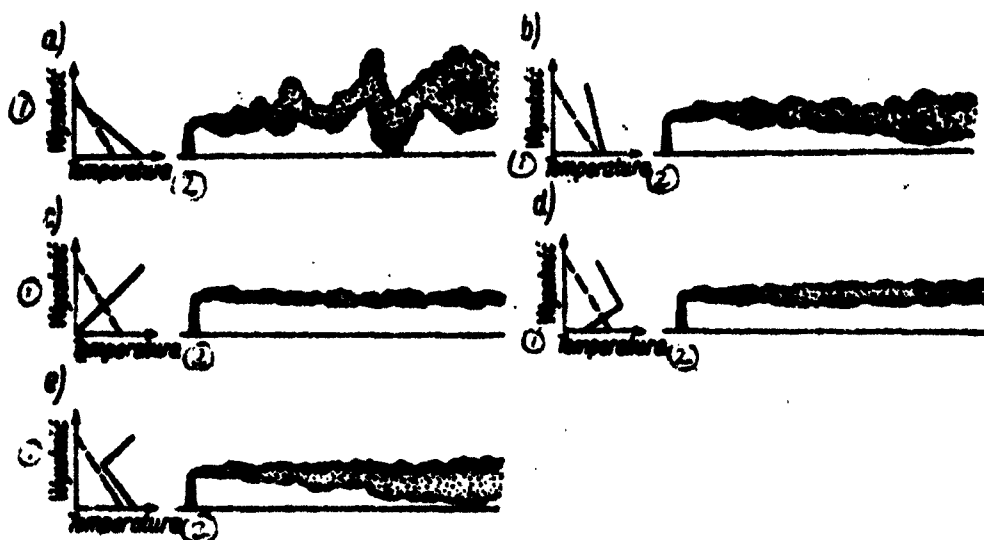


Fig. V.8. The nature of pollutant dispersion in the atmosphere depending on the vertical temperature gradient. a. Super-adiabatic gradient; b. Average gradient; c. Inversion; d. Inversion layer below emission source; e. Inversion layer starting above emission source.

Legend: 1. Altitude; 2. Temperature.

vertical temperature gradient values also show a regularity on the annual scale. Fig. V,9 shows a graph of temperature differences at 2 and 34 meters above Potsdam. It is seen from this Figure that the durations of inversion periods are much longer in the winter than in the summer. This is due entirely to the fact that the duration of insolation in the winter is much shorter than it is in the summer.

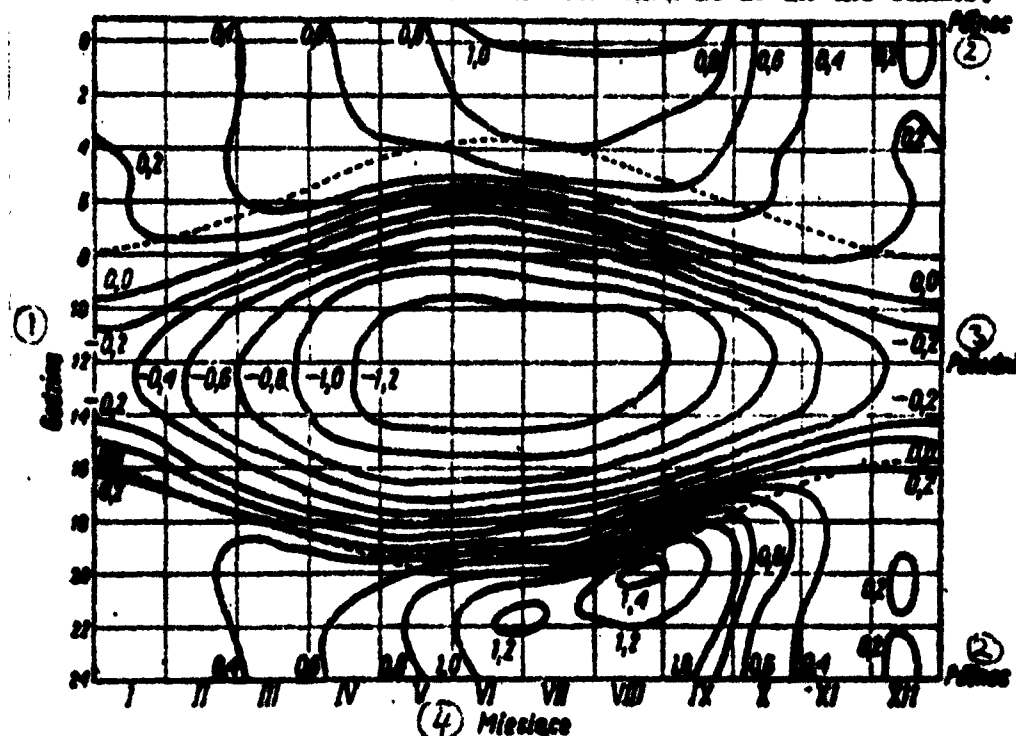


Fig. V,9. A graph of temperature differences at 2 and 34 meters at Potsdam. The dotted lines represent the sunrise and the sunset.

Legend: 1. Hour; 2. Midnight; 3. Midday; 4. Month.

Although the formation of a given vertical temperature gradient is most strongly affected by heat exchange with the surface of the Earth, it should not be forgotten that other factors are also significant. Wind velocity and direction, as well as the nature of the terrain can have a significant influence on the formation of the vertical temperature gradient. For instance, the temperature gradient rapidly becomes adiabatic as a result of the mixing of the individual atmospheric layers when there is a strong wind over a terrain conducive to considerable turbulence.

4. Vertical wind velocity gradient

In the case of an adiabatic vertical temperature gradient, the wind velocity at any given altitude is determined by the equation

$$\bar{v}_z = \frac{1}{k} \sqrt{\frac{g \tau_0}{\gamma}} \ln \frac{z}{z_0} \quad (V,11)$$

where k is the Karman constant;

τ_0 is the tangential wind intensity on ground level;

γ is the specific gravity;

z_0 is the roughness of the ground (this quantity is a measure of length, and is numerically expressed as 1/10 to 1/30 of the height of the objects present on the ground. For instance, z_0 for terrain covered with short grass is 0.1 cm, while in the case of terrain overgrown with trees about 10 meters in height, $z_0 = 100$ cm.).

The equation derived by Deacon (V,3) is more general:

$$\bar{v}_z = \sqrt{\frac{g \tau_0}{\gamma}} \frac{1}{k(1-\beta)} \left[\left(\frac{z-d}{z_0} \right)^{1-\beta} - 1 \right] \quad (V,12)$$

where β is a parameter dependent on the value of the vertical temperature gradient, and varies between 0.8 for inversion conditions and 1.2 for super-adiabatic conditions. The quantity d , which is a measure of length, and corresponds to the height of closely built-up urban areas or the height of trees in the analysis of the wind velocity distribution over forests, is frequently omitted in equation (V,12). For $\beta = 1$, equation (V,12) becomes identical with the Prandtl equation. The wind velocity distribution calculated from equation (V,12) for different vertical temperature gradients is shown in Fig. V,10.

Unfortunately, the complicated mathematical form of equations (V,11) and (V,12) does not permit their application in the formulas for dispersion of pollutants in the atmosphere. Instead, a simple relationship derived by O. G. Sutton on the basis of the statistical theory of turbulence is employed:

$$\frac{v}{v_1} = \left(\frac{z}{z_1} \right)^{\frac{n}{2-n}} \quad (V,13)$$

where v_1 is the average wind velocity at an altitude z_1 ;

n is the meteorological exponent dependent on the value of the vertical temperature gradient.



Fig. V,10. Graph of the changes in wind velocity with altitude for different values of the vertical temperature gradient. 1. Inversion; 2. Adiabatic temperature gradient; 3. Super-adiabatic temperature gradient.

Legend: a. Wind velocity.

It is accepted in the science of meteorology to measure wind velocity at 16 meters above the ground level.

The values of the meteorological exponent n are given in Table V,1.

Table V,1

Values of n for various meteorological conditions

Type of flow	Wind velocity, m/sec	Temperature gradient $^{\circ}\text{C}/100 \text{ m}$	Exponent n (average)
Turbulent	7	1.0	0.2
Transitional	5	0.6	0.25
Laminar	2	0.2	0.5

5. Fluctuations in wind velocity

The actual wind velocity at any given point is usually determined with the aid of four component vectors: the vector of average wind velocity $\bar{V}_w$ in the direction of the x -axis, and three pulsation components v'_{wx} , v'_{wy} and v'_{wz} in three directions perpendicular to axes x , y and z respectively. The sum of these four vectors gives the actual wind velocity at a given point and moment of time. In accordance with definition, the mean value of each of the three

pulsation components over a sufficiently long period of time is zero. Therefore, any anemometer with a relatively high inertia gives the average wind velocity.

The following expressions have been accepted as the measure of turbulence in the direction of the individual axes:

$$\sigma_x = \sqrt{\frac{\overline{v_{wx}^2}}{\overline{v_x^2}}} \quad (V,14a)$$

$$\sigma_y = \sqrt{\frac{\overline{v_{wy}^2}}{\overline{v_y^2}}} \quad (V,14b)$$

$$\sigma_z = \sqrt{\frac{\overline{v_{wz}^2}}{\overline{v_z^2}}} \quad (V,14c)$$

The turbulent wind is, in principle, independent of its velocity, but depends to a considerable degree on the vertical temperature gradient. At low altitudes, turbulence is essentially non-isotropic, i.e., $\sigma_x \neq \sigma_y \neq \sigma_z$, but according to some authors (V,1), it becomes fully isotropic at altitudes above 25 meters.

6. Mean wind direction and deviations therefrom

It is self-evident that the direction of wind influences in a decisive manner the distribution of pollutants in the vicinity of a given emission source. The highest pollution concentrations will be found downwind from the source, which is also seen from the formulas given in chapter VI. In order to define the degree of pollution of an area surrounding a given emission source, it is necessary to know the average annual, or better still, a long-term frequency of wind directions. In meteorology, this data is given in the form of tables or graphs. As a rule, the tables or graphs give the frequency of winds in the individual directions, taking into account the distribution of wind velocities. Fig. V,11 and Table V,2 show the frequency and velocity of winds in given directions.

It should be stressed that the data on wind frequency and direction can vary within relatively wide limits. For this reason, reliance on meteorological data obtained from a weather station between a few and several tens of kilometers from the emission source under study may lead to false results. It would be most appropriate to carry out wind velocity and direction measurements in the immediate vicinity of the source of emission. If this is impossible,

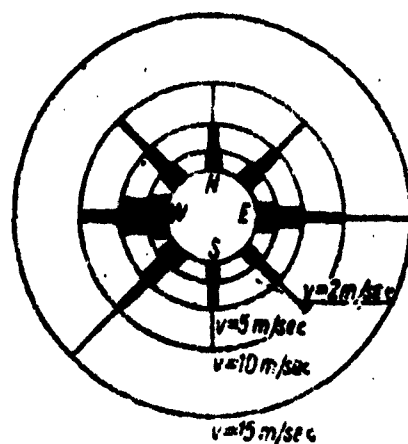


Fig. V,11. Rose of the winds representing the frequency of winds of various velocities and in various directions

use should be made of the data obtained at the nearest meteorological station, making a careful analysis of the possible divergence of these data from the conditions in the region of interest, particularly taking into account the different topographical conditions.

Table V,2

Average annual frequency of winds in given directions, with a division into velocity distribution, in percent

① Prędkość m/sec	② Kierunki wiatru								
	N	NE	E	SE	S	SW	W	NW	③ Razem
0-2	2,8	3,1	4,5	1,5	1,1	4,3	7,0	3,8	28,1
2-5	2,9	3,7	5,8	1,3	1,0	5,9	11,5	4,4	36,5
5-10	0,4	0,7	1,5	0,3	0,2	1,4	2,5	0,8	7,9
10-15	—	0,0	0,1	—	0,0	0,1	0,0	0,0	0,2
Suma ④	6,1	7,5	11,9	3,1	2,3	11,7	21,1	9,0	72,7

Legend: 1. Velocity, in m/sec; 2. Directions of winds; 3. Total; 4. Grand total.

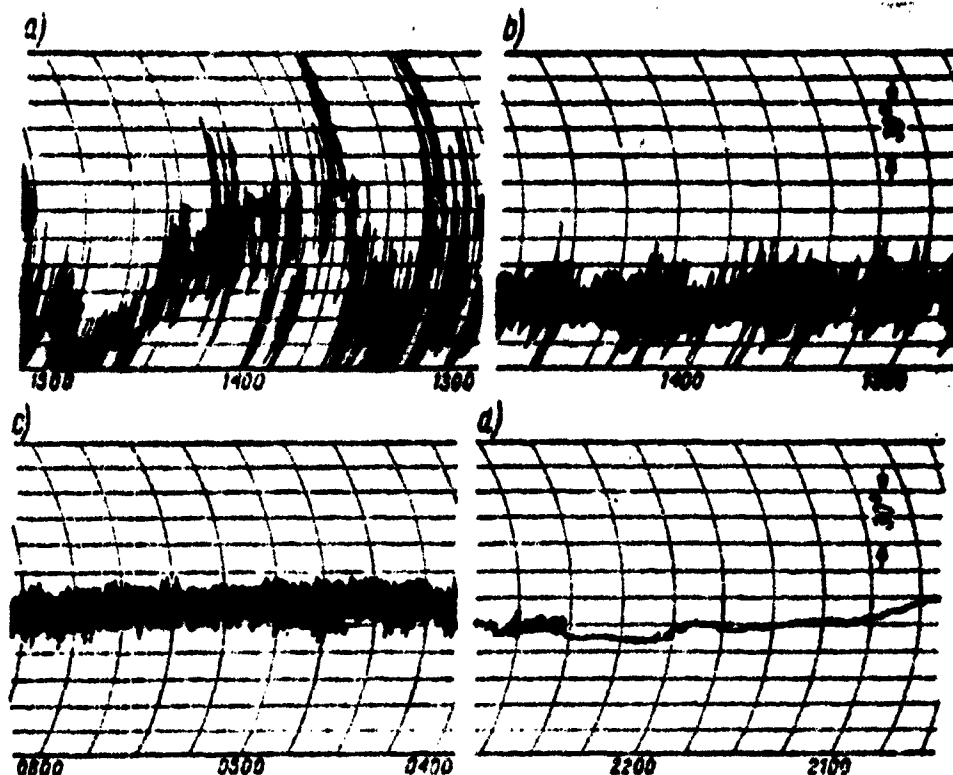


Fig. V,12. Recording of variations in the direction of the four characteristic types of wind: a. Type A; b. Type B; c. Type C; d. Type D.

The magnitude of the variation in wind direction has also a considerable effect on the pollutant concentration at the individual points around the source of emission.

The deviation of the wind from its prevailing direction is connected with the general turbulence of the air. W. P. Lowry (V,4) distinguishes four different types of wind depending on the magnitude and frequency of deviation from the prevailing direction of winds. Chart recordings of these wind types are shown in Fig. V,12. These have been used as the basis for the graphs shown in Fig. V,13, which represent deviation frequency of the different types of wind.

A comparison of these graphs shows that, other parameters being constant, type A wind scatters all emission over a segment with an angle of 40° , while type D wind scatters the same amount of emission over a segment with an angle of about 2° (ignoring diffusion).

Obviously, pollutant concentration in the second case will be incomparably greater than in the first.

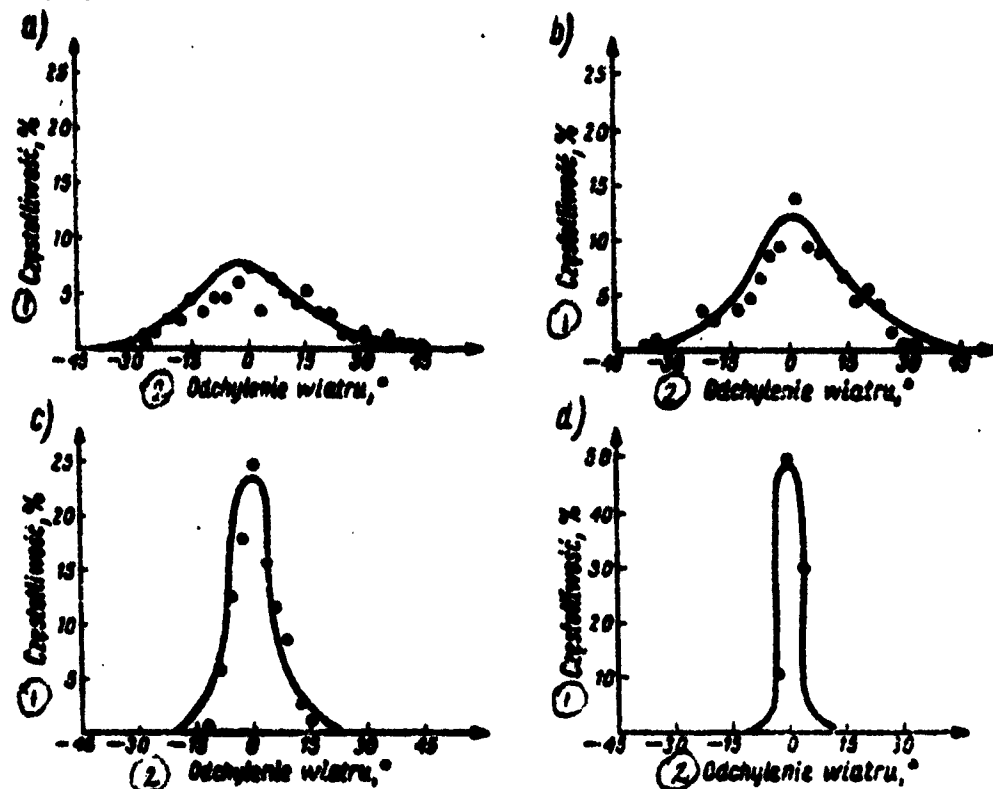


Fig. V,13. Distribution of deviations of the four types of characteristic winds: a. Type A; b. Type B; c. Type C; d. Type D.

Legend: 1. Frequency; 2. Deviation.

On the other hand, in the case of large deviations from the prevailing direction of the wind (types A and B), pollutant concentration measured at any given point depends largely on the duration of sampling. In the case of measurements lasting over short periods of time the results may show differences amounting to the order of magnitude of the measurement itself, both between themselves, and between the average results of measurements lasting several hours. This phenomenon is explained graphically in Fig. V,14.

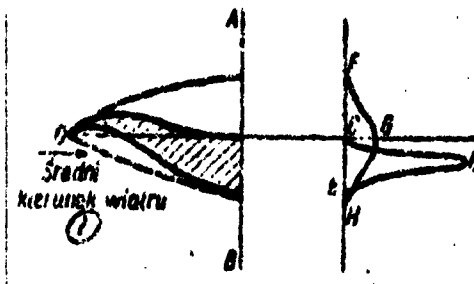


Fig.V,14. Pollutant distribution as a function of the duration of sampling.

AB - the plane in which the sampling is made; FGH - distribution of pollutant concentrations obtained from long-term sampling; CDE - distribution of pollutant concentration resulting from a brief sampling.

Legend: 1. Average wind direction.

7. The Richardson number and the phenomenon of atmospheric diffusion

No generally accepted theory of atmospheric diffusion has been developed to date. Nonetheless, there are many approximate methods of determining diffusion coefficients applicable to various atmospheric conditions.

Among the first to be developed, the Richardson (V.5) and Roberts (V.6) theory of turbulent diffusion is based on the premise that the value of the atmospheric diffusion coefficient is proportional to the molecular diffusion coefficient. This theory assumes that static stress τ and vertical heat stream q in the lower layers of the atmosphere at altitudes up to 50 meters are constant under given meteorological conditions. The second assumption was that air turbulence can only be caused by a supply of energy from outside.

The basic sources of energy are:

1. The work of tangent stress equal to $\tau \bar{V}_w$;
2. Supply of heat from outside equal to $\frac{q \bar{V}_w}{C_p T}$

If the heat stream is small, then air turbulence is caused mainly by tangent stress resulting in forced convection. In the opposite case, when $\bar{V}_w$ is small in comparison with $q \tau / C_p T$,

turbulence is caused mainly by the forces of buoyancy of air masses at different temperatures (free convection).

The degree and nature of turbulence in these two cases depends on the value of the ratio

$$Rf = \frac{g \theta z}{C_p T \overline{v_w}}$$

In view of the difficulties associated with the measurement of the heat stream q and static stress τ , Richardson introduced an analogous expression for air turbulence which takes into account the vertical temperature gradient and wind velocity. This is the so-called Richardson number, expressed as

$$Ri = \frac{g \left(\frac{\partial T}{\partial z} \right)}{T \left(\frac{\partial v_w}{\partial z} \right)^2} \quad (V,16)$$

Fig. V,15 shows the results of turbulence measurements as a function of Ri according to E. Deacon (V.2). The circles represent the measurements of the heat stream and tangential stress, while the crosses stand for the vertical temperature gradient and wind velocity measurements at different altitudes.

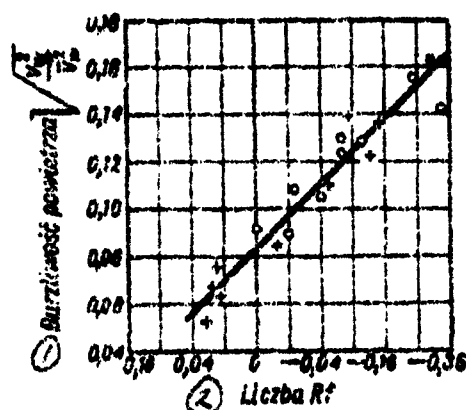


Fig. V,15. Graph of the dependence of air turbulence on the Richardson number

Legend: 1. Air turbulence; 2. Ri number.

Although the numbers Rf and Ri describe in a univocal manner the degree and nature of atmospheric turbulence, their application in the problems of atmospheric diffusion and dispersion of pollutants in air leads to very complicated relationships.

A wider application is enjoyed by the theory of turbulent diffusion developed by O. G. Sutton (V.6 and V.9) on the basis of the Taylor theory (V.10), assuming that the individual pollutant elements move in a random manner in accordance with the disordered state theory of Markov.

O. G. Sutton has solved the Taylor diffusion equation assuming a certain form of the Lagrange function which describes the medium's turbulence. In Sutton's assumption, the Lagrange function in the case of atmospheric diffusion depends on the meteorological exponent n , kinematic viscosity ν , and the mean square of wind pulsation rate in the direction of diffusion (for instance, $\overline{v_{wx}^2}$ for direction x).

Using these assumptions, Sutton derived the following equations for diffusion coefficient:

$$C_x = \frac{4 \nu^n}{(1-n)(2-n)\overline{v_w^n}} \left(\frac{\overline{v_{wx}^2}}{\overline{v_w^2}} \right)^{1-n} \quad (V.17a)$$

$$(V.17b)$$

$$C_y = \frac{4 \nu^n}{(1-n)(2-n)\overline{v_w^n}} \left(\frac{\overline{v_{wy}^2}}{\overline{v_w^2}} \right)^{1-n} \quad (V.17c)$$

$$C_z = \frac{4 \nu^n}{(1-n)(2-n)\overline{v_w^n}} \left(\frac{\overline{v_{wz}^2}}{\overline{v_w^2}} \right)^{1-n}$$

Although the vertical temperature gradient does not appear in these formulas, it is taken into account in expressions of the type

$$\left(\frac{\overline{v_{wx}^2}}{\overline{v_w^2}} \right) \text{ dependant on } Rf \text{ or } Ri.$$

Table V,3 shows the values of diffusion coefficients C_y and C_z for various conditions of air turbulence (for various n) and for different elevations of emission sources. The values of diffusion coefficient C_x in the direction of the wind have not been given,

since this term is ignored in all solutions as being negligible in comparison with the wind velocity v_{px} . It follows from the values of coefficients C_y and C_z given in Table V,3 that at an altitude of 25 meters $C_y > C_z$, while above 25 meters, atmospheric turbulence is isotropic ($C_y = C_z$). However, numerous observations have shown that this condition is not fulfilled in the case of inversion, and that $C_y > C_z$ at altitudes greater than 25 meters.

In deriving his formulas for diffusion coefficients, O. G. Sutton assumed that the surface of the earth is aerodynamically smooth, although this assumption is not justified in most cases. As a result, the pollutant concentration values calculated on the basis of the values given in Table V,3 are a little higher than actual. In his subsequent work (V.7), O. G. Sutton proved that the aerodynamic

Table V,3.

Values of coefficients C_y and C_z under various meteorological conditions

① Wysokość nad poziomym ziemi	n = 0,20		n = 0,25		n = 0,35		n = 0,50	
	C_y	C_z	C_y	C_z	C_y	C_z	C_y	C_z
0	0,42	0,24	0,24	0,14	0,15	0,09	0,12	0,07
10	0,42	0,24	0,24	0,14	0,15	0,09	0,12	0,07
25		0,24		0,14		0,090		0,070
30		0,23		0,13		0,085		0,065
45		0,21		0,12		0,075		0,060
60		0,19		0,11		0,070		0,055
75		0,18		0,10		0,065		0,050
90		0,16		0,09		0,055		0,045
105		0,13		0,07		0,045		0,035

Legend: 1. Altitude above ground level.

roughness of the earth's surface can be taken into account by replacing the values for kinematic viscosity in equation (V,17) by a parameter characterizing the earth's surface, i.e., by the so-called macro-viscosity. It is defined as the product of velocity and the roughness of the terrain.

In the Bosanquet and Pearson equations for dispersion of pollutants there are diffusion coefficients denoted by the symbols

Table V,4.

Values of coefficients p and q under various meteorological conditions

⁽¹⁾ Burzhtovsk	p	q	p/q
② Max	0,02	0,04	0,50
③ Srednia	0,05	0,08	0,63
④ Data	0,10	0,16	0,63

Legend: 1. Turbulence; 2. Low; 3. Medium; 4. High.

p and q . The values of the diffusion coefficient p in the vertical direction have been calculated on the basis of static stress between atmospheric layers, vertical velocity gradient, photographs showing the dispersion of pollutants emitted from stacks, and studies on the stoppage of small smoke clouds near the earth's surface. The values of the diffusion coefficient q in the horizontal direction have been calculated from the horizontal motions of small balloons.

The average values of coefficients p and q are given in Table V,4.

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Chapter VI

Dispersion of Pollutants in the Atmosphere

1. Introductory remarks

Nearly all calculation formulas concerning the dispersion of pollutants in the atmosphere are derived from the general diffusion equation

$$\frac{\partial \bar{S}}{\partial t} + \bar{v}_x \frac{\partial \bar{S}}{\partial x} = \frac{\partial}{\partial x} C_x \frac{\partial \bar{S}}{\partial x} + \frac{\partial}{\partial y} C_y \frac{\partial \bar{S}}{\partial y} + \frac{\partial}{\partial z} C_z \frac{\partial \bar{S}}{\partial z} \quad (\text{VI},1)$$

where x, y, z are the rectangular coordinates; axis x points in the direction of the wind, axis y is horizontally perpendicular to it, while axis z points upwards;

C_x, C_y, C_z are coefficients of atmospheric diffusion in the directions x, y and z .

$\bar{v}_x$ is the average wind velocity in the direction of x ;
 $\bar{S}$ is the mean pollutant concentration at a given point, being an average of samplings lasting at least three minutes each.

Equation (VI,1) is valid on the assumption that the pollutants have the properties of the surrounding parcels of air, i.e., they do not fall under the force of gravity, nor do they rise upward with respect to the surrounding air as a result of aerodynamic forces.

There are many solutions in the literature of the fundamental diffusion equation (VI,1) derived for the various characteristic types of emission sources.

Depending on their geometry, we distinguish the following emission sources:

1. Point sources;
2. Line sources;
3. Plane sources.

Further, emission sources are divided into continuous and intermittent depending on the character of emission.

Depending on their elevation, emission sources are divided

into those at the ground level ($H = 0$), and sources at a finite elevation H .

In industry, we usually encounter continuous point or line emission sources at a finite elevation with respect to the surrounding terrain. These are the industrial smoke stacks; stacks standing singly as point sources, and stacks standing in series across the direction of the wind as line sources. A plane source may have the form of a number of stacks treated as a unit (for instance the chimneys of domestic hearths in closely built-up urban areas).

Intermediate emission sources are encountered almost exclusively in all sorts of explosions. Obviously, these sources can be encountered at various elevations.

A characteristic example of continuous plane emission can be seen in smoke screen bombs used in war operations.

2. Calculation formulas for the individual types of emission sources

2.1. Point sources

The concentration of pollutants emitted by a point source at the ground level ($H = 0$) can be calculated from the Sutton formula:

$$S(x, y, z) = \frac{2E}{\pi C_y C_z v_w x^{2-n}} \exp \left[-x^{n-2} \left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2} \right) \right] \quad (\text{VI}, 2)$$

where S is the pollutant concentration;

E is the amount of pollutants emitted per unit time.

The formula for pollutant concentration in emission from a source situated at a height H above the ground level is given by O. G. Sutton in the following form:

$$S(x, y, z) = \frac{E}{\pi C_y C_z v_w x^{2-n}} \exp \left(-\frac{y^2}{C_y^2 x^{2-n}} \right) \left\{ \exp \left[-\frac{(z-H)^2}{C_z^2 x^{2-n}} \right] + \exp \left[-\frac{(z+H)^2}{C_z^2 x^{2-n}} \right] \right\} \quad (\text{VI}, 3)$$

On substituting $H = 0$, this equation becomes identical with (VI, 2), while for $z = 0$ this equation gives the pollutant concentra-

tion at ground level.

$$S(x, y) = \frac{2E}{\pi C_y C_z v_w x^{2-n}} \exp \left[-\frac{y^2}{C_y^2 x^{2-n}} - \frac{H^2}{C_z^2 x^{2-n}} \right] \quad (\text{VI},4)$$

In order to determine the distance from the source of emission $x_{\max}$ at which the maximum pollutant concentration at ground level is encountered, it is necessary to differentiate equation (VI,4) and substitute $y = 0$ and $z = 0$. Hence we obtain

$$x_{\max} = \left(\frac{H}{C_z} \right)^{\frac{2}{2-n}} \approx \frac{H}{C_z} \quad (\text{VI},5)$$

The maximum pollutant concentration at ground level is

$$S_{\max} = \frac{2E}{\pi e v_w H^2} \left(\frac{C_z}{C_y} \right) \approx 0,235 \frac{E}{v_w H^2} \left(\frac{C_z}{C_y} \right) \quad (\text{VI},6)$$

If the turbulence is isotropic ($C_z = C_y$), then equation (VI,6) is simplified to assume the form

$$S_{\max} = 0,235 \frac{E}{v_w H^2} \quad (\text{VI},7)$$

The equation derived by Bosanquet and Pearson (VI.3) has a somewhat different mathematical form. Pollutant concentration at ground level at any given point defined by coordinates x and y , assuming the elevation of emission to be H , is determined by the relationship

$$S(x, y) = \frac{E}{2\pi p q v_w x^2} \exp \left[-\frac{H}{px} - \frac{y^2}{2(qx)^2} \right] \quad (\text{VI},8)$$

Using the Bosanquet and Pearson equation, we can calculate the distance of the maximum pollutant concentration at ground level

$$x_{\max} = \frac{H}{2p} \quad (\text{VI},9)$$

and the maximum pollutant concentration

$$S_{\max} = \frac{4E}{\sqrt{2\pi} e^2 v_w^2 H^2} \frac{p}{q} = 0,216 \frac{E}{v_w^2 H^2} \frac{p}{q} \quad (\text{VI},10)$$

The concentration of pollutants emitted from a point source into an atmosphere characterized by the adiabatic vertical temperature gradient can be calculated from the approximate relationship derived by Calder (VI,4)

$$S = \frac{E \bar{v}_w}{2k^2 a v_0^2 x^2} \exp \left[- \frac{\bar{v}_w}{k x v_0} \left(\frac{\gamma}{a} + 1 \right) \right] \quad (\text{VI},11)$$

where k is the Karman constant;
 a is the degree of turbulence;

$$v_0 = \sqrt{\frac{\tau_0 g}{\gamma}}$$

τ_0 is the tangen.stress between two atmospheric layers;
 γ is the specific gravity.

Holland (VI,13) gives the following formula for the distribution of pollutant concentrations along the x-axis in the case of the adiabatic temperature gradient and at a high wind velocity

$$S = \frac{2E}{\pi C_y C_v \bar{v}_w (x^2 + H^2)^{\frac{2-\gamma}{2}}} \quad (\text{VI},12)$$

In the case of a vertical temperature gradient such as shown in Fig. V,8e, the pollutant concentration distribution at ground level along the x-axis according to Holland (VI,13) can be calculated from the formula

$$S = \frac{E}{\sqrt{\pi} C_y \bar{v}_w H_1 x^{\frac{2-\gamma}{2}}} \quad (\text{VI},13)$$

where H_1 is the altitude at which the inversion layer begins (obviously, $H_1 > H$).

2.2. Line sources of emission

The formula derived by O. G. Sutton for the concentration of pollutants emitted from a line source of continuous emission has the following form:

$$S_l(x, z) = \frac{2E_l}{\sqrt{\pi} C_y \bar{v}_w x^{\frac{2-\gamma}{2}}} \exp \left[- \frac{z^2}{C_v^2 x^{2-\gamma}} \right] \quad (\text{VI},14)$$

for a source situated at ground level.

In this equation it has been assumed that the source is infinitely long, and consequently the pollutant concentration does not depend on the y-coordinate. The quantity E_1 denotes in this case the amount of pollutants emitted in unit time per unit length of source.

The concentration of pollutants emitted from a line source situated at a height H above ground level is described by the equation

$$S_{l(x,z)} = \frac{E_1}{\sqrt{\pi} C_i v_w x^{\frac{1-n}{2}}} \left[\exp - \frac{(z-H)^2}{C_i^2 x^{2-n}} + \exp - \frac{(z+H)^2}{C_i^2 x^{2-n}} \right] \quad (\text{VI},15)$$

Substituting $z = 0$ in (VI,15), we obtain a relationship expressing the pollutant concentration at ground level

$$S_{l(x)} = \frac{2 E_1}{\sqrt{\pi} C_i v_w x^{\frac{1-n}{2}}} \exp - \frac{H^2}{C_i^2 x^{2-n}} \quad (\text{VI},16)$$

Differentiating equation (IV,16) with respect to x and equating with zero, we obtain the distance at which the maximum pollutant concentration arises

$$x_{l \max} = \left(\frac{2 H^2}{C_i^2} \right)^{\frac{1}{2-n}} \sim \sqrt{2} H / C_i \quad (\text{VI},17)$$

Therefore, the maximum pollutant concentration on ground level is

$$S_{l \max} = \frac{2 E_1}{\sqrt{2 \pi} v_w H} \sim 0,484 \frac{E_1}{v_w H} \quad (\text{VI},18)$$

According to Bosanquet and Pearson (VI,3), the ground level concentration of pollutants emitted by a line source at a height H can be calculated from the formula

$$S_l = \frac{E_1}{p v_w x} \exp \left(- \frac{H}{p x} \right) \quad (\text{VI},19)$$

In similarity with equation (VI,16), we can use the Bosanquet equation to calculate the distance from the source at which the maximum pollutant concentration occurs

$$x_{\max} = \frac{H}{p} \quad (\text{VI},20)$$

and the value of the maximum pollutant concentration is

$$S_{l \max} = \frac{E_l}{ev_w H} = 0,368 \frac{E_l}{v_w H} \quad (\text{VI},21)$$

For a line source situated at a height $H = z$, Calder derives a relationship which is valid only in the case of an adiabatic vertical temperature gradient

$$S_l = \frac{E_l}{k v_w x} \exp\left(-\frac{v_w z}{k v_w x}\right) \quad (\text{VI},22)$$

where the symbols are identical with those used in equation (VI,11). When determining the concentration of dust pollutants emitted by any given source, it is necessary to take into account also the settling velocity of the individual dust granules. On the basis of theoretical considerations of D. H. Lucas (VI,12), we can accept that if the settling velocity of dust particles u_p is greater than 0.1 of the average wind velocity v_w , then in addition to the forces of atmospheric diffusion, a considerable influence on the movement of particulate matter in air is exerted by the force of gravity. However, if the u_p/v_w ratio is less than 0.05, the decisive effect on the movement of dust particles is exerted by atmospheric turbidity, and the particles are subject to the laws of diffusion with an accuracy sufficient for practical calculations.

H. K. Krieb (VI,9) applied O. G. Sutton's equation (VI,3) to the calculation of the distribution of pollutant concentrations. The phenomenon of dust settling on the surface of the earth can be taken into account mathematically by removing from equation (VI,3) the term expressing the rebound of pollutants from the earth's surface

$\left(\exp - \frac{(z + H)^2}{C_s^2 x^2 - n}\right)$. The taking into account of the finite settling

velocity of dust particles amounts to the substitution in the equation of the quantity z by the quantity

$$z' = z + \frac{u_p}{v_w} x \quad (\text{VI},23)$$

Such substitution means that the horizontal axis of the pollutant dispersion cone is inclined to the horizontal at an angle equal to:

$$\operatorname{tg} \alpha = \frac{u_p}{v_w}$$

(VI,24)

When all the above assumptions are taken into account, we obtain the following equation:

$$S(x, y, z) = \frac{E_p}{\pi C_p C_w v_w x^{3-n}} \exp \left[-\frac{y^2}{C_p^2 x^{2-n}} \right] \exp \left[-\frac{\left(z + \frac{u_p}{v_w} x - H \right)^2}{C_p^2 x^{2-n}} \right]$$

(VI,25)

where E_p is the amount of particulate matter characterized by a given settling velocity u_p emitted per unit time.

G. H. Bosanquet and J. L. Pearson (VI,2) give a semi-empirical equation for the concentration of particulate pollutants emitted from a source at a height H . This equation was obtained from equation (VI,8), additionally taking into account the settling velocity of dust particles u_p .

$$S(x, y) = \frac{E \left(1.78 \frac{H}{p} \right) \frac{u_p}{v_w p}}{\sqrt{2\pi} 4 p v_w x^{2 + \frac{u_p}{v_w p}}} \exp \left(-\frac{H}{px} - \frac{y^2}{2(px)^2} \right)$$

(VI,26)

In the case of particulates having a slow settling velocity, equation (VI,26) becomes identical with equation (VI,8).

3. Calculation of dustfall

For technical reasons, it is frequently more convenient to measure dustfall than the concentration of particulate matter in air. Since the dustfall is a function of dust concentration in air, it can, in some cases, be re-calculated in terms of dust concentration, and vice-versa.

The clearest theoretical transition from dust concentration to dustfall has been derived by K. H. Krieb (VI.9). The starting point is provided by equation (VI,25) for dust concentration at any given point within the coordinate system xyz . In order to obtain the value of dustfall, it is necessary to integrate equation (VI,25) with respect to y and z for a constant x . The limits of integration should be chosen so as to obtain the amount of dust settling on the earth's surface at a distance x from the source. Thus, the limits with respect to y will be from $-\infty$ to $+\infty$, while with respect to z they will be

from $-\infty$ to 0. The solution of the integral has the form

$$\int_{-\infty}^0 \int_{-\infty}^0 S dy dz = \frac{E}{2v_w} \{1 + \Phi(\eta)\} \quad (\text{VI},27)$$

In this equation

$$\eta = \frac{\frac{u_p}{v_w} x - H}{C_1 x^{\frac{n-1}{n}}} \quad (\text{VI},28)$$

Function $\Phi(\cdot)$ is the Gauss error function, and has the form

$$\Phi(\eta) = \frac{2}{\sqrt{\pi}} \int_0^\eta e^{-\eta'^2} d\eta' \quad (\text{VI},29)$$

The values of this function are given in Table VI,1. Dividing equation (VI,29) by $\frac{E}{2v_w}$, we obtain the amount of dust (in percent) which has settled at a distance x

$$\alpha = 0,5[1 + \Phi(\eta)] \quad (\text{VI},30)$$

Figs. VI,1 and VI,2 give the curves of $\alpha = f(x)$ for various values of parameters entering into equation (VI,30). On the basis of these graphs, it is possible to estimate the influence of the meteorological exponent n and the settling velocity u_p .

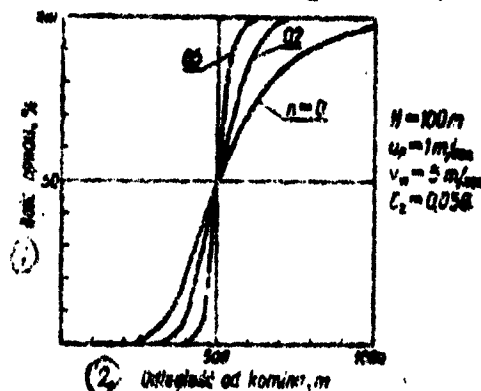


Fig. VI,1. The percentage amount of dust settling as a function of distance from a source of emission at elevation $H = 100$ meters, wind velocity $v_w = 5$ m/sec, and a settling velocity of dust particles $u_p = 1$ m/sec.

Legend: 1. Dustfall; 2. Distance from stack.

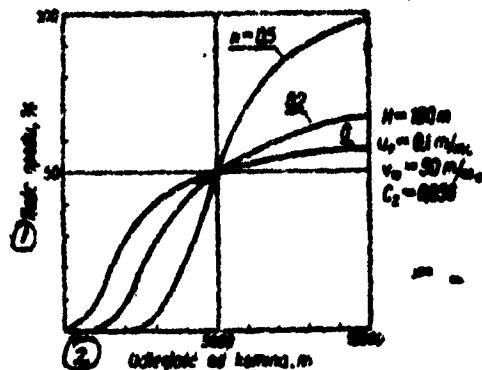


Fig. VI,2. The percentage amount of dust settling as a function of distance from a source of emission at elevation $H = 100$ meters, wind velocity $v_w = 5$ m/sec, and a settling velocity of dust particles $u_p = 0.1$ m/sec.

Legend: 1. Dustfall; 2. Distance from stack.

It is characteristic that all the curves corresponding to a given settling velocity intersect at one point at which $\alpha = 50\%$. The abscissa at this point corresponds to the distance from emission source at which a particle having a settling velocity of u_p falls to the ground, assuming that the movement is of the laminar type. This distance can be calculated from the formula

$$x = H \frac{v_w}{u_p} \quad (\text{VI},31)$$

We see from Figs VI,1 and VI,2 that the entire amount of dust settles nearer to the point determined by equation (VI,31) with an increase in the value of the meteorological exponent, i.e., with a decreased turbulence of air. The same effect is also exerted by an increase in the ratio of settling velocity up to wind velocity v_w . The actual amount of dustfall is calculated from the percentage amount by multiplying equation (VI,31) by E_f

$$\beta = E_f \alpha \quad (\text{VI},32)$$

By differentiating this equation with respect to the distance x , we obtain the value of dustfall Q_1 per unit length (distance) and unit time

Table VI, 1.

Values of the Gauss function $\Phi(\eta)$

η	$\Phi(\eta)$	η	$\Phi(\eta)$	η	$\Phi(\eta)$	η	$\Phi(\eta)$	η	$\Phi(\eta)$
0,00	0,000	0,40	0,311	0,80	0,576	1,20	0,770	1,60	0,890
0,01	0,008	0,41	0,318	0,81	0,582	1,21	0,774	1,61	0,893
0,02	0,016	0,42	0,326	0,82	0,588	1,22	0,778	1,62	0,895
0,03	0,024	0,43	0,333	0,83	0,593	1,23	0,781	1,63	0,897
0,04	0,032	0,44	0,340	0,84	0,599	1,24	0,785	1,64	0,899
0,05	0,040	0,45	0,347	0,85	0,605	1,25	0,789	1,65	0,901
0,06	0,048	0,46	0,354	0,86	0,610	1,26	0,792	1,66	0,903
0,07	0,056	0,47	0,362	0,87	0,616	1,27	0,796	1,67	0,905
0,08	0,064	0,48	0,369	0,88	0,621	1,28	0,800	1,68	0,907
0,09	0,072	0,49	0,376	0,89	0,627	1,29	0,803	1,69	0,909
0,10	0,080	0,50	0,383	0,90	0,632	1,30	0,806	1,70	0,911
0,11	0,088	0,51	0,390	0,91	0,637	1,31	0,810	1,71	0,913
0,12	0,096	0,52	0,397	0,92	0,642	1,32	0,813	1,72	0,915
0,13	0,103	0,53	0,404	0,93	0,648	1,33	0,816	1,73	0,916
0,14	0,111	0,54	0,411	0,94	0,653	1,34	0,820	1,74	0,918
0,15	0,119	0,55	0,418	0,95	0,658	1,35	0,823	1,75	0,920
0,16	0,127	0,56	0,425	0,96	0,663	1,36	0,826	1,76	0,922
0,17	0,135	0,57	0,431	0,97	0,668	1,37	0,829	1,77	0,923
0,18	0,143	0,58	0,438	0,98	0,673	1,38	0,832	1,78	0,925
0,19	0,151	0,59	0,445	0,99	0,678	1,39	0,835	1,79	0,927
0,20	0,159	0,60	0,451	1,00	0,683	1,40	0,838	1,80	0,928
0,21	0,166	0,61	0,458	1,01	0,688	1,41	0,841	1,81	0,930
0,22	0,174	0,62	0,465	1,02	0,692	1,42	0,844	1,82	0,931
0,23	0,182	0,63	0,471	1,03	0,697	1,43	0,847	1,83	0,933
0,24	0,190	0,64	0,478	1,04	0,702	1,44	0,850	1,84	0,934
0,25	0,197	0,65	0,484	1,05	0,706	1,45	0,853	1,85	0,936
0,26	0,205	0,66	0,491	1,06	0,711	1,46	0,856	1,86	0,937
0,27	0,213	0,67	0,497	1,07	0,715	1,47	0,858	1,87	0,939
0,28	0,221	0,68	0,504	1,08	0,720	1,48	0,861	1,88	0,940
0,29	0,228	0,69	0,510	1,09	0,724	1,49	0,864	1,89	0,941

Table VI,1. (continued)

0,30	0,236	0,70	0,516	1,10	0,729	1,50	0,866	1,90	0,943
0,31	0,243	0,71	0,522	1,11	0,733	1,51	0,869	1,91	0,944
0,32	0,251	0,72	0,528	1,12	0,737	1,52	0,871	1,92	0,945
0,33	0,259	0,73	0,535	1,13	0,742	1,53	0,874	1,93	0,946
0,34	0,266	0,74	0,541	1,14	0,746	1,54	0,876	1,94	0,948
0,35	0,274	0,75	0,547	1,15	0,750	1,55	0,879	1,95	0,950
0,36	0,281	0,76	0,553	1,16	0,754	1,56	0,881	1,96	0,950
0,37	0,289	0,77	0,559	1,17	0,758	1,57	0,884	1,97	0,951
0,38	0,296	0,78	0,565	1,18	0,762	1,58	0,886	1,98	0,952
0,39	0,303	0,79	0,570	1,19	0,766	1,59	0,888	1,99	0,953

η	$\Phi(\eta)$	η	$\Phi(\eta)$	η	$\Phi(\eta)$	η	$\Phi(\eta)$	η	$\Phi(\eta)$
2,00	0,955	2,20	0,972	2,40	0,984	2,60	0,991	2,80	0,996
2,01	0,956	2,21	0,973	2,41	0,984	2,61	0,991	2,92	0,996
2,02	0,957	2,22	0,974	2,42	0,984	2,62	0,991	2,94	0,997
2,03	0,958	2,23	0,974	2,43	0,985	2,63	0,991	2,96	0,997
2,04	0,959	2,24	0,975	2,44	0,985	2,64	0,992	2,98	0,997
2,05	0,960	2,25	0,976	2,45	0,986	2,65	0,992	3,00	0,997
2,06	0,961	2,26	0,986	2,46	0,986	2,66	0,992	3,10	0,998
2,07	0,962	2,27	0,977	2,47	0,986	2,67	0,992	3,20	0,999
2,08	0,962	2,28	0,977	2,48	0,987	2,68	0,993	3,30	0,999
2,09	0,963	2,29	0,978	2,49	0,987	2,69	0,993	3,40	0,999
2,10	0,964	2,30	0,979	2,50	0,988	2,70	0,993	3,50	0,9995
2,11	0,965	2,31	0,979	2,51	0,988	2,72	0,993	3,60	0,9997
2,12	0,966	2,32	0,980	2,52	0,988	2,74	0,994	3,70	0,9998
2,13	0,967	2,33	0,980	2,53	0,988	2,76	0,994	3,80	0,99986
2,14	0,968	2,34	0,981	2,54	0,989	2,78	0,994	3,90	0,99990
2,15	0,968	2,35	0,981	2,55	0,989	2,80	0,995		
2,16	0,969	2,36	0,982	2,56	0,990	2,82	0,995	4,00	0,99994
2,17	0,970	2,37	0,982	2,57	0,990	2,84	0,995		
2,18	0,971	2,38	0,983	2,58	0,990	2,86	0,996	5,00	0,9999994
2,19	0,971	2,39	0,983	2,59	0,990	2,88	0,996		

$$O_1 = \frac{d\beta}{dx} = E_f \frac{d\alpha}{dx} = \frac{E_f n \frac{u_p}{v_w} + (2-n) \frac{H}{x}}{2 \sqrt{\pi} C_s x^{1-\frac{n}{2}}} \exp \left[-\frac{\left(\frac{u_p}{v_w} x - H \right)^2}{C_s^2 x^{2-n}} \right] \quad (\text{VI}, 33)$$

We can readily calculate the value of dustfall per unit area and unit time from equation (VI,33) by taking into account the exponential distribution of dustfall along the y-axis

$$O_p = \frac{E_f n \frac{u_p}{v_w} + (2-n) \frac{H}{x}}{2\pi C_s C_s x^{1-\frac{n}{2}}} \exp \left[-\frac{y^2}{C_s^2 x^{2-n}} - \frac{\left(\frac{u_p}{v_w} x - H \right)^2}{C_s^2 x^{2-n}} \right] \quad (\text{VI}, 34)$$

This equation determines dustfall at a given settling velocity u_p at a point determined by coordinates y and x , on the assumption that the direction of wind does not change in time, and E_f denotes the amount of dust having a settling velocity of u_p , which is emitted per unit time.

As has been mentioned in Chapter V, in reality there are always deviations from prevailing wind direction. Assuming that the direction of wind oscillates over a segment of the circle with an internal angle β , the equation for average dustfall within this segment can be written as follows, taking equation (VI,33) as the starting point:

$$O_n = \frac{O_1}{\beta x} = \frac{E_f n \frac{u_p}{v_w} + (2-n) \frac{H}{x}}{2 \sqrt{\pi} \beta C_s x^{1-\frac{n}{2}}} \exp \left[-\frac{\left(\frac{u_p}{v_w} x - H \right)^2}{C_s^2 x^{2-n}} \right] \quad (\text{VI}, 35)$$

Figs VI,3 and VI,4 show curves plotted on the basis of equation (VI,35). These curves can provide a basis for estimating the influence of the individual parameters entering into equation (VI,35) on the distribution and maximum concentration of dustfall, as well as on the nature of fallout with respect to the distance from the source of emission. It is seen from Fig. VI,3 that in the case of low turbulence ($n = 0.5$) there is observed a strongly accentuated maximum of dustfall, whose distance from the source of emission corresponds to the point calculated from equation (VI,31). When atmospheric turbulence is stronger ($n = 0.2$ and $n = 0.25$), the maximum is not so pronounced, and is observed at a greater distance from emission source. It follows from the graph in Fig. VI,4 that in the case of relatively great settling velocity ($u_p = 1$ m/sec), a strongly pronounced dustfall maximum is observed even in moderate turbidity ($n = 0.25$).

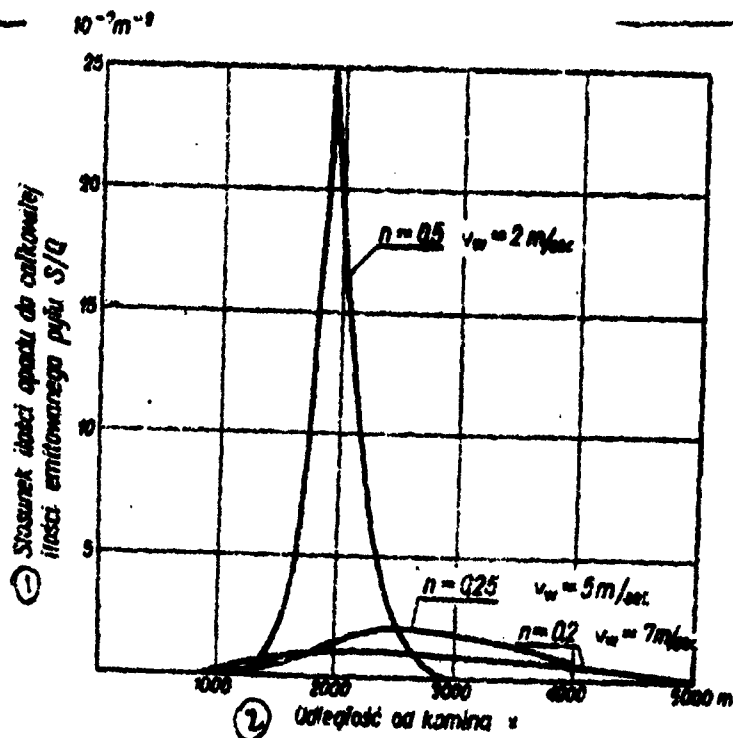


Fig. VI,3. Dustfall as a function of the distance from emission source for a settling velocity $u_p = 0.1$ m/sec

Legend: 1. Ratio of dustfall to total particulate emission;
2. Distance from stack. $10^{-3} m^{-1}$

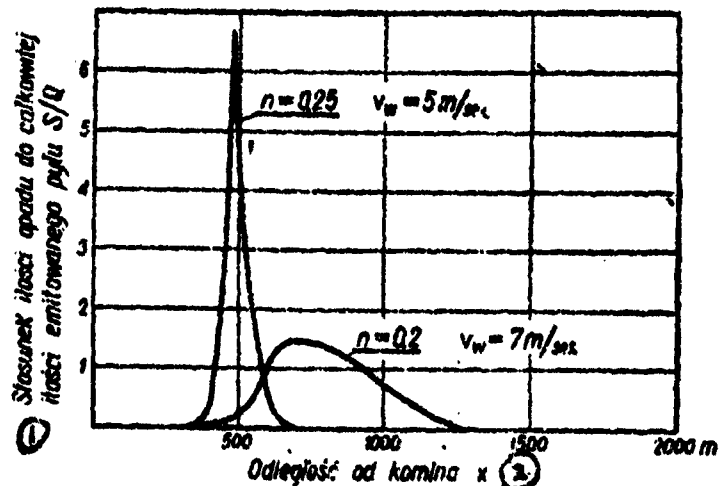


Fig. VI,4. Dustfall as a function of the distance from emission source for a settling velocity $u_p = 1$ m/sec

Legend: 1. Ratio of dustfall to total particulate emission;
2. Distance from stack.

Then the maximum value is greater than in the cases of dust with a low settling velocity, as has been shown in Fig. VI,3, where $u_p = 0.1$ m/sec.

Bosanquet, Carey and Halton (VI.2) have derived a formula for dustfall taking formula (VI,26) as the starting point of their theoretical considerations. This formula described the dustfall in a segment of the circle with an angle of 45° , if the direction of wind coincides with the bisector of this angle. This formula has the following form:

$$O_p = 1,27 \frac{p^2 \left(\frac{u_p}{p v_w} \right) \left(\frac{H}{px} \right)^{\frac{u_p}{p v_w} + 1}}{H^2 \Gamma \left(1 + \frac{u_p}{p v_w} \right)} \exp \left(- \frac{H}{px} \right) \quad (\text{VI},36)$$

In this formula, $\Gamma \left(1 + \frac{u_p}{p v_w} \right)$ is the Euler gamma function. the numerical values of this function for different values of $\frac{u_p}{p v_w}$ are given in Table VI,2.

Another form of equation (VI,36) corresponding to $p = 0.05$ is frequently encountered in the literature:

$$O_p = 0,0032 \frac{E \left(\frac{20 H}{x} \right)^{\frac{20 u_p}{v_w} + 1}}{H^2 \Gamma \left(\frac{20 u_p}{v_w} \right)} \exp \left(- \frac{20 H}{x} \right) \quad (\text{VI},37)$$

Substituting in equation (VI,37) the values of H and x in meters, and u_p and v_w in m/sec, we can write it in the following form:

$$O_p = \frac{E}{H^2} \cdot F \left(\frac{u_p}{v_w}, \frac{x}{H} \right) \quad (\text{VI},38)$$

where

$$F \left(\frac{u_p}{v_w}, \frac{x}{H} \right) = \frac{\left(\frac{20 H}{x} \right)^{\frac{20 u_p}{v_w} + 1}}{\Gamma \left(\frac{20 u_p}{v_w} \right)} \exp \left(- \frac{20 H}{x} \right) \quad (\text{VI},39)$$

For the calculated ratios of $\frac{u_p}{v_w}$ and $\frac{x}{H}$, the value of function $F\left(\frac{u_p}{v_w}, \frac{x}{H}\right)$ can be determined from Fig. VI,5.

Table VI,2

The value of function $\Gamma\left(1 + \frac{u_p}{pv_w}\right)$

$\frac{u_p}{pv_w}$	$\Gamma\left(1 + \frac{u_p}{pv_w}\right)$	$\frac{u_p}{pv_w}$	$\Gamma\left(1 + \frac{u_p}{pv_w}\right)$	$\frac{u_p}{pv_w}$	$\Gamma\left(1 + \frac{u_p}{pv_w}\right)$	$\frac{u_p}{pv_w}$	$\Gamma\left(1 + \frac{u_p}{pv_w}\right)$
0,00	1,000	0,40	0,887	0,80	0,951	1,20	1,102
0,02	0,989	0,42	0,886	0,82	0,937	1,22	1,114
0,04	0,978	0,44	0,886	0,84	0,943	1,24	1,126
0,06	0,969	0,46	0,886	0,86	0,949	1,26	1,139
0,08	0,959	0,48	0,886	0,88	0,955	1,28	1,153
0,10	0,951	0,50	0,886	0,90	0,962	1,30	1,167
0,12	0,944	0,52	0,887	0,92	0,969	1,32	1,181
0,14	0,936	0,54	0,888	0,94	0,976	1,34	1,195
0,16	0,930	0,56	0,890	0,96	0,984	1,36	1,210
0,18	0,924	0,58	0,891	0,98	0,992	1,38	1,227
0,20	0,918	0,60	0,894	1,00	1,000	1,40	1,242
0,22	0,913	0,62	0,896	1,02	1,009	1,42	1,258
0,24	0,908	0,64	0,899	1,04	1,017	1,44	1,276
0,26	0,904	0,66	0,902	1,06	1,027	1,46	1,294
0,28	0,901	0,68	0,905	1,08	1,036	1,48	1,311
0,30	0,898	0,70	0,909	1,10	1,046	1,50	1,329
0,32	0,895	0,72	0,913	1,12	1,057		
0,34	0,892	0,74	0,917	1,14	1,067		
0,36	0,890	0,76	0,921	1,16	1,079		
0,38	0,889	0,78	0,926	1,18	1,090		

For emission sources at high elevations, G. T. Csandy (VI.6) derived a formula on the assumption that $\frac{u_p}{v_w} \ll 1$ and $\frac{u_p}{v_w} \ll \frac{1}{8} H$

$$O_p = \frac{E u_p (1 + a_s)}{2 \pi S_y S_z v_w} \exp \left[-\frac{y^2}{2 S_y^2} - \frac{\left(H - \frac{u_p}{v_w} x \right)^2}{2 S_z^2} \right] \quad (\text{VI,40})$$

where

$$\alpha_0 = \frac{(Hv_v - u_p x) \frac{S'_x}{S_x} - v_v H'}{2u_p - v_v H' + (Hv_v - u_p x) \frac{S'_x}{S_x}} \quad (\text{VI}, 41)$$

The quantities S_x and S_y are connected with the diffusion coefficients of O. G. Sutton by the following relationships:

$$S_x = C_x x^{\frac{2-\alpha}{2}} \quad \text{and} \quad S_y = C_y x^{\frac{2-\alpha}{2}}$$

where S'_x and H' are derivatives of x .

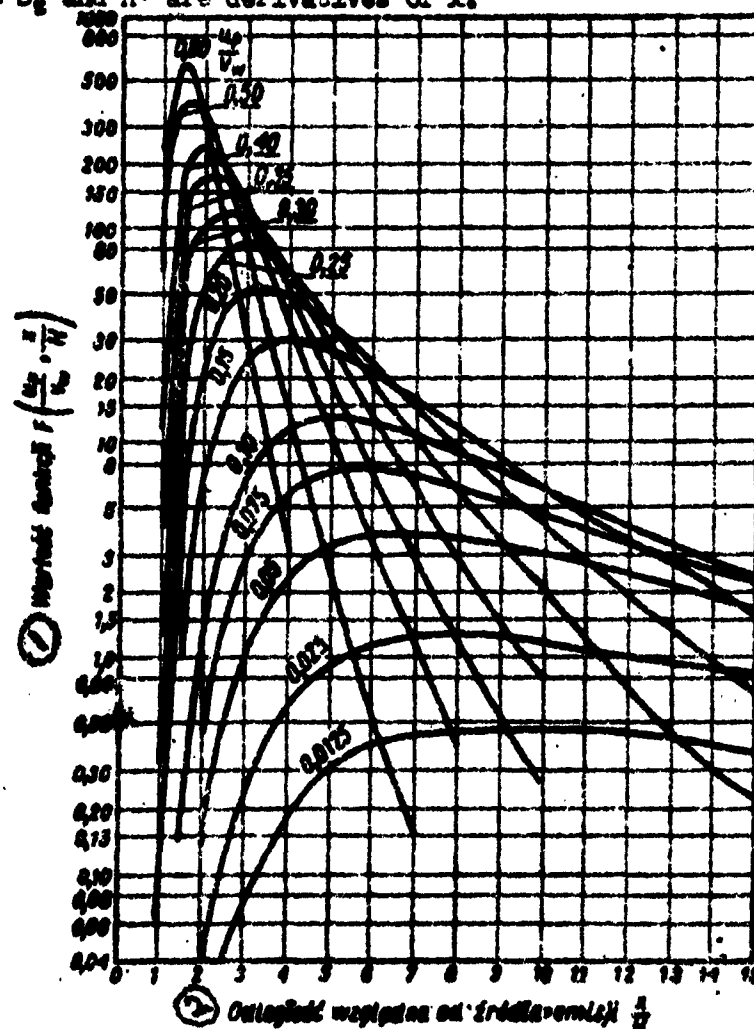


Fig. VI,5. Nomogram for the calculation of the values of

function $f\left(\frac{u_p}{v_v}, \frac{x}{H}\right)$ Key: 1) Value of function; 2) Relative distance from source of emission

The quantity H is not treated as the elevation of the source of emission, but as the height of the axis of symmetry of the dispersing pollutants, and thus can also be a function of x .

The assumption made by H. Gregory and A. Chamberlain (VI.5) for the purpose of calculating the amount of dustfall are somewhat different from the preceding ones. They assume that: 1), the distribution of particulate pollutant concentrations in air is not distorted by finite settling velocity of dust particles, and is determined by equation (VI,3); 2), the dustfall at a point determined by coordinates x and y is the product of particulate pollutant concentration at ground level and the settling velocity of a given particulate fraction. The essential characteristic of the method adopted by these authors is the replacement of a constant emission source by a source with an emission $E(x)$ which depends on the distance x

$$\frac{dE}{dx} = - \int_{-\infty}^{+\infty} u_p S(x, y) dy = - \frac{2 u_p E}{\sqrt{\pi} C_v x^{\frac{n}{2}}} \quad (\text{VI},42)$$

After integrating equation (VI,42) with respect to x over the limits from 0 to x , we obtain an expression for emission by an effective emission source, which is a function of distance x . An effective emission source has, at each point, emission rate equal to the amount of dust settling on the ground in unit time

$$\int \frac{dE}{E} = - \int \frac{2 u_p}{\sqrt{\pi} C_v} x^{-\frac{n}{2}} dx \quad (\text{VI},43)$$

hence

$$E(x) = E \exp \left(- \frac{4 u_p x^{\frac{n}{2}}}{\sqrt{\pi} C_v n} \right) \quad (\text{VI},44)$$

Substituting $E(x)$ for E in equation (VI,2), we obtain a corrected expression for dust pollutant concentration at a point x, y, z

$$S(x, y, z) = \frac{2E}{\pi C_v C_v x^{\frac{n}{2}}} \exp \left(- \frac{4 u_p x^{\frac{n}{2}}}{\sqrt{\pi} C_v n} \right) \exp \left[- \frac{y^2}{C_v^2 x^{\frac{n}{2}}} - \frac{z^2}{C_v^2 x^{\frac{n}{2}}} \right] \quad [\text{VI},45]$$

The amount of dustfall at a point x, y will be, in accordance with the definition,

$$O_p = S u_p = \frac{2 u_p}{\pi C_y C_z v_w x^{2-n}} \exp\left(-\frac{4 u_p x^{\frac{n}{2}}}{\sqrt{\pi} C_z v_w n}\right) \exp\left(\frac{-y^2}{C_z^2 x^{2-n}}\right) \quad (\text{VI},46)$$

Particulate concentration at ground level, as well as the dustfall along the axis of the main wind direction, can be readily calculated from equations (VI,45) and (VI,46) after substituting $y = z = 0$, if the remaining parameters entering into the equations are known.

At each given distance x from the source, we can calculate the particle size of the dust granules whose settling rate will attain a maximum at that point. The settling velocity of a particle of a given size is calculated by differentiating equation (VI,46) with respect to x , and equating with zero:

$$u_{p \max}(x) = 4 \pi v_w \sqrt{\pi} C_z x^{-\frac{n}{2}} \quad (\text{VI},47)$$

thus, for instance, for $n = 0.25$, $v_w = 5$ m/sec, $C_z = 0.12$, we obtain

$$u_{p \max}(x) = 0.0665 x^{-0.125} \text{ m/sec}$$

In order to determine the maximum dustfall of particulate matter with a settling velocity $u_{p \max}$, it is necessary to substitute the value of $u_{p \max}$ calculated from formula (VI,47) in equation (VI,46). Then we obtain

$$O_{p \max} = \frac{E \pi}{4 \sqrt{\pi} C_y x^{2-\frac{n}{2}}} \exp\left(-\frac{y^2}{C_z^2 x^{2-n}}\right) \quad (\text{VI},48)$$

The above reasoning applied to a source of emission situated on ground level ($H = 0$). However, an equation for dustfall from a source situated at a height H can be derived in a similar manner.

The following general conclusions can be drawn from an analysis of the theoretical formulas describing the distribution of pollutants in the vicinity of a source, as well as from actual measurements:

1. The average pollutant concentration downwind from the source is directly proportional to the amount of pollutant emitted;
2. The concentration of pollutants emitted from the source does not, as a rule, influence the pollutant concentration on ground

level. A certain (small) influence is discernible in the immediate vicinity of the source in the case of low wind velocities;

3. The average pollutant concentration downwind from the source is inversely proportional to wind velocity;

4. The average pollutant concentration downwind from the source is approximately inversely proportional to the elevation of the source of emission. A doubling of the source elevation brings about a four-fold decrease in the pollutant concentration on ground level;

5. The theoretical formulas have been derived on the assumption that the surface of the earth is horizontal and smooth. Varying topographical conditions can be taken into account by taking a different elevation of the source;

6. The position of the point of the maximum pollutant concentration on ground level depends on the meteorological conditions. Under the conditions of considerable atmospheric instability, this point is situated relatively close to the emission source. As the atmospheric stability increases, this point becomes further removed from the source.

4. The influence of meteorological precipitation on the concentration and fallout of particulate matter

The phenomenon of atmospheric purification by rain is generally known. In periods of draught, the only dust settling on the ground is that in the immediate vicinity of the source, while the rain drops entrain all the particles they encounter on their way, decreasing dust concentration in the entire atmospheric layer up to the altitude to which the precipitation extends, and causing increased dust fallout.

Let us consider a unit volume containing non-dispersion dust. Let spherical rain drops with a diameter d pass through this volume at a velocity u_v . Let N and n denote the respective concentrations of rain drops and dust particles in the volume under consideration at a moment t . The dust particles will settle on the rain drops in an amount determined by coefficient D which is a function of the diameter and falling velocity of the rain drops, and the particle size of dust granules. The number of dust particles which have settled on the rain drops and removed together with them from the volume under consideration is determined by the relationship

$$-\frac{dn}{dt} = \frac{\pi d^2}{4} D u_v n N \quad (\text{VI}, 49)$$

In an actual rain, the drops are of various diameters, and so the decrease of dust concentration in air will be as follows:

$$-\frac{dn}{dt} = n \sum \frac{\pi d^2}{4} D u_r N \quad (\text{VI},50)$$

Summation relates to all the drop diameters present in the rain.

The dust particle concentration in the volume under consideration after a lapse of time t can be calculated with respect to the initial concentration n_0 by integrating equation (VI,50)

$$\frac{n}{n_0} = \exp\left(-\sum \frac{\pi d^2}{4} D u_r N t\right) \quad (\text{VI},51)$$

The numerical values of coefficient D dependent on the size of rain drops d and particle size of dust granules r_p (at $\gamma = 1$) are given in Table VI,3, from which it follows that for dust particles smaller than 4μ , the value of D does not exceed 0.1 even in the case of very large rain drops. Therefore, the purifying action of rain is relatively low if the dust particles are smaller than about 5μ .

Table VI,3

The values of coefficient D for various values of rain drop diameter d and dust particle radius r_p

d, μ	r_p, μ							
	2	3	4	6	8	10	15	20
30	0,018	0,04	0,071					
50	0,006	0,014	0,026	0,206	0,662			
80	0,003	0,006	0,017	0,368	0,671	0,920		
140	0,001	0,002	0,095	0,460	0,685	0,860	1,18	1,44
200	—	0,001	0,183	0,510	0,698	0,835	1,09	1,28
300	—	0,014	0,276	0,572	0,730	0,850	1,04	1,16
400	—	0,10	0,358	0,615	0,756	0,854	1,01	1,11
600	—	0,225	0,435	0,675	0,800	0,885	1,00	1,06
800	0,04	0,315	0,495	0,710	0,820	0,892	0,985	1,05
1200	0,12	0,376	0,545	0,740	0,852	0,912	0,988	1,03
2000	0,14	0,355	0,525	0,730	0,836	0,894	0,965	1,00

The phenomenon of decrease in dust pollutant concentration by the rainfall was given the mathematical form by Chamberlain (VI.5)

by introducing an additional coefficient into O. G. Sutton's equation (VI,2). The Chamberlain equation has the form

$$S_{(x,y,z)} = \frac{2E \exp\left(\frac{px}{v_w}\right)}{\pi v_w C_y C_z x^{3-n}} \exp\left[-\frac{y^2}{C_y^2 x^{2-n}} - \frac{z^2}{C_z^2 x^{2-n}}\right] \quad (\text{VI},52)$$

The quantity p in the above equation is determined from the formula

$$p = \frac{1}{4} \sum d^3 D u_w N \quad (\text{VI},53)$$

Equation (VI,52) defines dust concentration in the atmosphere at a point determined by coordinates x, y, z , taking into account the effect of rain. The emission source is situated at ground level.

We can similarly write an equation for an emission source situated at a height H :

$$S_{(x,y,z)} = \frac{E}{\pi C_y C_z v_w x^{3-n}} \exp\left(-\frac{px}{v_w}\right) \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right) \left\{ \exp\left[-\frac{(z-H)^2}{C_z^2 x^{2-n}}\right] + \exp\left[-\frac{(z+H)^2}{C_z^2 x^{2-n}}\right] \right\} \quad [\text{VI},54]$$

Dustfall caused by the rain can also be described mathematically as follows:

$$O_p(x,y) = p \int_{z=0}^{\infty} S_{p(x,y,z)} dz = \frac{pE}{\sqrt{\pi} C_y v_w x^{\frac{3-n}{2}}} \exp\left(-\frac{px}{v_w}\right) \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right) \quad [\text{VI},55]$$

for an emission source situated at ground level.

5. Coagulation of dust particles in air

In order to be able approach the phenomenon of dust coagulation in air mathematically, it is necessary to know the effect of the degree of air turbulence on the frequency of collision between the individual dust particles. Unfortunately, there is not, as yet, a satisfactory theoretical explanation of this phenomenon. It has been established that an increase in turbulence causes an increase in the coagulation constant K , which in turn leads to a decrease in dust concentration and an increase in the amount of dustfall due to increased dust particle size (i.e., increased settling velocity).

M. Smolushowski was the first to develop a theory of coagulation phenomena in the case of laminar flow (0.12). According to this theory, decrease in concentration n of monodispersed dust particles with a radius r depends on the number of collisions in accordance with the following equation:

$$-\frac{dn}{dt} = \frac{32}{3} r^2 \omega n^2 = K_w n^2 \quad (\text{VI},56)$$

Wiegand and Frankenberger (0.12) have applied equation (VI,56) to the phenomenon of coagulation in the atmosphere, assuming that

$$\omega = \frac{v_w}{4}. \text{ However, this assumption is not in agreement with the actual conditions.}$$

Considerably better approximation is achieved if we assume, after Tunitskiy (VI,20), that the average velocity in atmospheric micro-eddies $\omega = 10$ cm/sec. Substituting this value in equation (VI,56), we obtain, for particles with a radius $r = 0.1 \mu$, the value of $K_w = 10^{-3}$ cm³/sec, which is negligibly small in comparison with the coagulation constant k due to Brownian movement.

For particles with $r = 1 \mu$, coagulation constant $K_w = 10^{-10}$, i.e., of the same order of magnitude as the coagulation constant due to Brownian movement. As the particle size of dust granules increases, so does coagulation constant due to atmospheric turbulence. On the other hand, small particles coagulate mainly on account of Brownian movement. Therefore, there must be a particle size which shows the least tendency to coagulation. Assuming that the turbulent and Brownian coagulation effects can be added up, we obtain the following expression for decrease in the concentration of dust pollutants:

$$-\frac{dn}{dt} = \left[K \left(1 + \frac{\lambda}{r} \right) + \frac{32}{3} r^2 \omega \right] n^2 \quad (\text{VI},57)$$

The right-hand side of this equation has its maximum at the following value:

$$r = \left(\frac{K \lambda}{32 \omega} \right)^{\frac{1}{4}} \quad (\text{VI},58)$$

Substituting the Brownian coagulation constant $K = 3 \times 10^{-3}$ cm³/sec, $\lambda = 10^{-5}$ cm, and $\omega = 10$ cm/sec, we obtain $r = 0.5 \mu$. This is the particle size which shows least tendency to coagulation under the conditions of normal atmospheric turbulence.

A different approach to the theoretical solution of coagula-

tion in the atmosphere was tried by Tenenowski /N.B.: Tenenowski in the bibliography/ (VI,17). As his starting point, he took O. G. Sutton's equation (VI,14) for a line source. Particulate pollutant concentration at ground level is

$$S_1 = \frac{2E}{\sqrt{\pi C_s v_w x}} \quad (\text{VI},59)$$

The number of dust particles (assuming that they are spherical) is

$$n = \frac{S_1}{\frac{4}{3} \pi r^3 \frac{\gamma}{g}} = \frac{E}{\frac{2}{3} \pi C_s \frac{\gamma}{g} r^3 v_w x} = \frac{A}{x} \quad (\text{VI},60)$$

where γ is the specific gravity of a dust particle.

Decrease in the number of dust particles with distance x is

$$\frac{dn}{dx} = -\frac{A}{x^2} = -\frac{1}{A} n^2 \quad (\text{VI},61)$$

On the other hand, it follows from the theory of normal coagulation that

$$-\frac{dn}{dt} = Kn^2 \quad (\text{VI},56)$$

where K is coagulation constant. Since in the case in point $x = v_w t$, equation (VI,56) can be transformed into the form

$$-\frac{dn}{dx} = \frac{K}{v_w} n^2 \quad (\text{VI},62)$$

Assuming that the coagulation and diffusion processes are mutually independent, we can write the final expression for decrease of dust pollutant concentration as a result of diffusion and coagulation

$$-\frac{dn}{dx} = \left(\frac{K}{v_w} + \frac{1}{A} \right) n^2 \quad (\text{VI},63)$$

After integration, we have

$$\frac{1}{n} - \frac{1}{n_0} = \left(\frac{K}{v_w} + \frac{1}{A} \right) (x - x_0) \quad (\text{VI},64)$$

6. The meteorology of the smokestack

In the formulas given above, H denoted the elevation of the emission source above the ground level. In practical application, the value of H is not generally equal to the geometrical height of the stack emitting pollutants, since the gases issuing from the stack have a velocity which causes the transport of pollutants to a certain height h above the smokestack outlet. The second factor responsible for an increase (by a height h) in the actual height of the stack is the temperature differential between the emitted gases and the surrounding air.

Therefore, it is necessary to introduce into the formulas a substitute value of H which is the sum of the geometrical height of the stack, the height of velocity rise h_v , and the height of thermal rise h_t .

$$H = h + h_v + h_t \quad (\text{VI}, 65)$$

The calculation of the substitute value of H is complicated, since the values of velocity and thermal rises are parameters of not only the emitted gases, but also of temporary meteorological conditions, particularly the wind velocity and the vertical temperature gradient of the atmosphere.

The Bosanquet (VI.2) formula for calculating the maximum velocity rise $h_{v \max}$ has the form:

$$h_{v \max} = \frac{4.77}{1 + 0.43 \frac{v_w}{v_k}} \left(\frac{\sqrt{Q_{T1} v_k}}{v_w} \right) \quad (\text{VI}, 66)$$

where v_k is the velocity of gas issuing from the stacks;
 Q_{T1} is the amount of emitted gas, reduced to the temperature of the surrounding air.

A nomogram is given in Fig. VI,6 for the graphical solution of equation (VI,66).

The height of velocity rise at any given distance x from the emission source can be calculated from the relationship

$$h_{v,x} = h_{v \max} \left(1 - 0.8 \frac{h_{v \max}}{x} \right) \quad (\text{VI}, 67)$$

This relationship is valid for $x > 2 h_{v \max}$.

Calculation of thermal rise h_t is considerably more complicated. Bosanquet gives the following formula for the maximum thermal rise $h_{t \max}$:

$$h_{t \max} = 6,37 g \frac{Q_{T_1} \Delta T}{v_w^3 T_1} Z \quad (\text{VI}, 68)$$

where

$$Z = \ln J^2 + \frac{2}{J} - 2 \quad (\text{VI}, 69)$$

and

$$J = \frac{v_w^2}{\sqrt{Q_{T_1} v_k}} \left(0,43 \sqrt{\frac{T_1}{g(\varphi - \Gamma)}} - 0,28 \frac{v_k}{g} \frac{T_1}{\Delta T} \right) + 1 \quad (\text{VI}, 70)$$

The height of thermal rise shows a considerably greater dependence on the wind velocity than does the height of velocity rise $h_v \max$. A two-fold increase in wind velocity causes an eight-fold decrease in the value of thermal rise $h_{t \max}$. The influence of the vertical temperature gradient is taken into account in equation (VI, 68) by the term $\varphi - \Gamma$. A decrease in atmospheric turbulence causes a decrease in the maximum thermal rise $h_{t \max}$.

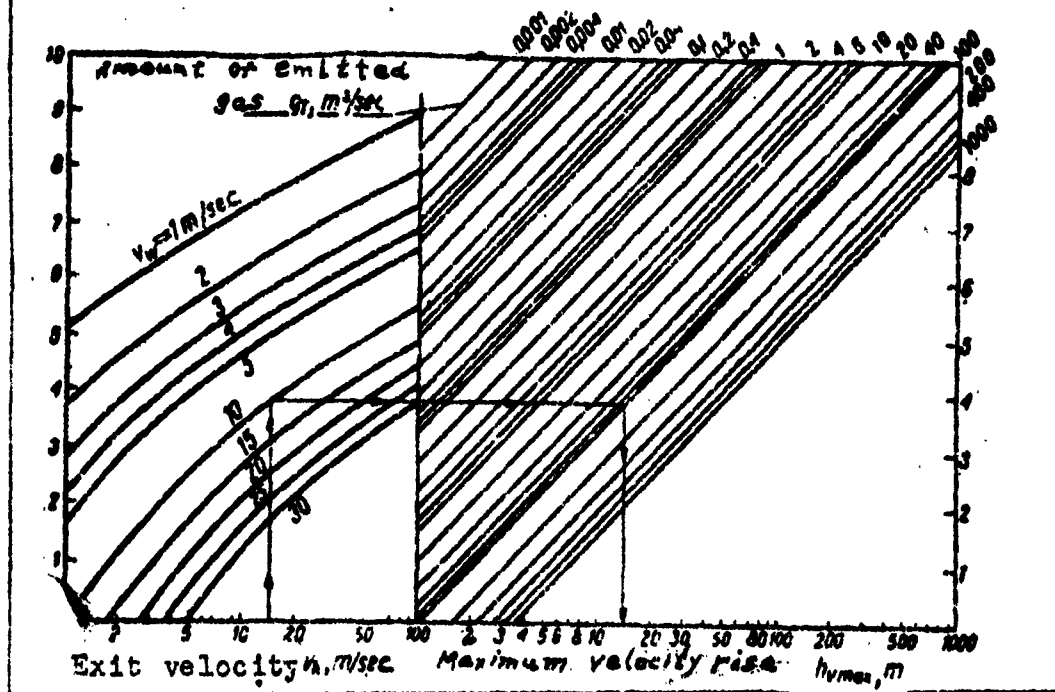


Fig. VI, 6. Nomogram for the calculation of the maximum velocity rise $h_v \max$

Changes in thermal rise depending on the height above the stack can be calculated from the following relationships:

$$h_{t,z} = 6,37 g \frac{Q_{T_1} \Delta T}{v_w^3 T_1} Z \quad (\text{VI},71)$$

$$x = 3,57 \sqrt{\frac{Q_{T_1} v_k}{v_w}} X \quad (\text{VI},72)$$

The relationship between quantities X and Z is shown in Fig. VI,7.

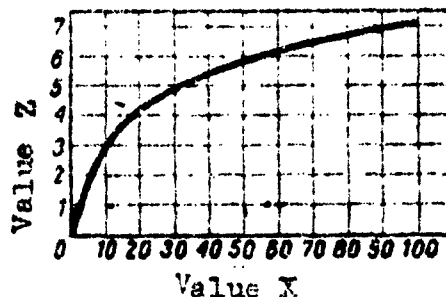


Fig. VI,7. The dependence of Z on X in the case of the adiabatic vertical temperature gradient

7. The effect of topography on the dispersion of pollutants in the atmosphere

The topographic conditions of an area where a source of emission is located affect to a significant degree the pollutant distribution and dustfall around the source.

The topography can exert either a direct, or indirect influence on the dispersion of pollutants in the atmosphere.

The direct effect of given topograph conditions consists in causing local changes in the direction and velocity of the wind, formation of eddies, disordered ascent and descent of air masses, etc.

Indirect influence is manifested in such meteorological factors as the vertical temperature gradient, degree of atmospheric turbulence in the layers close to ground level, average wind velocity, etc. The value of the vertical temperature gradient depends, to a large degree, on the shape and type of terrain which affect the heating and cooling of the ground. There are considerable differences between the maximum diurnal temperature differences for various types of terrain, such as sand, meadowland, water, built-up areas, etc.

The mathematical expression of the influence of the type of terrain on the vertical temperature gradient, as well as other meteorological parameters, is extremely difficult, since this influence depends also on the atmospheric and meteorological conditions. As a result, the actual pollutant concentration and dustfall experience local fluctuations which cannot, and usually are not taken into account in any theoretical calculation.

The wind velocity and distribution are dependent to a large degree on the horizontal relief of the terrain. Abrupt changes in the relief, such as deep ravines, mountains, etc. cause atmospheric eddies which largely alter the linear distribution of wind velocities assumed in theoretical considerations.

Further differences in the behavior of air masses are seen in enclosed hollows and valleys where the movement of air is caused by an uneven heating of the valley slopes. Exchange of air with the adjoining areas takes place very seldom, i.e., only during high winds. This exchange is hindered by the phenomenon of inversion which frequently arises under such conditions. Hollows represent a particularly disadvantageous type of terrain because of the possibility of formation of high pollutant concentrations in them.

Of considerable importance to the distribution of pollutant concentrations is the degree and nature of arboreal cover of the terrain. Trees influence the changes in wind velocity, and the large surface areas of needles or leaves (between five and eight square meters per square meter of forest surface) mainly at heights between five and 15 meters act as a filter for all types of air pollutants. The high degree of adhesiveness of particulate matter to the leaves or needles of trees causes a large drop in the pollutant concentration in wooded areas. If, for instance, particulate pollutant concentration over a given length drops to 10% of its original value over wooded terrain, it will merely halve over a similar length of terrain devoid of trees. Terrain supporting shrubs, grain crops or grass also exerts a significant influence on pollutant concentrations, since they prevent a re-entry of the settled dusts into the atmosphere.

Vegetation also plays a considerable role with regard to gaseous pollutants because of the possibility that it may assimilate large amounts of them.

The distribution of particulate concentrations over open country and a forest at two different wind velocities is shown in Fig. VI,8a and VI,8b, from which it can be seen that there is a substantial increase in dust concentration at the edge of the forest, and this concentration decreases gradually further into the forest.

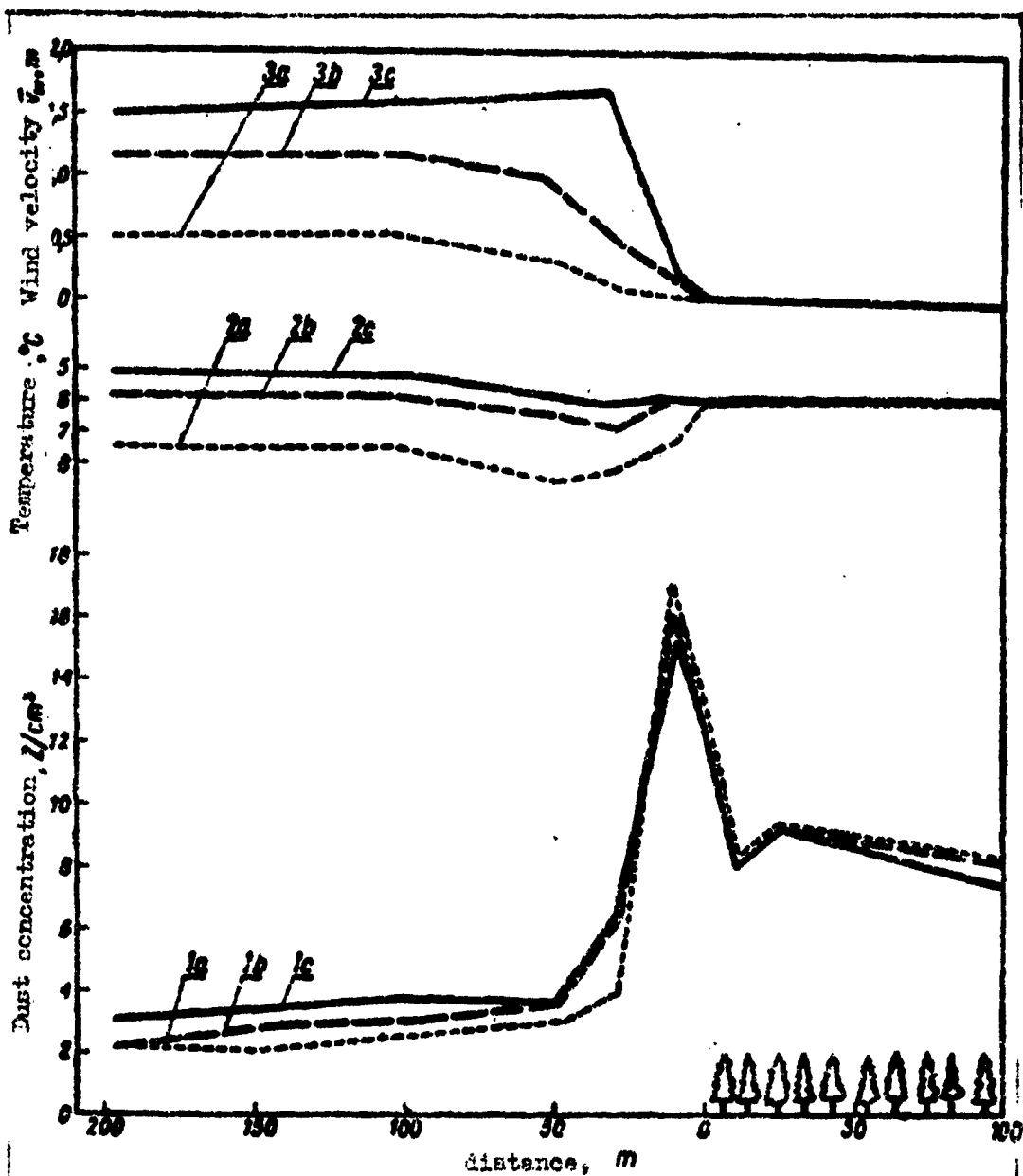


Fig. VI,8. Changes in wind velocity, temperature, and particulate pollutant concentration in low wind over a forest. 1. Particulate pollutant concentration; 2. Air temperature; 3. Wind velocity measured at the following altitudes: a -- 0 meters; b -- 1 meter; c -- 2 meters.

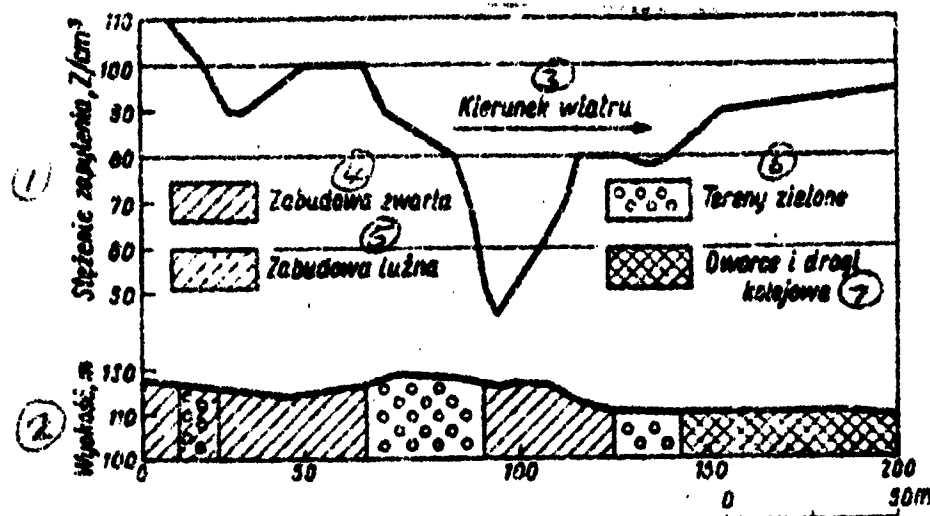


Fig. VI.9. The pattern of particulate pollutant concentration in downtown Leipzig

Legend: 1. Particulate concentration; 2. Height, in m; 3. Direction of wind; 4. Densely built-up area; 5. Sparsely built-up area; 6. Green spaces; 7. Railroad lines and stations.

Fig. VI.9 shows the pattern of particulate pollutant concentrations over various terrains in downtown Leipzig (VI.11). A very pronounced drop in dust concentration is seen over treed areas.

Thus there are great possibilities for reducing pollutant concentrations by a suitable planning of built-up and park areas.

The distribution of particulate pollutant concentrations in densely built-up areas (city streets and squares) exhibits wide irregularities, making it impossible to apply the theoretical formulas given at the beginning of the present chapter. The most important factors determining the distribution of particulate concentrations over urban areas, especially in the lower atmospheric layers, are: pronounced variations in wind direction due to buildings and directions of streets, and a considerable extent of secondary transport of the settled dust into the atmosphere. As an example, Fig. VI.10 shows the intersection of two streets in Leipzig. The Figure shows wind directions at some points in the streets. It is seen that wind directions measured at points quite close to each other can vary by as much as 130°. Differences in particulate concentration can amount to 100%.

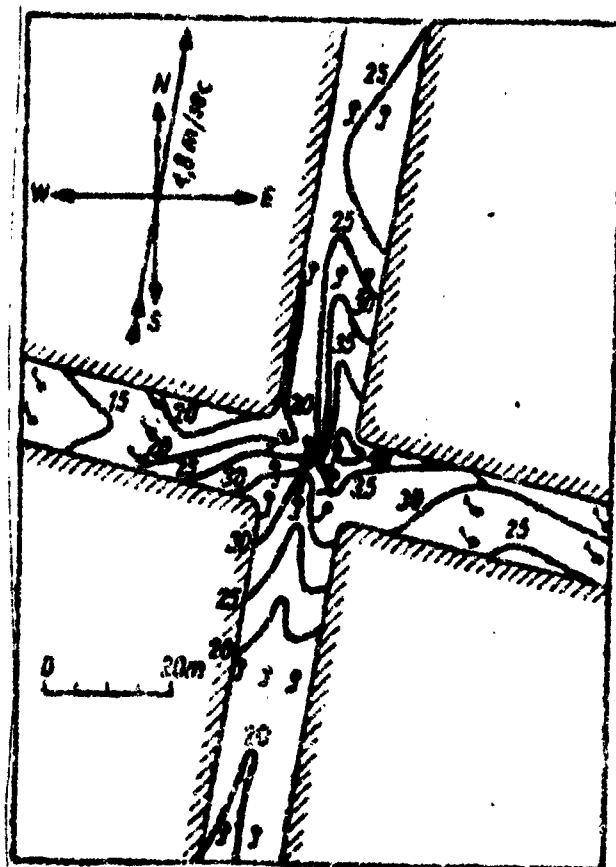


Fig. VI,10. Distribution of particulate pollutant concentrations at a street intersection in Leipzig (figures denote dust count in particles per cm^3)

8. Comparison of results obtained using various formulas

The results of calculating dust concentration distributions or dustfall values obtained using different formulas frequently show considerable variation. These discrepancies may arise out of empirical or semi-empirical coefficients used in calculation, derived by various authors in different ways and intended to take into account given meteorological conditions. For instance, there is no theoretical relationship between the coefficient of vertical diffusion C_v derived by Sutton, and the coefficient p derived by Bosanquet. On the other hand, each of the equations given at the beginning of the present chapter is in best agreement with reality only under specified atmospheric conditions.

At the same time it should be stressed that we cannot declare definitely that any particular formula is the best, i.e., that it describes most accurately the actual course of diffusion of pollutants in the atmosphere. In order to recognize one of these formulas as being the best, it would be necessary to compare it with the results of measurements carried out in an absolutely accurate manner over the whole range of parameters entering the equation in question. These measurements would have to embrace pollutant concentrations and dustfall, as well as all the meteorological factors. However, such extensive measurements have not yet been carried out.

Given this state of affairs, there are two methods of checking theoretical formulas: 1), to compare theoretical results arrived at by various methods, and, possibly, to verify them at some points for which there exist relatively reliable measurement data; 2), to calculate diffusion coefficients from theoretical formulas by substituting in them the results of pollutant concentration measurements at given points, and to compare them with diffusion coefficients theoretically derived for similar meteorological conditions.

The first method is used most frequently because of its simplicity, but the second method has an undoubted advantage, since the resultant diffusion coefficients can be applied, with a large degree of confidence, to more extensive theoretical investigations of the pollutant distribution over an area having similar meteorological conditions.

A comparison of the results obtained using the Sutton formula with those based on the Bosanquet - Pearson formula can best be done on the basis of equations (VI,6) and (VI,10).

According to Sutton (VI,6), the maximum pollutant concentration at ground level is

$$S_{max} = 0,235 \frac{E}{v_w H^2} \left(\frac{C_z}{C_y} \right)$$

while according to Bosanquet - Pearson (VI,10),

$$S_{max} = 0,216 \frac{E}{v_w H^2} \frac{p}{q}$$

Assuming that the ratios of diffusion coefficients $\frac{C_z}{C_y}$ and $\frac{p}{q}$ have the same value, equations (VI,6) and (VI,10) differ from

each other only in the proportionality constants. Actually, the difference between them is relatively small, since it amounts to only 9%. However, according to Sutton the ratio $\frac{C_z}{C_y}$ altitudes greater than

25 meters is equal to unity (see Table V,3), while the numerical value of $\frac{E}{P}$ varies between 0.35 and 0.7 depending on the meteorological conditions and terrain. Thus in practice the values of pollutant concentration obtained from equation (VI,6) are nearly twice as great as those obtained from equation (VI,10).

In calculating the pollutant concentrations at ground level, Sutton's assumption that $C_z = C_y$ seems debatable. Even if we accept that at altitudes above 25 meters atmospheric turbulence is isotropic, then in order to reach the surface of the earth, pollutants have to diffuse through a decidedly non-isotropic (even according to Sutton) layer adjacent to the ground. In addition, Sutton's assumption is not fully true in the case of inversion, as has been mentioned in Chapter V.

In view of the fact that Sutton's equation (VI,6) gives excessively high values of the maximum pollutant concentration S_{max} , Lowry (VI,10) proposed the following modification:

$$S_{max} = \frac{2E}{\pi H^2 v_w} a_m = 0,235 \frac{E}{v_w H^2} a_m \quad (VI,73)$$

In this equation, a_m replaces the ratio of diffusion coefficients $\frac{C_z}{C_y}$. Coefficient a_m is dependent on the wind fluctuation (cf.

chapter V), and expresses the frequency of winds in the prevailing direction. Therefore, the physical sense of coefficient a_m is basically different from that of $\frac{C_z}{C_y}$. Dependence of coefficient a_m

on the type of wind as an average of sampling lasting one hour is shown in Table VI,4.

Table VI,4

The value of coefficient a_m for different types of wind

① Type of wind	a_m
A	0,075
B	0,15
C	0,25
D	0,50

Legend: 1. Type of wind.

Table VI, 5

Pollutant concentration at ground level in the case of constant emission by a source situated at ground level

	Zródło punktowe sięcznia przy emisji 1 G/sec ① mg/m ³			Zródło liniowe sięcznia przy emisji 1 G/m sek ② mg/m ³			oddalenie m niemniej ③ m		oddalenie m niemniej ④ m	
	100 m	1000 m	5000 m	100 m	1000 m	5000 m	100 m	1000 m	100 m	1000 m
⑤ Odległość od źródła emisji x	100 m	1000 m	5000 m	100 m	1000 m	5000 m	100 m	1000 m	100 m	1000 m
⑥ Wyniki pomiarów	2,0	$3,4 \cdot 10^{-2}$	$5,4 \cdot 10^{-4}$	35	3,2	0,4	35	3,2	35	10
⑦ Wg wzoru Suttona $a = 0,25$, $C_1 = 0,21$, $C_2 = 0,12$	1,6	$2,8 \cdot 10^{-2}$	$1,8 \cdot 10^{-3}$	34	4,4	1,1	34	4,4	34	10
⑧ Wg wzoru Caldera $a = 2$, $s = 20$ cm/sec, $k = 0,45$	2,5	$2,5 \cdot 10^{-2}$	$1,0 \cdot 10^{-3}$	44	4,4	0,9	41	4,4	41	10

Legend: 1. Point source emitting 1 g/sec; 2. Line source emitting 1 g/sec; 3. The width of cloud of pollutants; 4. The height of cloud of pollutants; 5. Distance x from emission source; 6. Results of sampling; 7. According to Sutton's formula; 8. According to Calder's formula.

Expressions for the distance $x_{\max}$ at which the maximum pollutant concentration is encountered have a similar form in both equations (VI,6) and (VI,10). If under the conditions of moderate turbulence $p = 0.05$ and $C_2 = 0.13$, the values of the same order of magnitude are obtained from both expressions, and $x_{\max}$ varies between eight and 10 times the height of the stack. The value of $x_{\max}$ varies between five and 20 times the stack height over the entire range of meteorological conditions.

Table VI,5 shows the results of pollutant concentration measurements at ground level carried out by Porton (0.12). Point and line sources at ground level were investigated. For the sake of comparison the Table also gives the results of calculations based on Sutton's and Calder's formulas for point and line sources situated at ground level. It can be seen that the values obtained using Sutton's formulas are lower than those obtained experimentally. The same is true of Calder's with the difference that values higher than the actual ones are obtained for points close to the source. In the case of a line source, Sutton's formula is in good agreement with experimental results for small values of x , while values higher than the actual are obtained for longer distances. Calder's formula always gives results on the high side.

A considerable degree of correlation with experimental results is obtained from both formulas in the case of determining the transverse dimensions of the plume of contaminants. This is seen from the last two columns of Table VI,5.

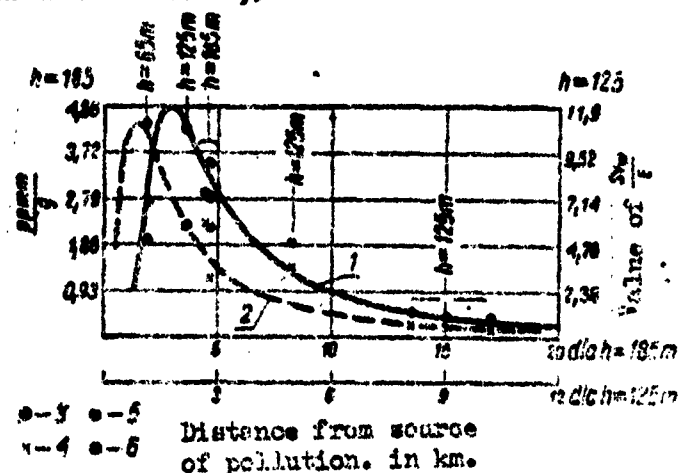


Fig. VI,11. A comparison SO_2 concentration measurements with the theoretical calculations obtained using the Sutton and Bosanquet-Pearson formulas. 1. Theoretical curve after Sutton for $C_2 = C_3 = 0.07$, $n = 0$; 2. Theoretical curve after Bosanquet-Pearson for $p = q = 0.07$; 3. Annual average from 30-minute samplings; 4. Monthly average from 30-minute samplings; 5. Maximum values from two-minute samplings; 6. Monthly average from two-minute samplings.

The results of investigations carried out by D. M. Thomas, G. R. Hill and J. N. Abersold (VI,18) show good correlation with the theoretical calculations. The results of the SO_2 concentration measurements at different distances from the source, as well as the theoretical curves plotted according to the Sutton (VI,4) and Bosanquet-Pearson (VI,8) formulas are given in Fig. VI,11. It follows from the position of the experimental points in relation to the theoretical curves that there is a considerable degree of correlation between the experimental results and the theoretical calculations for emission sources at an elevation greater than 100 meters if the diffusion coefficients in the Sutton and Bosanquet-Pearson equations are taken to be within the limits 0.05 - 0.07, and the meteorological exponent $n = 0$. In order to obtain good correlation for sources at lower elevations, it would be necessary to accept, in the Sutton equation, values of C_z and C_y between 0.05 and 0.01, and a value of $n = 0.25$.

The investigations carried out by H. Startman (VI,14) confirm the foregoing conclusions. H. Startman measured the SO_2 concentrations in the vicinity of two power generating stations. Power station A was located in a densely built-up area, while power station B was three kilometers away from the nearest buildings. Figs. VI,12 and VI,13 show SO_2 concentrations in the neighborhood of the power stations in terms of five-monthly averages, this being the duration of the investigation. It follows from these figures that the high SO_2 concentrations expected on the basis of theoretical calculations do not arise in reality. This is undoubtedly due to the fact that the average wind velocity and direction are assumed to be constant in the calculation formulas. This condition is never fulfilled in reality, so that the point at which the maximum pollutant concentration should arise constantly changes its location. Long-term measurements invariably yield lower average pollutant concentrations, usually much lower than the theoretical values. Fig. VI,14 gives the lines of constant pollutant concentrations at ground level calculated from Sutton's formula (VI,4) for two elevations of emission source. These graphs clearly show sharp maxima over relatively small areas. A similar graph drawn on the basis of the Bosanquet-Pearson formula (VI,8) is given in Fig. VI,15.

A considerable degree of correlation between theoretical calculations and practical measurements is seen from the data given in Tables VI,6 and VI,7. This correlation is better in the case of power station B, which ensues from the fact that the topographical conditions in its vicinity are close to those assumed in the derivation of the equations.

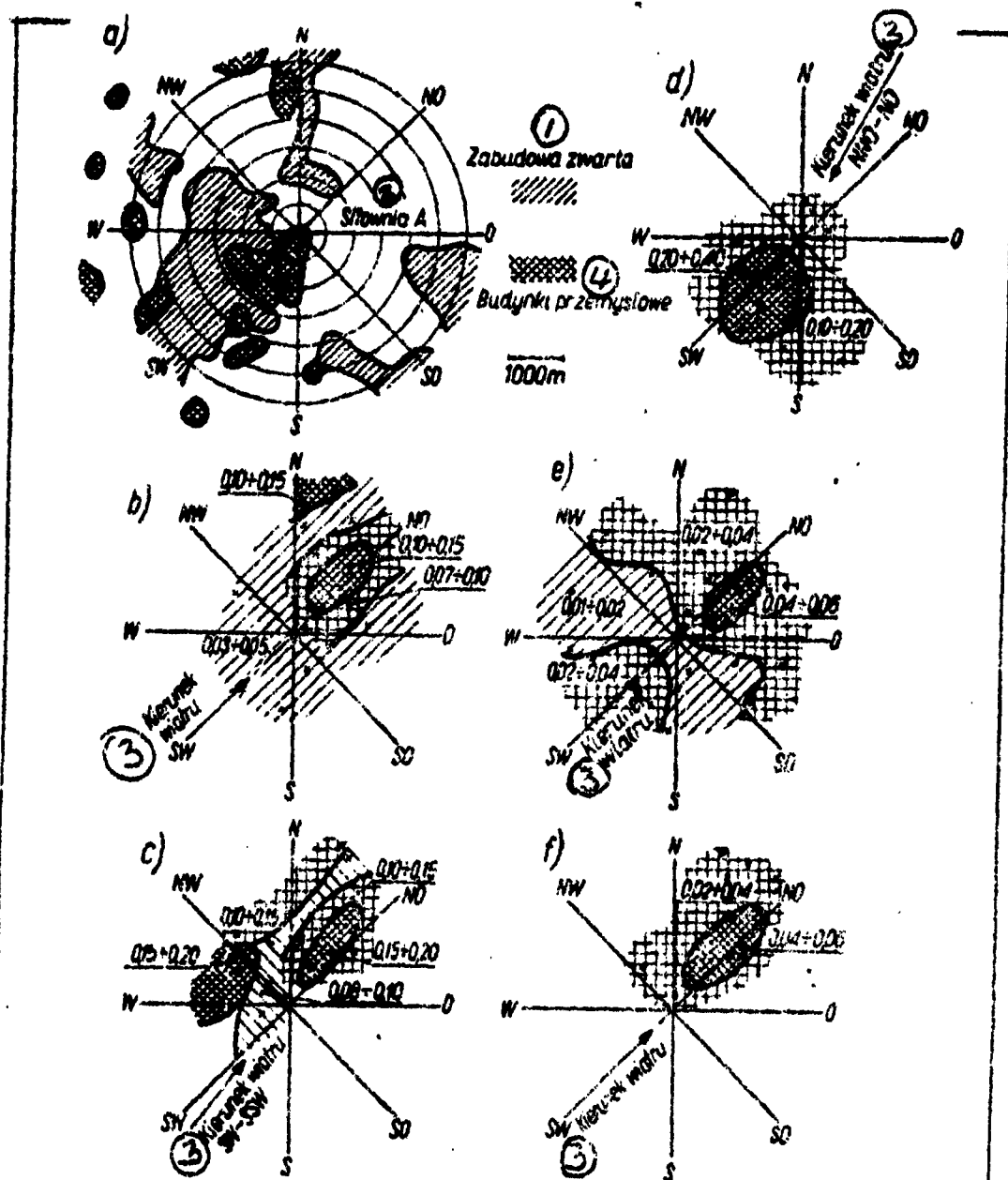


Fig. VI, 12. Distribution of the average sulfur dioxide concentration in the neighborhood of power station A. a. Situation plan of the power station; b. Average concentration of CO_2 /sic/ in July, wind velocity $v_w = 1 - 3$ m/sec, average temperature $t_{av} = 28 - 30^\circ C$; c. Average concentration of CO_2 in August, $v_w = 0.5 - 2$ m/sec, $t_{av} = 20 - 22^\circ C$; d. Average concentration of CO_2 in July, $v_w = 0.5 - 1.5$ m/sec, $t_{av} = 18 - 23^\circ C$; e. Average CO_2 concentration in August, $v_w = 2 - 4$ m/sec, $t_{av} = 13 - 20^\circ C$; f. Average CO_2 concentration in September, $v_w = 2 - 4$ m/sec, $t_v = 22 - 25^\circ C$.

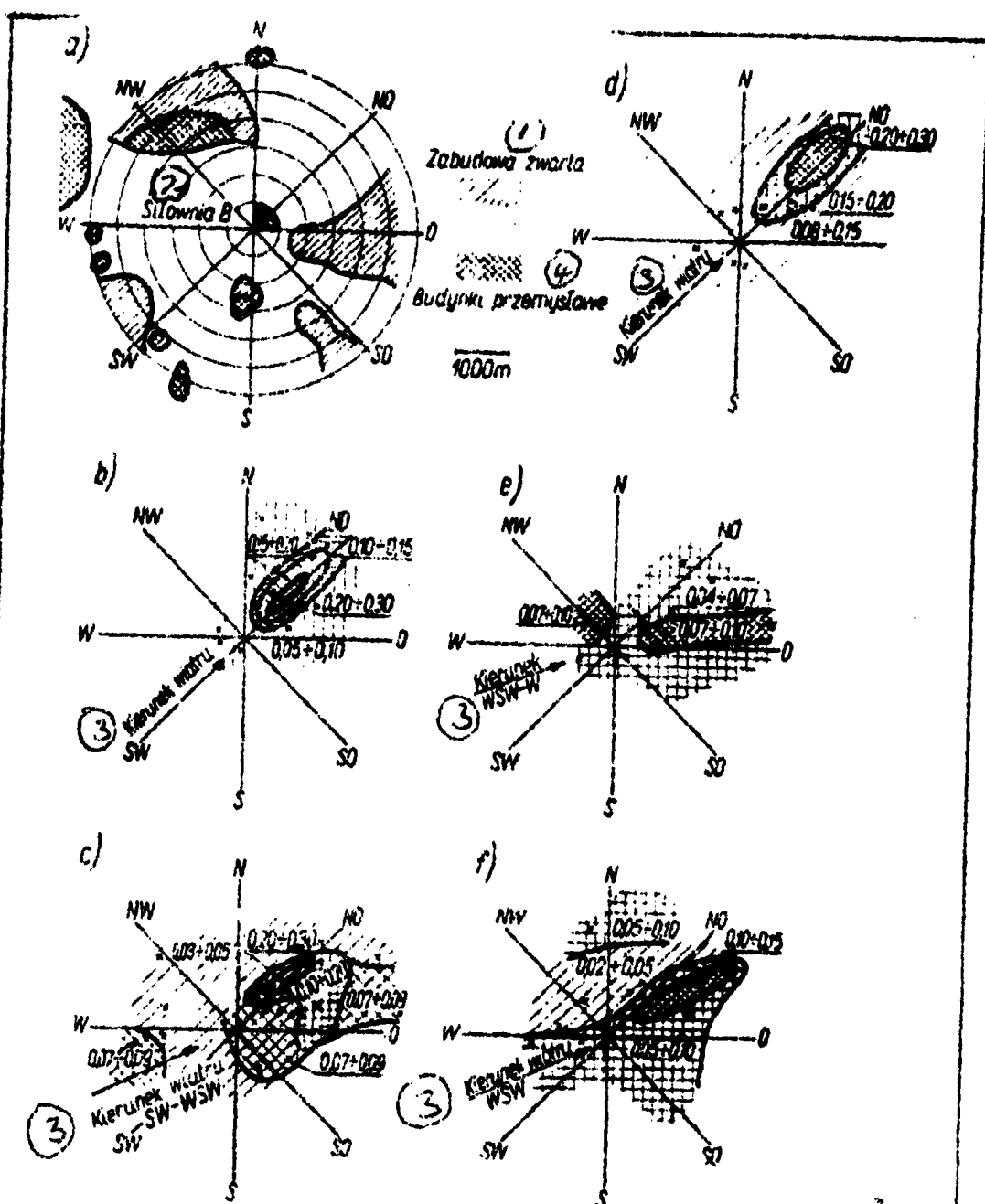


Fig. VI,13. Distribution of the average sulfur dioxide concentration in the neighborhood of power station B. a. Situation plan of the power station; b. Average CO₂ /sic/ concentration in May, average wind velocity $v_w = 5 - 8$ m/sec, average temperature $t_{av} = 12 - 15^\circ\text{C}$; c. Average CO₂ concentration in January, $v_w = 3 - 6$ m/sec, $t_{av} = 4 - 8^\circ\text{C}$; e. Average concentration in July, $v_w = 2 - 4$ m/sec, $t_{av} = 13 - 15^\circ\text{C}$; f. Average concentration of CO₂ in September, $v_w = 2 - 4$ m/sec, $t_{av} = 20 - 22^\circ\text{C}$.

Legend: 1. Densely built-up area; 2. Power station A; 3. Direction of wind; 4. Industrial buildings.

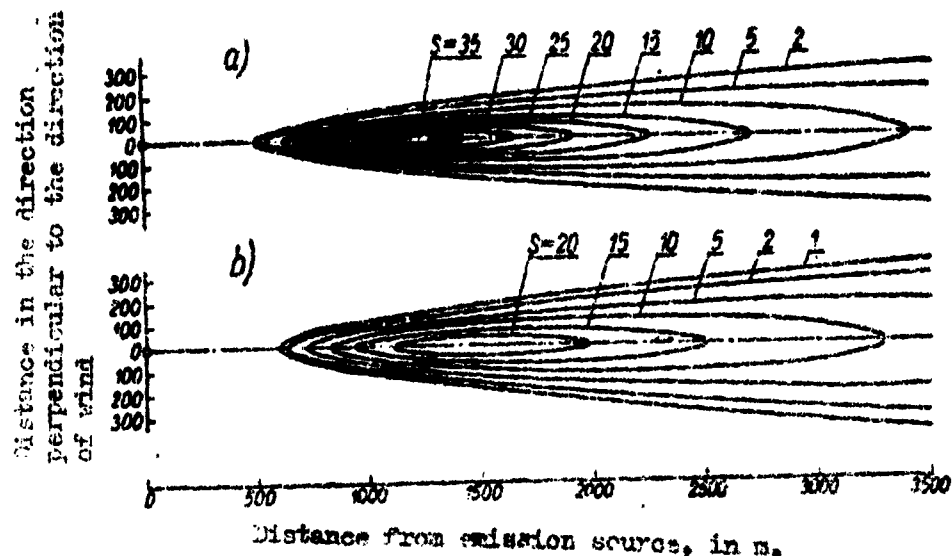


Fig. VI,14. Lines of constant pollutant concentrations at ground level calculated from the Sutton formula for emission source elevations: a), $H = 80$ m; b), $h = 100$ m.

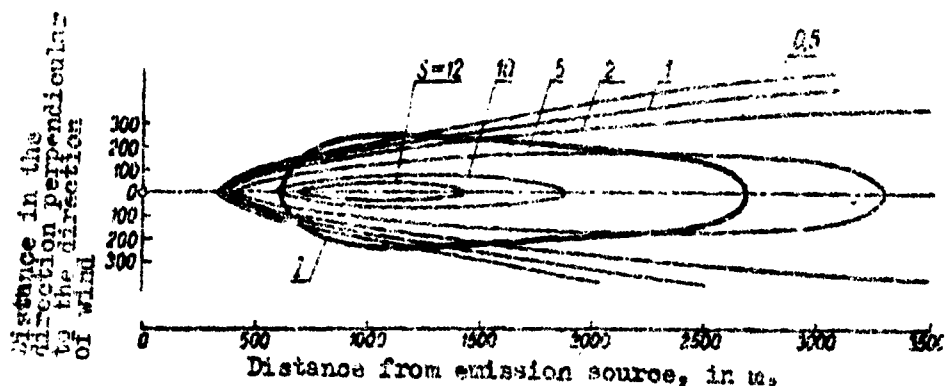


Fig. VI,15. Lines of constant pollutant concentrations at ground level calculated from the Bosanquet-Ferguson formula for a source at $H = 100$ meters. L is the line delimiting the experimentally verified area of high pollutant concentrations.

The buildings around power station A caused an increase in turbulence, which should be taken into account by a suitable selection of diffusion coefficients. Apart from this, the SO_2 concentration measured during protracted rainy periods was always considerably lower than the calculated value.

Table VI,6

A comparison of the theoretical and experimental values of SO₂ concentration in the vicinity of power station A

(1) Miesiąc	(2) Wyniki pomiaru mg/m ³	(3) Stężenie niezależ- ne od emisji	(4) Wg Suttona	(5) Wg Bosan- queta	(6) Prędkość wiatru	(7) Pogoda
Styczeń (8)	0,30	0,15	0,54	0,82	0,5-1,5	słoneczna (12)
Lipiec (9)	0,13	0,14	0,64	0,80	1-3	bezchmurna (13)
Sierpień (10)	0,18	0,09	1,45	0,91	0,5-2	słoneczna (12)
Wrzesień (11)	0,05	0,03	0,45	0,38	2,	częściowe zachmurzenie (14)

Legend: 1. Month; 2. Results of measurements, in mg/m³; 3. Concentration independent of emission; 4. According to Sutton; 5. According to Bosanquet; 6. Wind velocity; 7. Weather; 8. January; 9. July; 10. August; 11. September; 12. Sunny; 13. Cloudless; 14. Partly cloudy.

Nearly all investigators agree that the results obtained from theoretical formulas are higher than the measured values.

Thus, for instance, C. A. Goslin (VI.8) found, on the basis of concentration measurements of NO₂ emitted from a stack 25 meters in height, that experimental results are two times lower than those calculated from the formulas of Sutton and Bosanquet-Pearson.

With regard to the Bosanquet-Pearson formulas, Falk (0.14) has found that the point at which the maximum concentration occurs at ground level is located about 1/3 further than predicted by theoretical calculation, and that at distances greater than x_{max} the concentration of pollutants at ground level decreases with distance faster than expected on theoretical grounds.

Therefore, we can state the following on the basis the above investigation results:

1. Pollutant concentration and dustfall values as calculated on theoretical grounds are usually higher than those encountered in practice. Therefore, theoretical calculation assures a relatively high degree of certainty that the concentration of pollutants emitted by a given source is not higher than the calculated value. For this

Table VI,7

A comparison of the theoretical and experimental values of SO_2 concentrations in the vicinity of power station B

① Miesiąc	② Wyniki pomiaru mg/m^3	③ Stężenie niezależ- ne od emisji	④ Wg Suttona	⑤ Wg Besan- queta	⑥ Prędkość wiatru	⑦ Pogoda
Styczeń ⑧ ⑨ obszar 1 obszar 2	0,25 0,18	0,11	0,21 0,15	0,25 0,16	3-6	pochmurno, deszcz ⑭
Maj ⑩ obszar 1 ⑨ obszar 2 obszar 3	0,23 0,18 0,13	0,08	0,20 0,13 0,10	0,22 0,12 0,11	5-8	pochmurno, deszcz ⑭
Lipiec ⑪ ⑨ obszar 1	0,30	0,06	0,16	0,21	2-4	ciężły deszcz ⑮
Sierpień ⑫ ⑨ obszar 1 obszar 2	0,25 0,15	0,0	0,23 0,14	0,28 0,13	2-5	pochmurno ⑮
Wrzesień ⑬ ⑨ obszar 1	0,13	0,04	0,29	0,37	1-3	pochmurno ⑮

Legenda: 1. Month; 2. Results of measurements, in mg/m^3 ; 3. Concentration independent of emission; 4. According to Sutton; 5. According to Besanquet; 6. Wind velocity; 7. Weather; 8. January; 9. Area; 10. May; 11. July; 12. August; 13. September; 14. Cloudy, rain; 15. Continuous rain; 16. Cloudy.

reason, theoretical calculations are most valuable, and provide the only method of a relatively accurate plotting of pollutant distribution patterns in planning the siting of new industrial objectives with relation to dwellings or other social amenities.

2. Theoretical calculations and practical measurements show very good correlation in experimental determination of meteorological

parameters (mainly diffusion coefficients). This permits a very accurate prediction of the effect of a new source of emission on the state of atmospheric pollution in a given area.

9. Graphs and nomograms for determining dispersion of pollutants

The calculations can be speeded up significantly through the use of nomograms, especially in calculating the minimum permissible height of smoke stacks emitting pollutants, or the maximum permissible emissions on the basis of the permissible value of pollutant concentrations at ground level, or permissible dustfall.

If we define the non-dimensional distance in the direction of x as the ratio

$$P_x = \frac{x}{x_{max}} \quad (VI,74)$$

and the non-dimensional concentration of pollutants at ground level as

$$P_s = \frac{S}{S_{max}} \quad (VI,75)$$

we can write Sutton's equation (VI,4) for distribution of pollutant concentrations at ground level as a function of P_x in the form:

$$P_{s,(y=0)} = P_x^{n-1} \exp(1 - P_x^{n-2}) \quad (VI,76)$$

We can write the Bosanquet-Pearson equation in a similar manner

$$P_{s,(y=0)} = P_x^{-2} \exp\left(2 \frac{P_x - 2}{P_x}\right) \quad (VI,77)$$

The solutions of equations (VI,76) and (VI,77) are given in the form of graphs for $P_x = f(P_x)$ in Fig. VI,16. As can be seen from the graph, calculation using the Sutton formula for $n = 0.25$ is not advisable, since excessively high pollutant concentrations are obtained for high values of x .

It is necessary to know the values of S_{max} and x_{max} in order to be able to determine the concentration of pollutants at any given distance x from the source using the graphs in Fig. VI,16 for given parameters of the source and of meteorological conditions. These can

be calculated each time from formulas (VI,5) and (VI,6), or (VI,9) and (VI,10), or found from previously prepared graphs. Fig. VI,17 gives the solutions of equations (VI,9) and (VI,10). These can be used for easy determination of $S_{\max}$ and $x_{\max}$, for given emission source parameters and known meteorological conditions.

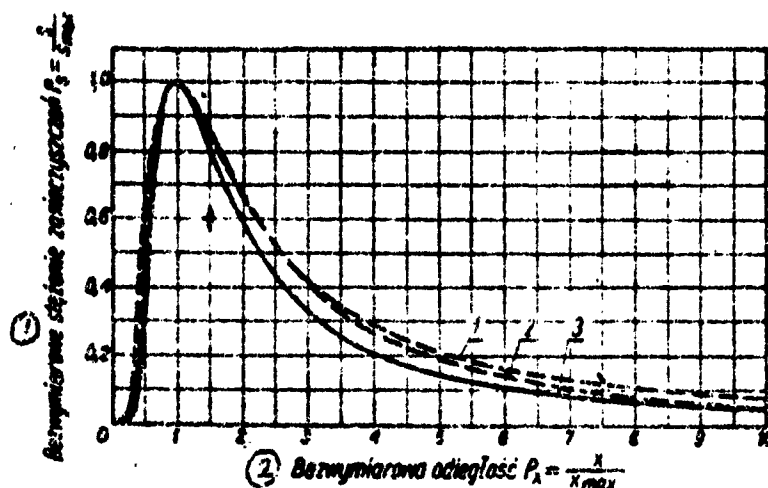


Fig. VI,16. Solution of non-dimensional equations for dispersion of pollutants:

1. Solution of the Sutton equation (VI,76) for $n = 0.5$; 2. Solution of the Bosanquet-Pearson equation (VI,77); 3. Solution of equation (VI,76) for $n = 0.25$.

Legend: 1. Non-dimensional concentration of pollutants; 2. Non-dimensional distance.

Distribution of pollutants in the direction perpendicular to that of the wind can be given graphically as a function of non-dimensional distance in the direction of y . One of the possible assumptions is to consider the non-dimensional distance y as

$$\frac{y}{y_{0,1 \max}} \quad (\text{VI,78})$$

where $y_{0,1 \max}$ is the distance between the point at which $S_{\max}$ obtains, and the point at which $S = 0,1 S_{\max}$. Having assumed this, we can write in relation to Sutton's equation

$$\frac{y}{y_{0,1 \max}} = \left\{ \frac{P_x^{2-n}}{\ln 0,1} \left[\ln P_x + (2-n) \ln P_x + \frac{1}{P_x^{2-n}} - 1 \right] \right\}^{1/2} \quad (\text{VI,79})$$

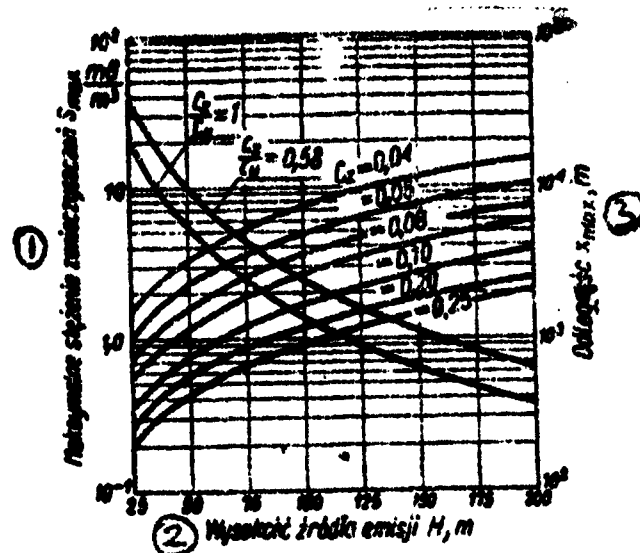


Fig. VI,17. Graphs for the calculation of $S_{\max}$ and $x_{\max}$ according to equations (VI,5) and (VI,6)

Legend: 1. Maximum concentration of pollutants; 2. Elevation of emission source; 3. Distance.

while in relation to the Bosanquet-Pearson equation we have

$$\frac{y}{y_{0,1 \max}} = P_x \left[\frac{1}{\ln 0.1} \left(\ln P_s + 2 \ln P_x + \frac{2}{P_x} - 2 \right) \right]^{1/2} \quad (\text{VI},80)$$

Equation (VI,79) is represented graphically in Fig. VI,19 in the form of a family of curves for different values of P_s , while equation (VI,80) is given in Fig. VI,20.

It is necessary to know the values of $S_{\max}$ and $x_{\max}$ in order to make use of Figures VI,19 and VI,20.

In order to further simplify the calculation of pollutant dispersion in the atmosphere, K. Gasiórowski (VI,7) has developed a special calculation slide rule and a special method of graphical solution.

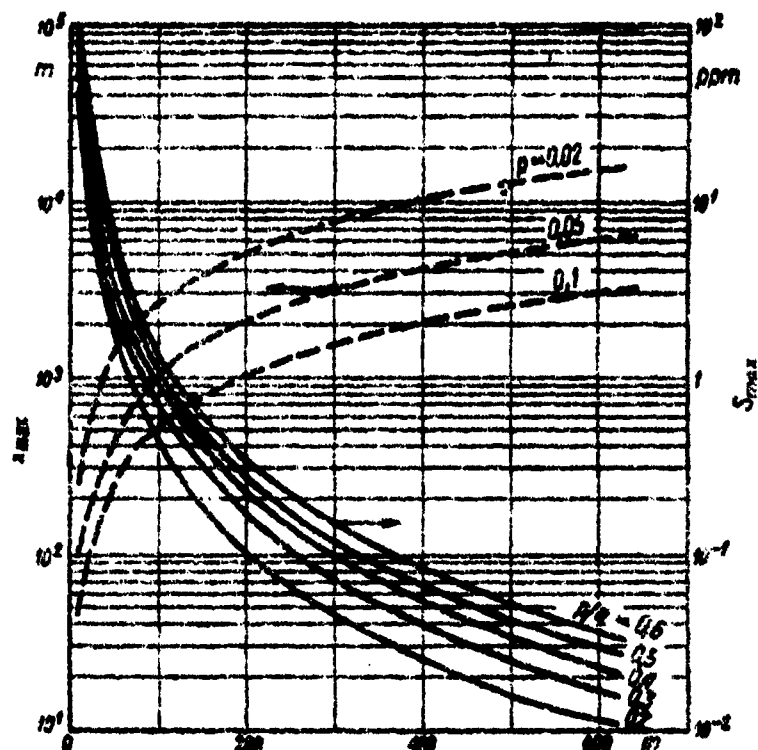


Fig. VI,18. Graphs for the calculation of $S_{\max}$ and $x_{\max}$ according to equations (VI,9) and (VI,10)

The starting point for the development of the slide rule was provided by Sutton's equation (VI,3). Since the pollutant concentrations of most interest are those at ground level, equation (VI,3) was simplified by assuming that $z = 0$. Another simplification has its origin in the fact that in most cases a rough estimate of the individual emissions from sources is adequately done knowing the maximum pollutant concentration $S_{\max}$ and its distance from the source $x_{\max}$.

Fig. VI,21 shows the scales of this slide rule. Thanks to a suitable selection of scales, a single setting of the slide at a given value of $\frac{K}{C_y}$ makes it possible to read off $S_{\max}$ for any combination of stack height K and average wind velocity v_w . This is particularly convenient when the object of the calculation^w is to determine the minimum permissible elevation of the source for an assumed maximum permissible pollutant concentration at ground level.

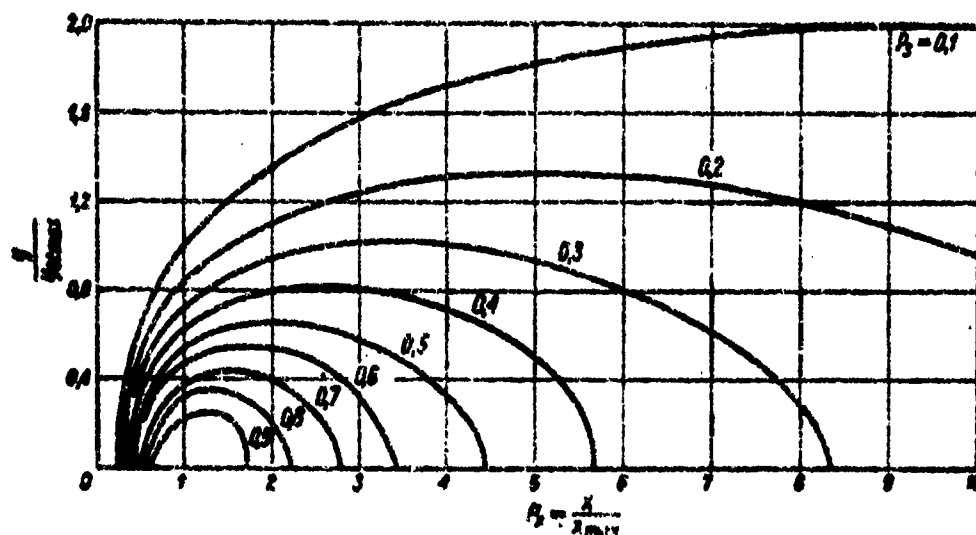


Fig. VI,19. Graphical representation of non-dimensional solution of Sutton's equation (VI,79) for the distribution of pollutant concentrations in the direction of y

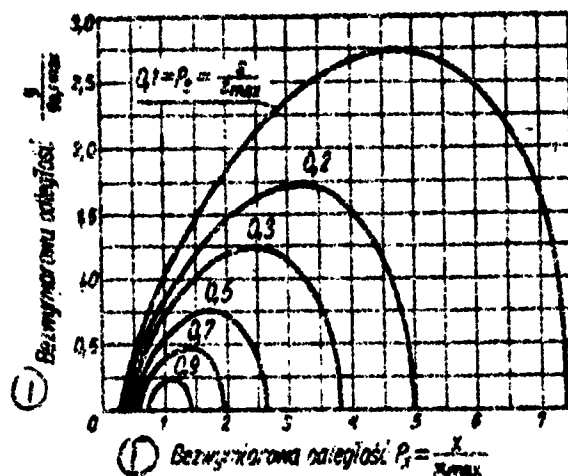


Fig. VI,20. Graphical representation of non-dimensional solution of the Bosanquet-Pearson equation (VI,80) for the distribution of pollutants in the direction of y

Legend: 1. Non-dimensional distance.

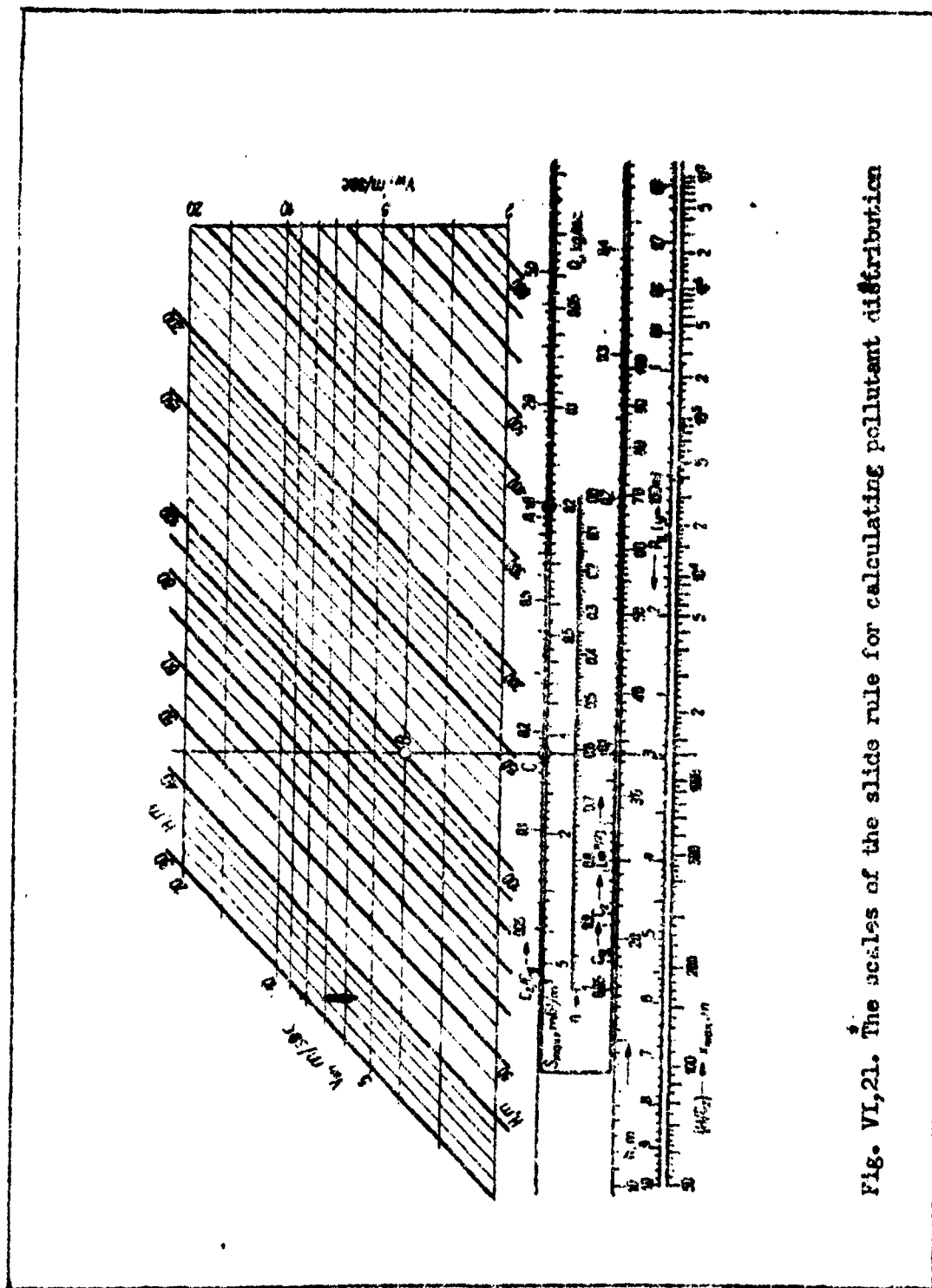


Fig. VI,21. The scales of the slide rule for calculating pollutant distribution

The method of slide rule operation can be best explained by the following example. Let the following values be included in the calculation: $Q = 0.2$ kg/sec; $H = 100$ meters; $n = 0.28$; $C_y = 0.40 \frac{h}{z}$; and hence $\frac{C_z}{C_y} = 0.975$.

The value of $Q = 0.2$ on the slide should be set under the reading of 0.975 on scale $\frac{C_z}{C_y}$ (point A). Setting the hair of the cursor on the intersection of the line $H = 100$ meters and the average wind velocity v_w (point B), we can read on scale S_{max} the value of the maximum pollutant concentration at ground level in mg/m³ (point C).

For instance, we obtain, for various wind velocities

v_w	m/sec	4	5	6	8	10	15
C_{max}	$h = 100m$	1.14	0.90	0.75	0.57	0.45	0.30
mg/m ³	$h = 150m$	0.80	0.63	0.53	0.40	0.32	0.26

Development of a slide rule which could be used for determining pollutant concentration at any given point within the coordinates x y z according to formula (VI,3) seems impracticable in view of the large number of variables involved. It is much simpler to employ the graphical method with whose aid it is possible to determine the general distribution of pollutant concentrations.

In order to find a general solution of the equation for pollutant distribution, equation (VI,3) must be presented in a non-dimensional form. It has been found most convenient to adopt the following non-dimensional proportionality coefficients in order to obtain the simplest form of solution

$$P_x = \frac{S}{S_{max}} \quad (VI,81)$$

$$P_x = \left(\frac{x}{x_{max}} \right)^{2-n} = \frac{x^{2-n}}{H^2/C_z^2} \quad (VI,82)$$

$$P_y = \frac{y/C_z}{x_{max}^{\frac{2-n}{2}}} = \frac{y/C_z}{H/C_z} \quad (VI,83)$$

$$P_z = \frac{z}{h} \quad (VI,84)$$

Dividing equation (VI,3) by (VI,6) and substituting the above proportionality coefficients, we obtain the following expression for spatial distribution of pollutants:

$$P_z = \frac{S}{S_{max}} = \frac{1}{2P_x} \exp\left(1 - \frac{P_y^2}{P_x}\right) \left[\exp - \frac{(P_x - 1)^2}{P_x} + \exp - \frac{(P_x + 1)^2}{P_x} \right] \quad (VI,85)$$

Substituting $z = 0$, i.e., $P_z = 1$, we obtain the following expression for pollutant concentration at ground level:

$$P_x = \frac{S_{z=0}}{S_{max}} = \frac{1}{P_x} \exp\left[1 - \frac{1}{P_x}(P_y^2 + 1)\right] \quad (VI,86)$$

The solution of equations (VI,85) and (VI,86) in the graphical form is given in Fig. VI,22. The upper part of the Figure contains a family of curves for different values of P_y assuming that $P_z = 0$. It represents the distribution of pollutant concentrations in the vertical direction in the wind axis x . Although the ground level distribution of pollutants is generally the one of most interest, the knowledge of the vertical distribution is useful in certain cases, i.e., in the investigation of pollutant concentrations on the individual floors of tall buildings. The lower part of the Figure represents the distribution of pollutant concentrations in the horizontal plane at ground level, i.e., on the assumption that $P_z = 0$ (equation (VI,4)).

Solution of equations (VI,85) and (VI,86) on graphs drawn on the semi-log scale permits the determination of pollutant concentration distribution with an accuracy adequate for practical purposes within the significant range of distances x , y and z .

For the practical application of the solution presented in Fig. VI,22 it is necessary to adjust the real distances x , y and z to the non-dimensional scales of the axes P_x , P_y and P_z , as well as the actual pollutant concentrations to the non-dimensional values P_s .

The slide rule described above can be used to determine S_{max} on the basis of given conditions. Its value corresponds to that of $P_s = 1$ in Fig. VI,22.

The description of scale P_z does not present any difficulties in view of the simple relationship between P_z and H . At $P_z = 1$, z is equal to source elevation in meters used in the calculation. The z -scale is linear.

The distance y can be aligned with the individual values of

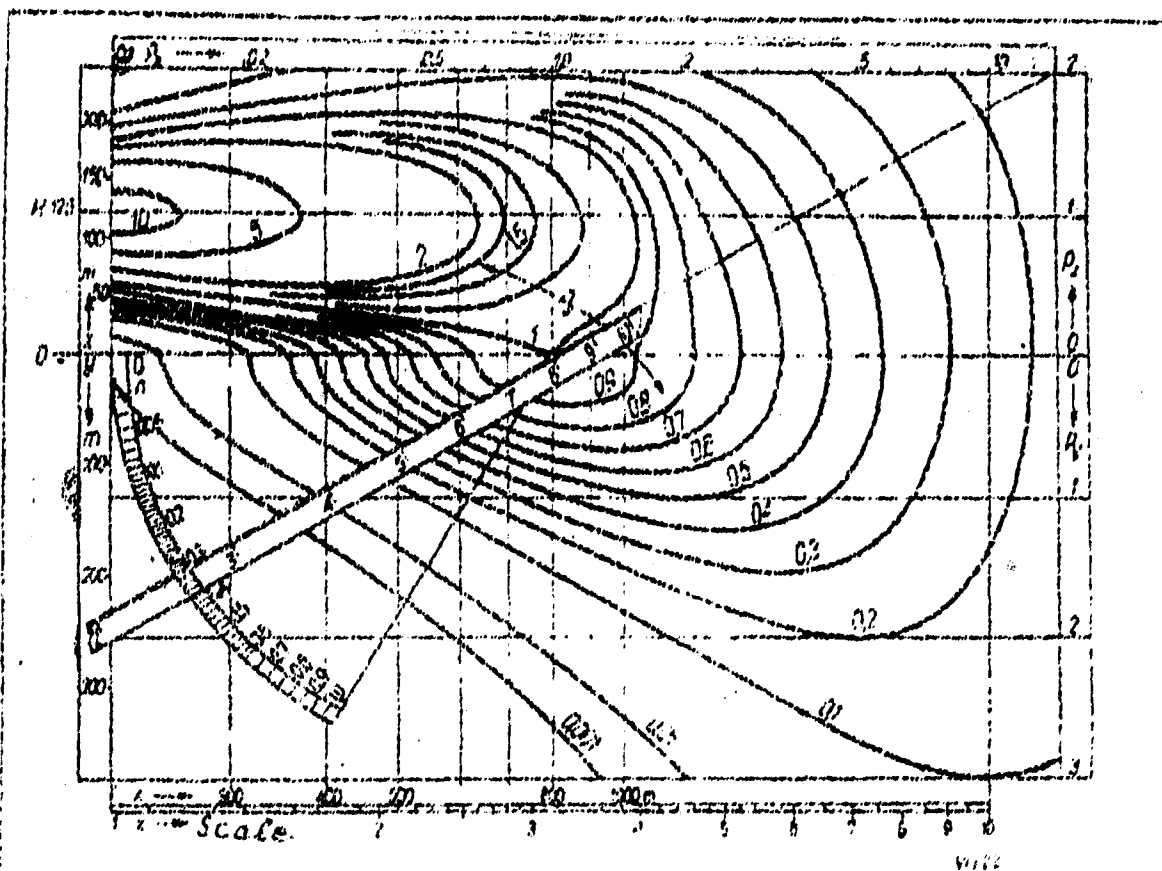


Fig. VI,32. Graphical solution of non-dimensional equations (VI,35) and (VI,36) according to K. Dzierżewski

on the basis of relationship (VI,35). In order to facilitate this calculation, the necessary mathematical operations can be carried out using the slide rule. The sequence of operations on the slide rule is as follows: The value of h on the lower scale of the slide rule is made to coincide with the value of U_1 on the slide. The value of U_2 can be read directly under U_1 on the slide. The value of F_1 , as read, corresponds to the actual distance of 1.0 meters. Since the value is directly proportional to F_2 , the scale is linear.

Before scale F_2 can be described in terms of real values, it is necessary first to calculate the value of x_{max} which corresponds to $F_2 = 1$. This calculation can be carried out using the lowest scale (log-log) and scale n of the slide. Before the actual calculation is done on the slide rule, it is necessary to calculate the ratio n/U_2 . The found value of this ratio is then made to coincide with the appropriate value on scale n . The value of x_{max} is read off under $n = 0$ on scale n . In view of the exponential dependence of x on n ,

calculation of the individual values of x would be troublesome. It is much more convenient to use the following graphic method. In the lower left corner of Fig. VI,22 there is an arc scale of the meteorological exponent n . A straight line is drawn through the point corresponding to n and the center of the Figure ($P_x = 1, P_z = 0$). Then the logarithmic scale in the lower part of the Figure should be aligned with this straight line so that the previously calculated value of x_m on this scale coincides with the point $P_x = 1$. Vertical straight lines are then drawn through further points corresponding to given distances on the logarithmic scale. The graphs obtained in this manner are not clear, particularly if it is desired to compare the distribution of pollutant concentrations under various meteorological conditions, or for different parameters of the source. For this reason it is convenient to transfer the values obtained in the manner described above onto graphs which have a single scale of distances for all cases.

Using Sutton's equation (VI,4) as his starting point, R. Trappenbergl (VI.19) calculated the average maximum pollutant concentrations at ground level and the average maximum dustfall for all practical combinations of meteorological parameters and various source elevations. He assumed that the maximum pollutant concentration determined by equation (VI,6) arises at one point only, and then only under the assumption that the direction and velocity of wind remain strictly constant. Such a clear maximum never arises under actual conditions. Therefore, he took the maximum average pollutant concentration to mean the average pollutant concentration over a rectangle having the sides $2x_0 = 1,000$ meters and $2y_0 = 500$ meters, whose center is at a point x_{max} determined from equation (VI,5). In accordance with this assumption, the maximum average pollutant concentration is expressed by the following relationship:

$$S_{k: max} = \frac{\int_{-y_0}^{y_0} \int_{x_1}^{x_2} S \, dx \, dy}{\int_{-y_0}^{y_0} \int_{x_1}^{x_2} dx \, dy} \quad (VI,87)$$

where

$$\begin{aligned} x_1 &= x_{max} - x_0 \\ x_2 &= x_{max} + x_0 \\ x_0 &= 500 \text{ m} \\ y_0 &= 250 \text{ m} \end{aligned}$$

After certain simplifying assumptions, we obtain the following

result of integration:

$$\int_{-y_0}^{y_0} \int_{x_1}^{x_2} S dx dy = \frac{4}{\pi} \frac{EH^{\frac{n}{2-n}}}{v_w C_x x^{\frac{1}{2-n}}} \Phi \left(\frac{y_0}{C_y x_{max}^{\frac{1}{2-n}}} \right) \int_{u_1}^{u_2} \frac{e^{-u^2}}{u^{\frac{1}{2-n}}} du \quad (VI,88)$$

where

$$u^2 = \frac{H^2}{C_x^2 x^{\frac{1}{2-n}}}$$

$$u_1 = \frac{1}{\left(1 - \frac{x_0}{x_{max}}\right)^{\frac{1}{2-n}}}$$

$$u_2 = \frac{1}{\left(1 + \frac{x_0}{x_{max}}\right)^{\frac{1}{2-n}}}$$

The following values were used in solving equation (VI,88):

$$n = 0,1, 0,2, 0,3, 0,4, 0,5, 1, 0,6$$

$$C_x = 0,05, 0,10, 0,15, 0,20, 0,25, 0,30, 0,40, 0,50, 0,60 \text{ cm}^2/\text{s},$$

$$C_y = 0,1,$$

$$v_w = 2, 4, 6, 8 \text{ m/sec},$$

$$h = 20, 40, 60, 80, 100, 120 \text{ m}$$

$$E = 100 \text{ G/sec}$$

Since both the pollutant concentration and the dustfall are directly proportional to emission, re-calculation for different values of emission requires a simple multiplication of the result by a suitable coefficient.

It follows from an analysis of the results of calculations that in the case of constant wind velocity, pollutant concentration depends on the meteorological parameters n , C_x and C_y only to a small degree. In view of this, it was possible to represent these relationships in graphs (Figs. VI,23, VI,24, VI,25 and VI,26). Each of these

Figures corresponds to a different wind velocity. The maximum average pollutant concentration is plotted along the abscissa. The dotted lines encircle all the possible values obtained in various combinations of n , C_2 and C_3 . The solid line represents the average value.

To show the influence of wind velocity on the average maximum pollutant concentration, Fig. VI,27 contains also the curves of average values from Figs. VI,23, VI,24, VI,25 and VI,26. The dotted line represents possible deviations from the average values for a given wind velocity in percent of pollutant concentration. At high source elevations, these deviations may reach 50%. However, since in the case of high source elevations the absolute value of pollutant concentration is small, even deviations as high as 50% are not very significant.

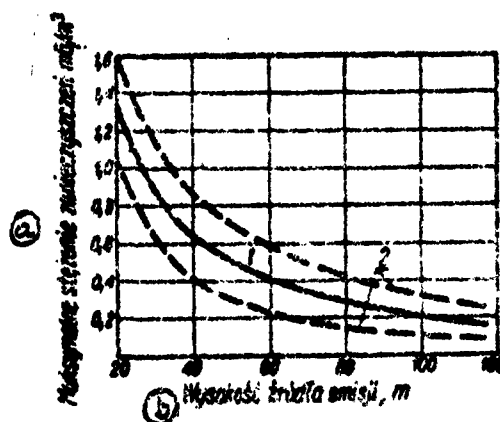


Fig. VI,23. Average maximum concentration of pollutants, in mg/m^3 for wind velocity $v_w = 2 \text{ m/sec}$, $n = 0.1 - 0.6$, $C_2 = 0.05 - 0.6$. 1. The average value; 2. Extreme values corresponding to given limits of n and C_2 .

Legend: a. Maximum pollutant concentration, in mg/m^3 ; b. Elevation of source.

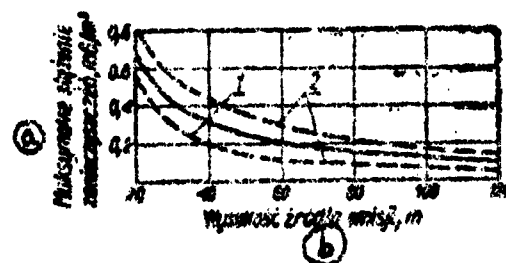


Fig. VI,24. Average maximum concentration of pollutants, in mg/m^3 , at a wind velocity $v_w = 4 \text{ m/sec}$, $n = 0.1 - 0.6$, $C_2 = 0.05 - 0.6$. 1. Average value; 2. Extreme values corresponding to given limits of n and C_2 .

Legend: a. Maximum pollutant concentration; b. Elevation of source.

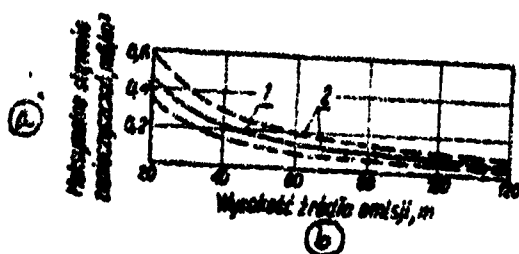


Fig. VI,25. Average maximum concentration of pollutants, in mg/m^3 at a wind velocity $v_w = 6 \text{ m/sec}$, $n = 0.1 - 0.6$, $C_z = 0.05 - 0.6$. 1. Average value; 2. Extreme values corresponding to given limits of n and C_z .

Legend: a. Maximum pollutant concentration; b. Elevation of source.

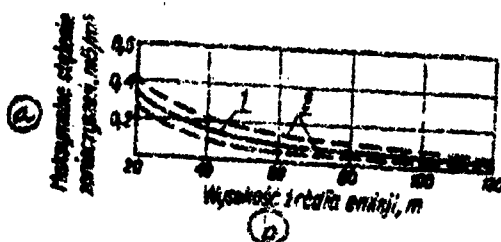


Fig. VI,26. Average maximum concentration of pollutants, in mg/m^3 at a wind velocity $v_w = 8 \text{ m/sec}$, $n = 0.1 - 0.6$, $C_z = 0.05 - 0.6$. 1. Average value; 2. Extreme values corresponding to given limits of n and C_z .

Legend: a. Maximum pollutant concentration; b. Elevation of source.

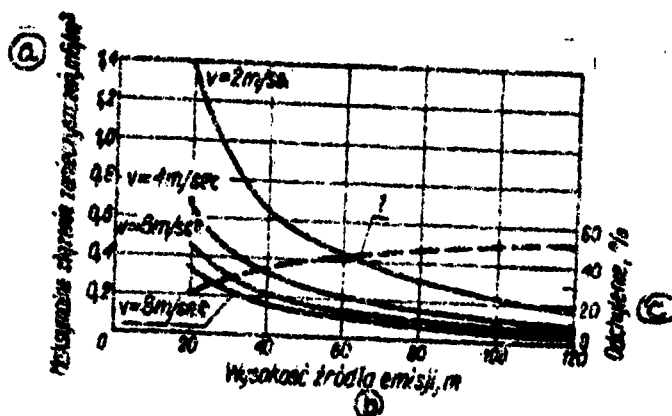


Fig. VI,27. A composite graph of the average maximum concentration of pollutants, in mg/m^3 , for different wind velocities. 1. Curve of possible deviations from the average value

Legend: a. Maximum pollutant concentration; b. Elevation of source; c. Deviation, in %.

The values of the distance $x_{\max}$ at which maximum concentrations $S_{Q\max}$ arise are given in Table VI,8 which embodies all the possible combinations of parameters n , C_z and h within the previously given limits.

According to R. Trappenberg, tabulation of the average maximum dustfall can be done in the following manner. Transformation of formula (VI,3) gives the following relationship for dustfall distribution around the source of emission

$$O_p = \frac{bE(2-n)Hv_w^{1-n}}{\pi C_y C_z x^{2-n}} \left| \frac{dv_w}{dz} \right|_{z=0}^{1-n} \exp \left(-\frac{y^2}{C_y^2 x^{2-n}} - \frac{H^2}{C_z^2 x^{2-n}} \right) \quad (\text{VI},89)$$

The distance from the source at which maximum dustfall occurs is

$$x_{\max} = \left(\frac{H^2}{2C_z^2} \right)^{\frac{1}{2-n}} \quad (\text{VI},90)$$

The maximum value of dustfall is

$$O_{p\max} = \frac{b4E(2-n)v_w^{1-n}C_z^3}{\pi e^2 H^2 \left(\frac{dv_w}{dz} \right)_{z=0}^{1-n} C_y} \quad (\text{VI},91)$$

Average maximum dustfall is determined in a manner analogous to that for the maximum pollutant concentration.

$$O_{p\text{ av max}} = \frac{\int_{-y_0}^{y_0} \int_{x_1}^{x_2} O_p dx dy}{\int_{-y_0}^{y_0} \int_{x_1}^{x_2} dx dy} \quad (\text{VI},92)$$

After integrating within the same limits as those in (VI,87), we obtain

$$\int_{-y_0}^{y_0} \int_{x_1}^{x_2} O_p dx dy = \frac{1,2}{\sqrt{\pi}} \frac{Ev_w^{1-n}}{\left(\frac{H}{C_z} \right)^{2(1-n)(2-n)} \left| \frac{dv_w}{dz} \right|_{z=0}^{1-n}} \quad (\text{VI},93)$$

$$\cdot \Phi \left(\frac{y_0}{C_y x_{\max}^{\frac{2-n}{2}}} \right) \int_{u_1}^{u_2} e^{-u^2} u^{\frac{2(1-n)}{2-n}} du$$

Table VI,8.

Distance $x_{\max}$, in kilometers, from the source at which maximum pollutant concentrations arise

n	C_s cm ³ /s	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,1	0,05	0,7	1,1	1,4	1,8	2,2	2,6	3,0	3,4	3,8	4,2	4,6
	10		0,5	0,7	0,9	1,1	1,3	1,4	1,6	1,8	2,0	2,2
	15			0,5	0,6	0,7	0,8	1,0	1,1	1,2	1,3	1,4
	20					0,5	0,6	0,7	0,8	0,9	1,0	1,1
	25						0,5	0,6	0,6	0,7	0,8	0,9
	30							0,5	0,5	0,6	0,6	0,7
	40										0,5	0,5
	50											
	60											
	60											
0,2	0,05	1,3	2,0	2,8	3,6	4,4	5,2	6,0	6,9	7,8	8,7	9,6
	10	0,6	0,9	1,3	1,6	2,0	2,4	2,8	3,2	3,6	4,0	4,4
	15		0,6	0,9	1,0	1,2	1,5	1,8	2,1	2,4	2,6	2,8
	20			0,6	0,8	0,9	1,1	1,3	1,5	1,7	1,9	2,1
	25			0,5	0,6	0,7	0,9	1,0	1,2	1,3	1,5	1,6
	30				0,6	0,7	0,8	0,9	1,0	1,1	1,2	1,3
	40						0,5	0,6	0,7	0,7	0,8	0,9
	50							0,5	0,5	0,6	0,7	0,7
	60									0,5	0,5	0,6
	60											
0,3	0,05	2,6	4,2	5,9	7,7	9,5	11,3	13,2	15,2	17,2	19,2	21,3
	10	1,2	1,9	2,6	3,3	4,1	5,0	5,9	6,8	7,6	8,6	9,3
	15	0,7	1,1	1,6	2,1	2,6	3,1	3,6	4,2	4,7	5,3	5,9
	20	0,5	0,8	1,1	1,5	1,8	2,2	2,6	3,0	3,4	3,8	4,2
	25		0,6	0,9	1,2	1,4	1,7	2,0	2,3	2,6	2,9	3,2
	30		0,5	0,7	0,9	1,2	1,4	1,6	1,8	2,1	2,4	2,6
	40			0,5	0,7	0,8	1,0	1,2	1,4	1,5	1,7	1,8
	50				0,5	0,6	0,8	0,9	1,1	1,2	1,3	1,4
	60					0,5	0,6	0,7	0,8	0,9	1,1	1,2
	60											
0,4	0,05	5,7	9,4	13,4	17,7	22,4	27,1	32,1	37,0	42,3	47,6	53,0
	10	2,3	4,0	5,7	7,4	9,4	11,4	13,4	15,6	17,7	20,0	22,4
	15	1,4	2,3	3,4	4,5	5,6	6,8	8,1	9,4	10,6	12,0	13,4
	20	0,9	1,6	2,3	3,1	4,0	4,8	5,7	6,6	7,4	8,4	9,4
	25	0,8	1,3	1,8	2,3	2,9	3,6	4,3	4,9	5,6	6,3	7,1
	30	0,6	1,0	1,4	1,8	2,3	2,9	3,4	4,0	4,5	5,1	5,7
	40		0,7	1,0	1,3	1,7	2,0	2,3	2,7	3,1	3,5	4,0
	50		0,5	0,7	0,9	1,2	1,5	1,8	2,1	2,3	2,6	2,9
	60			0,6	0,8	1,0	1,2	1,4	1,6	1,8	2,1	2,3
	60											

Table VI,8. (continued)

n	C _t cm ^{n/s}	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,5	0,05	13,6	23,5	34,4	46,5	59,2	72,7	87,0	101,7	117,0	132,8	149,2
	10	5,4	9,4	13,8	18,6	23,6	29,0	34,8	40,6	46,8	53,2	59,7
	15	3,2	5,4	7,9	10,8	13,6	16,8	20,2	23,5	27,0	30,6	34,4
	20	2,2	3,7	5,4	7,3	9,4	11,6	13,8	16,2	18,6	21,1	23,6
	25	1,6	2,8	4,0	5,5	7,0	8,6	10,2	11,9	13,6	15,6	17,5
	30	1,3	2,2	3,2	4,3	5,4	6,7	8,1	9,4	10,8	12,2	13,8
	40	0,8	1,4	2,1	2,9	3,7	4,6	5,4	6,3	7,3	8,4	9,4
	50	0,6	1,1	1,6	2,2	2,7	3,3	4,0	4,8	5,5	6,2	7,0
	60	0,5	0,8	1,2	1,7	2,2	2,7	3,2	3,7	4,3	4,9	5,4
0,6	0,05	37,6	67,0	101,1	139,0	180,3	224,8	272,1	322,0	374,1	428,8	485,6
	10	13,9	24,9	37,3	51,4	68,3	84,7	100,4	118,8	138,2	158,2	179,2
	15	7,9	13,9	21,0	28,9	37,6	46,8	56,6	67,0	77,9	89,3	101,1
	20	5,1	9,2	13,9	19,0	24,8	30,9	37,3	44,1	51,4	58,7	66,6
	25	3,8	6,7	10,2	13,9	18,1	22,5	27,2	32,3	37,6	43,0	48,7
	30	3,0	5,1	7,7	10,7	13,9	17,2	20,8	24,8	28,7	33,0	37,3
	40	2,0	3,4	5,1	7,1	9,2	11,5	13,9	16,4	19,0	21,8	24,8
	50	1,3	2,5	3,8	5,1	6,7	8,4	10,0	12,0	13,9	15,9	18,1
	60	1,1	2,0	3,0	3,9	5,1	6,4	7,7	9,2	10,7	12,3	13,9

where

$$u = \frac{\sqrt{2}}{\left(1 + \frac{x_0}{x_{max}}\right)^{\frac{2-n}{2}}}$$

$$u_2 = \frac{\sqrt{2}}{\left(1 - \frac{x_0}{x_{max}}\right)^{\frac{2-n}{2}}}$$

Table VI, 9.

Average maximum dustfall $C_{\text{per max}}$, in $\text{g/m}^2/\text{day}$ at a wind velocity
 $v_w = 2 \text{ m/sec}$ and unit emission $E = 100 \text{ g/sec}$

n	C_r cm^3/s	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,1	0,05		0,88	0,61	0,42	0,31	0,23	0,18	0,15	0,12	0,10	0,08
	10				1,21	0,95	0,75	0,61	0,51	0,43	0,36	0,31
	15						1,41	1,15	0,95	0,81	0,70	0,61
	20								1,82	1,28	1,02	0,95
	25										1,39	1,30
	30											
	40											
	50											
	60											
0,2	0,05	1,31	0,67	0,41	0,27	0,19	0,14	0,11	0,08	0,07	0,06	0,05
	10		1,82	1,30	0,92	0,68	0,51	0,40	0,33	0,27	0,22	0,19
	15			2,30	1,72	1,31	1,03	0,83	0,68	0,58	0,48	0,41
	20				2,74	2,23	1,72	1,43	1,15	0,96	0,82	0,70
	25					2,87	2,33	1,85	1,52	1,30	1,13	0,98
	30						3,34	2,79	2,35	2,01	1,77	1,57
	40									3,23	2,88	2,55
	50											
	60											
0,3	0,05	0,90	0,42	0,24	0,16	0,11	0,08	0,06	0,05	0,04	0,03	0,03
	10	2,80	1,44	0,89	0,60	0,42	0,31	0,24	0,19	0,15	0,12	0,10
	15		2,73	1,69	1,20	0,90	0,68	0,52	0,42	0,34	0,28	0,24
	20		4,33	2,67	1,92	1,47	1,16	0,93	0,76	0,63	0,53	0,46
	25			3,94	2,86	2,12	1,64	1,30	1,07	0,93	0,75	0,67
	30				4,72	3,54	2,63	2,17	1,85	1,57	1,33	1,13
	40					5,35	4,08	3,39	3,13	2,52	1,98	1,87
	50						5,99	4,76	4,12	3,57	3,13	2,72
	60								5,73	4,72	4,08	3,57
0,4	0,05	0,53	0,24	0,13	0,08	0,06	0,04	0,03	0,03	0,02	0,02	0,01
	10	1,95	0,87	0,52	0,34	0,23	0,17	0,13	0,10	0,09	0,07	0,06
	15	3,85	1,82	1,10	0,74	0,53	0,40	0,30	0,24	0,19	0,16	0,13
	20	5,55	2,90	1,77	1,22	0,88	0,65	0,50	0,40	0,33	0,27	0,23
	25	8,13	4,21	2,88	1,96	1,41	1,05	0,81	0,65	0,53	0,44	0,38
	30		5,80	4,48	3,17	2,38	1,87	1,49	1,19	0,99	0,84	0,73
	40			6,06	4,55	3,43	2,74	2,23	1,85	1,54	1,30	1,11
	50				6,58	5,52	4,49	3,70	3,08	2,60	2,22	1,94
	60				8,74	7,00	5,59	4,51	3,72	3,17	2,78	2,35

Table VI,9. (continued)

H	C _z cm ³ /m ³	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0.5	0,05	0,29	0,13	0,07	0,05	0,03	0,02	0,02	0,01	0,01	0,01	0,01
	10	1,14	0,48	0,28	0,18	0,13	0,10	0,08	0,06	0,05	0,04	0,03
	15	2,48	1,09	0,63	0,42	0,30	0,22	0,17	0,13	0,11	0,09	0,07
	20	4,26	1,94	1,14	0,74	0,52	0,38	0,29	0,23	0,19	0,16	0,13
	25	6,15	3,08	1,79	1,16	0,81	0,60	0,46	0,36	0,29	0,24	0,20
	30	8,00	4,12	2,52	1,65	1,14	0,84	0,66	0,52	0,42	0,35	0,29
	40	12,42	6,82	4,26	2,86	2,04	1,52	1,16	0,92	0,75	0,62	0,52
	50		10,13	6,12	4,21	3,05	2,27	1,79	1,41	1,15	0,96	0,81
	60		14,47	8,00	5,88	4,26	3,23	2,52	2,02	1,64	1,36	1,14
0,6	0,05	0,16	0,07	0,04	0,03	0,02	0,01	0,01	0,01	0,01	0,01	0,00
	10	0,66	0,29	0,16	0,10	0,07	0,05	0,04	0,03	0,03	0,02	0,02
	15	1,46	0,59	0,35	0,23	0,16	0,12	0,09	0,07	0,06	0,05	0,04
	20	2,60	1,06	0,62	0,38	0,26	0,18	0,13	0,11	0,09	0,08	0,07
	25	3,94	1,79	1,02	0,65	0,45	0,33	0,26	0,20	0,16	0,13	0,11
	30	5,56	2,44	1,46	0,94	0,66	0,49	0,37	0,29	0,24	0,20	0,16
	40	9,30	4,12	2,45	1,60	1,08	0,75	0,56	0,44	0,36	0,29	0,24
	50	13,16	6,45	3,96	2,61	1,82	1,34	1,04	0,81	0,66	0,54	0,47
	60	17,54	9,35	5,68	3,70	2,47	1,79	1,33	1,05	0,85	0,67	0,56

The calculated values of average maximum dustfall are given in Tables VI,9, VI,10, VI,11 and VI,12.

It should be pointed out that the values of Q_{psr} compiled in these Tables, as well as the graphs in Figs. VI,23 thru VI,27 apply only to the case of $C_y = C_{z1}$. However, they can be used also with other values of C_y after introducing a simple correction. Diffusion coefficient in the horizontal direction C_y appears in equations (VI,88) and (VI,93) only under the symbol of the Gauss function Φ . The value of Φ can be made dependent on C_z/C_y and H (instead of C_y and x_{max}) in the following manner.

For particulate concentration

$$\Phi\left(\frac{y_0}{C_y x_{max} \sqrt{\frac{2-\alpha}{2}}}\right) = \Phi\left(\frac{y_0}{H} \cdot \frac{1}{C_z/C_y}\right) \quad (VI,94)$$

Table VI, 10.

Average maximum dustfall $Q_{\text{per max}}$ in $\text{g/m}^2/\text{day}$ at a wind velocity v_w
 $= 4 \text{ m/sec}$ and unit emission $E = 100 \text{ g/sec}$

H	C_a cm^3/s	Elevation wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,1	0,05		1,64	1,14	0,78	0,58	0,43	0,34	0,26	0,22	0,19	0,15
	10				2,26	1,77	1,40	1,14	0,95	0,80	0,67	0,58
	15						2,63	2,15	1,77	1,51	1,31	1,14
	20								3,40	2,39	1,90	1,77
	25										2,59	2,43
	30											
	40											
	50											
	60											
	60											
0,2	0,05	2,28	1,17	0,71	0,47	0,33	0,24	0,19	0,14	0,12	0,10	0,09
	10		3,17	2,26	1,60	1,20	0,89	0,70	0,57	0,47	0,38	0,33
	15			4,00	2,98	2,28	1,79	1,44	1,18	1,01	0,84	0,71
	20				4,77	3,88	2,99	2,49	2,00	1,67	1,43	1,22
	25					4,99	4,05	3,22	2,64	2,09	1,97	1,71
	30						5,81	4,85	4,09	3,50	3,08	2,73
	40									5,62	5,01	4,44
	50											
	60											
	60											
0,3	0,05	1,46	0,68	0,39	0,26	0,18	0,13	0,10	0,08	0,07	0,05	0,05
	10	4,53	2,34	1,45	0,98	0,68	0,50	0,39	0,31	0,24	0,20	0,16
	15		4,44	2,75	1,95	1,46	1,11	0,85	0,68	0,55	0,46	0,39
	20		7,04	4,34	3,12	2,39	1,89	1,51	1,24	1,02	0,86	0,75
	25			6,40	4,65	3,45	2,67	2,11	1,74	1,51	1,22	1,09
	30				7,67	5,75	4,27	3,53	3,01	2,55	2,16	1,84
	40					8,69	6,63	5,51	5,09	4,10	3,22	3,04
	50						9,73	7,74	6,70	5,80	5,09	4,42
	60								9,31	7,67	6,63	5,80
	60											
0,4	0,05	0,80	0,36	0,20	0,12	0,09	0,06	0,05	0,04	0,03	0,02	0,02
	10	2,96	1,32	0,79	0,52	0,35	0,26	0,20	0,15	0,14	0,11	0,09
	15	5,84	2,76	1,67	1,12	0,80	0,61	0,45	0,36	0,29	0,24	0,20
	20	8,41	4,40	2,68	1,85	1,33	0,99	0,76	0,61	0,50	0,41	0,35
	25	12,33	6,38	4,37	2,97	2,14	1,59	1,23	0,99	0,80	0,67	0,58
	30		8,79	6,79	4,81	3,61	2,83	2,26	1,80	1,50	1,27	1,11
	40			9,19	6,90	5,20	4,15	3,38	2,80	2,33	1,97	1,68
	50				9,98	8,37	6,81	5,61	4,67	3,94	3,37	2,94
	60				13,25	10,61	8,47	6,84	5,64	4,81	4,21	3,58
	60											

Table VI,10 (continued)

n	C _s cm ² /s	Elevation Wysokość H, m.										
		20	30	40	50	60	70	80	90	100	110	120
0,5	0,05	0,41	0,18	0,10	0,07	0,04	0,03	0,02	0,01	0,01	0,01	0,01
	10	1,61	0,68	0,40	0,25	0,18	0,14	0,11	0,08	0,07	0,06	0,04
	15	3,51	1,54	0,89	0,59	0,42	0,31	0,24	0,18	0,16	0,13	0,10
	20	6,02	2,74	1,61	1,05	0,74	0,54	0,41	0,33	0,27	0,23	0,18
	25	8,70	4,36	2,53	1,64	1,15	0,85	0,65	0,51	0,41	0,34	0,28
	30	11,31	5,83	3,56	2,33	1,61	1,19	0,93	0,74	0,59	0,49	0,41
	40	17,56	9,64	6,02	4,04	2,88	2,15	1,64	1,30	1,06	0,88	0,74
	50		14,32	8,65	5,95	4,31	3,21	2,53	1,99	1,63	1,36	1,15
	60		20,46	11,31	8,31	6,02	4,57	3,56	2,86	2,32	1,92	1,62
0,6	0,05	0,21	0,09	0,05	0,04	0,03	0,02	0,02	0,01	0,01	0,01	0,01
	10	0,87	0,38	0,21	0,13	0,09	0,07	0,05	0,04	0,04	0,03	0,03
	15	1,93	0,78	0,46	0,30	0,21	0,16	0,12	0,09	0,08	0,07	0,05
	20	3,43	1,40	0,82	0,50	0,34	0,24	0,17	0,15	0,12	0,11	0,09
	25	5,20	2,36	1,35	0,86	0,59	0,44	0,34	0,26	0,21	0,17	0,15
	30	7,34	3,22	1,93	1,24	0,87	0,65	0,49	0,38	0,32	0,26	0,21
	40	12,28	5,44	3,23	2,11	1,43	0,99	0,74	0,58	0,48	0,38	0,32
	50	17,37	8,51	5,23	3,45	2,40	1,77	1,37	1,07	0,87	0,71	0,62
	60	23,15	12,34	7,50	4,88	3,26	2,36	1,76	1,39	1,12	0,88	0,74

For dustfall

$$\Phi \left(\frac{y_0}{C_y x_{\max}} \cdot \frac{1}{z-n} \right) = \Phi \left(\frac{y_0}{H} \cdot \frac{\sqrt{2}}{C_y/C_s} \right) \quad (\text{VI,95})$$

If $C_y/C_s \leq 1$, $\Phi = 1.00$ can be substituted in equations (VI,88) and (VI,93). Table VI,13 gives the coefficients dependent on C_y (at $C_y > 0.1$) by which the values of C_{psr} and $S_{\max}$ obtained from the appropriate Tables of graphs should be multiplied.

Table VI.11.

Average maximum dustfall $Q_{\text{per max}}$ in $\text{g/m}^2/\text{day}$ at wind velocity
 $v_w = 5 \text{ m/sec}$ and unit emission $E = 100 \text{ g/sec}$

n	C_p cm^2/s	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,1	0,05		2,37	1,64	1,13	0,83	0,62	0,48	0,40	0,32	0,27	0,22
	10				3,25	2,55	2,02	1,64	1,37	1,16	0,97	0,83
	15						3,79	3,09	2,55	2,18	1,88	1,64
	20								4,89	3,44	2,74	2,55
	25										3,74	3,49
	30											
	40											
	50											
	60											
0,2	0,05	3,15	1,61	0,99	0,65	0,46	0,34	0,26	0,19	0,17	0,14	0,12
	10		4,38	3,13	2,22	1,64	1,23	0,96	0,79	0,65	0,53	0,46
	15			5,54	4,14	3,15	2,48	2,00	1,64	1,40	1,16	0,99
	20				6,60	5,37	4,14	3,44	2,77	2,31	1,97	1,69
	25					6,91	5,61	4,45	3,66	3,13	2,72	2,36
	30						8,04	6,72	5,66	4,84	4,26	3,78
	40									7,78	6,94	6,14
	50											
	60											
0,3	0,05	1,94	0,91	0,52	0,35	0,24	0,17	0,13	0,11	0,09	0,06	0,06
	10	6,04	3,11	1,92	1,29	0,91	0,67	0,52	0,41	0,32	0,26	0,22
	15		5,89	3,65	2,59	1,94	1,47	1,12	0,91	0,73	0,60	0,52
	20		9,34	5,76	4,14	3,17	2,50	2,01	1,64	1,36	1,14	0,99
	25			8,50	6,17	4,57	3,54	2,81	2,31	2,01	1,62	1,45
	30				10,19	7,64	5,68	4,68	3,99	3,39	2,87	2,44
	40					11,55	8,80	7,32	6,75	5,44	4,27	4,04
	50						12,93	10,27	8,89	7,70	6,75	5,87
	60								12,37	10,19	8,80	7,70
0,4	0,05	1,02	0,46	0,25	0,15	0,12	0,08	0,06	0,06	0,04	0,04	0,02
	10	3,77	1,68	1,01	0,66	0,44	0,33	0,25	0,19	0,17	0,14	0,12
	15	7,44	3,52	2,13	1,43	1,02	0,77	0,58	0,46	0,37	0,31	0,25
	20	10,73	5,61	3,42	2,36	1,70	1,26	0,97	0,77	0,64	0,52	0,44
	25	15,72	8,14	5,57	3,79	2,73	2,03	1,57	1,26	1,02	0,85	0,73
	30		11,21	8,66	6,13	4,60	3,61	2,88	2,30	1,91	1,62	1,41
	40			11,71	8,80	6,63	5,30	4,81	3,58	2,98	2,51	2,15
	50				12,72	10,67	8,68	7,15	5,95	5,03	4,29	3,75
	60				16,89	13,53	10,81	8,72	7,19	6,13	5,37	4,54

Table VI,11. (continued)

N	C _s cm ³ /s	Elevation				Wysokość H, m							
		20	30	40	50	60	70	80	90	100	110	120	
0,5	0,05	0,50	0,23	0,12	0,09	0,05	0,03	0,03	0,02	0,02	0,02	0,02	
	10	1,97	0,83	0,48	0,31	0,23	0,17	0,14	0,10	0,09	0,07	0,05	
	15	4,30	1,89	1,09	0,73	0,52	0,38	0,29	0,23	0,19	0,16	0,12	
	20	7,38	3,36	1,97	1,28	0,90	0,66	0,50	0,40	0,33	0,28	0,23	
	25	10,65	5,33	3,10	2,01	1,40	1,04	0,80	0,62	0,50	0,42	0,35	
	30	13,86	7,14	4,36	2,86	1,97	1,45	1,14	0,90	0,73	0,61	0,50	
	40	21,51	11,81	7,38	4,95	3,53	2,63	2,01	1,59	1,30	1,07	0,90	
	50		17,55	10,60	7,29	5,28	3,93	3,10	2,44	1,99	1,66	1,40	
	60		25,06	13,96	10,18	7,38	5,59	4,36	3,50	2,84	2,36	1,97	
0,6	0,05	0,25	0,11	0,06	0,05	0,03	0,02	0,02	0,02	0,02	0,02	0,02	
	10	1,02	0,45	0,25	0,16	0,11	0,08	0,06	0,05	0,05	0,03	0,03	
	15	2,27	0,92	0,54	0,36	0,25	0,19	0,14	0,11	0,09	0,08	0,06	
	20	4,04	1,65	0,96	0,59	0,40	0,28	0,20	0,17	0,14	0,12	0,11	
	25	6,11	2,78	1,58	1,01	0,70	0,51	0,40	0,31	0,25	0,20	0,17	
	30	8,63	3,79	2,27	1,46	1,02	0,76	0,57	0,45	0,37	0,31	0,25	
	40	14,43	6,39	3,80	2,48	1,68	1,16	0,87	0,68	0,56	0,45	0,37	
	50	20,42	10,01	6,15	4,05	2,82	2,08	1,61	1,26	1,02	0,84	0,73	
	60	27,22	14,51	8,82	5,74	3,83	2,78	2,06	1,63	1,32	1,04	0,87	

In order to facilitate calculations, distances x_{max} at which maximum dustfall occurs as calculated on the basis of equation (VI,90) are given in Table VI,14.

Tables VI,8 thru VI,14 list numerical values for $x_{max} > 0.5$ kilometer. This follows from the accepted practice of re-calculating the values for standard surface area ($x_p = 500$ meters) on the one hand, and from the fact that considerable disturbances in wind direction and velocity can arise in the vicinity of the source on the other.

As has been previously remarked, the average maximum values of pollutant concentration and dustfall are considerably smaller in the event of large variations in the direction of wind. This decrease can be taken into account using Fig. VI,28 which gives a family of curves for various values of deviations in wind direction. The values of x_{max} are plotted on the abscissa, and the ordinate represents the

Table VI,12.

Average maximum dustfall O_{avg} , in $\text{g}/\text{m}^2/\text{day}$ at wind velocity $v_w = 8 \text{ m/sec}$ and unit emission $E = 100 \text{ g/sec}$

x	C_s cm^2/s^2	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,1	0,05		3,06	2,12	1,46	1,08	0,80	0,63	0,52	0,42	0,35	0,28
	10				4,21	3,31	2,61	2,12	1,78	1,50	1,25	1,08
	15						4,91	4,00	3,31	2,82	2,44	2,12
	20								6,34	4,46	3,55	3,31
	25										4,84	4,53
	30											
	40											
	50											
	60											
0,2	0,05	3,97	2,03	1,24	0,82	0,58	0,42	0,33	0,24	0,21	0,18	0,15
	10		5,52	3,94	2,79	2,06	1,55	1,21	1,00	0,82	0,67	0,58
	15			6,97	5,21	3,97	3,12	2,52	2,06	1,76	1,45	1,24
	20				8,30	6,76	5,21	4,33	3,49	2,91	2,49	2,12
	25					8,70	7,06	5,61	4,61	3,94	3,43	3,97
	30						10,12	8,46	7,12	6,09	5,36	4,76
	40									9,79	8,73	7,73
	50											
	60											
0,3	0,05	2,38	1,11	0,63	0,42	0,29	0,21	0,16	0,13	0,11	0,08	0,08
	10	7,39	3,80	2,35	1,58	1,11	0,82	0,63	0,50	0,40	0,32	0,26
	15		7,20	4,46	3,17	2,38	1,79	1,37	1,11	0,90	0,74	0,63
	20		11,43	7,05	5,07	3,88	3,06	2,45	2,01	1,66	1,40	1,21
	25			10,40	7,55	5,59	4,33	3,43	2,82	2,45	1,98	1,77
	30				12,46	9,34	6,94	5,73	4,88	4,14	3,51	2,96
	40					14,12	10,77	8,95	8,26	6,63	5,23	4,93
	50						15,81	12,56	10,87	9,42	8,26	7,18
	60								15,12	12,46	10,77	9,42
0,4	0,05	1,22	0,55	0,30	0,18	0,14	0,09	0,07	0,07	0,05	0,05	0,02
	10	4,48	2,00	1,19	0,78	0,53	0,39	0,30	0,23	0,21	0,16	0,14
	15	8,84	4,18	2,53	1,70	1,22	0,92	0,69	0,55	0,44	0,37	0,30
	20	12,75	6,66	4,07	2,80	2,02	1,49	1,15	0,92	0,76	0,62	0,53
	25	18,67	9,67	6,62	4,50	3,24	2,41	1,86	1,49	1,22	1,01	0,87
	30		13,32	10,29	7,28	5,47	4,30	3,42	2,73	2,27	1,93	1,68
	40			13,92	10,45	7,88	6,29	5,12	4,25	3,54	2,99	2,55
	50				15,11	12,68	10,21	8,50	7,07	5,97	5,10	4,46
	60				20,08	16,08	12,84	10,36	8,54	7,28	6,39	5,40

Table VI,12. (continued)

n	C _r cm ^{n/2}	Elevation				Wysokość H, m						
		20	30	40	50	60	70	80	90	100	110	120
0,5	0,05	0,58	0,16	0,14	0,10	0,06	0,04	0,04	0,02	0,02	0,02	0,02
	10	2,28	0,96	0,56	0,36	0,26	0,20	0,16	0,12	0,10	0,08	0,06
	15	4,96	2,18	1,26	0,84	0,60	0,44	0,34	0,26	0,22	0,18	0,14
	20	8,52	3,88	2,28	1,48	1,04	0,76	0,58	0,46	0,38	0,32	0,26
	25	12,30	6,16	3,58	2,32	1,62	1,20	0,92	0,72	0,58	0,48	0,40
	30	16,00	8,24	5,04	3,30	2,28	1,68	1,32	1,04	0,82	0,70	0,58
	40	24,84	13,64	8,52	5,72	4,08	3,04	2,32	1,84	1,50	1,24	1,04
	50		20,26	12,24	8,42	6,10	4,54	3,58	2,82	2,30	1,92	1,62
	60		28,94	16,00	11,76	8,52	6,46	5,04	4,04	3,28	2,72	2,28
0,6	0,05	0,28	0,12	0,07	0,05	0,03	0,02	0,02	0,02	0,02	0,02	0,00
	10	1,15	0,50	0,28	0,17	0,12	0,09	0,07	0,05	0,05	0,03	0,03
	15	2,54	1,03	0,61	0,40	0,28	0,21	0,16	0,12	0,10	0,09	0,07
	20	4,53	1,85	1,08	0,66	0,45	0,31	0,23	0,19	0,16	0,14	0,12
	25	6,86	3,12	1,78	1,13	0,78	0,57	0,45	0,35	0,28	0,23	0,19
	30	9,68	4,25	2,54	1,64	1,15	0,85	0,64	0,50	0,42	0,35	0,28
	40	16,19	7,17	4,27	2,79	1,88	1,31	0,97	0,77	0,63	0,50	0,42
	50	22,89	11,23	6,89	4,54	3,17	2,33	1,81	1,41	1,15	0,94	0,82
	60	30,54	16,28	9,89	6,44	4,30	3,12	2,32	1,83	1,48	1,17	0,97

Table VI,13.

Corrections for C_y ≠ 0.1

H, m	① W obliczeniach S			② W obliczeniach O _p		
	C _y /C _r =8	C _y /C _r =4	C _y /C _r =2	C _y /C _r =8	C _y /C _r =4	C _y /C _r =2
20	0,97	1,00	1,00	1,00	1,00	1,00
40	0,73	0,97	1,00	0,88	1,00	1,00
60	0,54	0,86	1,00	0,71	0,96	1,00
80	0,43	0,75	1,00	0,56	0,88	1,00
100	0,36	0,66	0,99	0,47	0,79	0,99
120	0,33	0,61	0,97	0,44	0,71	0,98

Legend: 1. In calculation of S; 2. In calculation of O_p.

coefficient by which it is necessary to multiply the values obtained from the graph in Fig. VI,23, or from Tables VI,9 thru VI,12.

Table VI,14.

Distances $x_{\max}$ from the source of pollution at which maximum pollutant concentrations arise

n	C, cm ³ /2	Elevation Wysokość H, m										
		20	30	40	50	60	70	80	90	100	110	120
0,1	0,05		0,8	1,0	1,3	1,5	1,8	2,1	2,4	2,6	2,9	3,2
	10				0,6	0,7	0,9	1,0	1,1	1,3	1,4	1,5
	15						0,6	0,7	0,7	0,8	0,9	1,0
	20								0,6	0,6	0,7	0,7
	25										0,6	0,6
	30											
	40											
	50											
	60											
0,2	0,05	0,9	1,4	1,9	2,4	3,0	3,6	4,1	4,7	5,3	5,9	6,5
	10		0,6	0,9	1,1	1,4	1,6	1,9	2,2	2,5	2,7	3,0
	15			0,6	0,7	0,9	1,0	1,2	1,4	1,6	1,7	1,9
	20				0,5	0,6	0,8	0,9	1,0	1,2	1,3	1,4
	25					0,5	0,6	0,7	0,8	0,9	1,0	1,1
	30						0,5	0,6	0,6	0,7	0,8	0,9
	40									0,5	0,6	0,6
	50											
	60											
0,3	0,05	1,7	2,8	3,9	5,1	6,3	7,5	8,8	10,1	11,5	12,8	14,2
	10	0,8	1,2	1,7	2,2	2,8	3,3	3,9	4,5	5,0	5,7	6,2
	15		0,7	1,1	1,4	1,7	2,1	2,4	2,8	3,1	3,5	3,9
	20		0,5	0,8	1,0	1,2	1,5	1,7	2,0	2,2	2,5	2,8
	25			0,6	0,8	0,9	1,1	1,3	1,5	1,7	1,9	2,1
	30				0,6	0,8	0,9	1,1	1,2	1,4	1,6	1,7
	40					0,5	0,7	0,8	0,9	1,0	1,1	1,2
	50						0,5	0,6	0,7	0,8	0,9	0,9
	60								0,5	0,6	0,7	0,8

Table VI, 14. (continued)

0,4	0,05	3,7	6,1	8,7	11,5	14,5	17,6	20,9	24,0	27,4	30,9	34,4
	10	1,5	2,6	3,7	4,8	6,1	7,4	8,7	10,1	11,5	13,0	14,5
	15	0,9	1,5	2,2	2,9	3,7	4,4	5,3	6,1	6,9	7,8	8,7
	20	0,6	1,1	1,5	2,0	2,6	3,1	3,7	4,3	4,8	5,5	6,1
	25	0,5	0,8	1,2	1,5	1,9	2,3	2,8	3,2	3,7	4,1	4,6
	30		0,6	0,9	1,2	1,5	1,9	2,2	2,6	2,9	3,3	3,7
	40			0,6	0,9	1,1	1,3	1,5	1,8	2,0	2,3	2,6
	50				0,6	0,8	1,0	1,2	1,4	1,5	1,7	1,9
	60				0,5	0,6	0,8	0,9	1,1	1,2	1,4	1,5

n	C ₂ cm ² /s	Elevation			Wysokość H, m							
		20	30	40	50	60	70	80	90	100	110	120
0,5	0,05	8,6	14,8	21,7	29,3	37,3	45,8	54,8	64,1	73,7	83,7	94,0
	10	3,4	5,8	8,7	11,7	14,9	18,3	21,9	25,6	29,5	33,5	37,6
	15	2,0	3,4	5,0	6,8	8,6	10,6	12,7	14,8	17,0	19,3	21,7
	20	1,4	2,3	3,4	4,6	5,9	7,3	8,7	10,2	11,7	13,3	14,9
	25	1,0	1,7	2,5	3,4	4,4	5,4	6,4	7,5	8,6	9,8	11,0
	30	0,8	1,4	2,0	2,7	3,4	4,2	5,1	5,9	6,8	7,7	8,7
	40	0,5	0,9	1,4	1,8	2,3	2,9	3,4	4,0	4,6	5,3	5,9
	50		0,7	1,0	1,4	1,7	2,1	2,6	3,0	3,4	3,9	4,4
	60		0,5	0,8	1,1	1,4	1,7	2,0	2,3	2,7	3,1	3,4
0,6	0,05	22,9	40,8	61,6	84,7	109,9	137,0	165,8	196,2	228,0	261,3	295,9
	10	8,5	15,2	22,7	31,3	40,6	50,6	61,2	72,4	84,2	96,4	109,2
	15	4,8	8,5	13,8	17,6	22,9	28,5	34,5	40,8	47,5	54,5	61,6
	20	3,1	5,6	8,5	11,6	15,1	18,8	22,7	26,9	31,3	35,8	40,6
	25	2,3	4,1	6,2	8,5	11,0	13,7	16,6	19,7	22,9	26,2	29,7
	30	1,8	3,1	4,7	6,5	8,5	10,5	12,7	15,1	17,5	20,1	22,7
	40	1,2	2,1	3,1	4,3	5,6	7,0	8,5	10,0	11,6	13,3	15,1
	50	0,8	1,5	2,3	3,1	4,1	5,1	6,1	7,3	8,5	9,7	11,0
	60	0,7	1,2	1,8	2,4	3,1	3,9	4,7	5,6	6,5	7,5	8,5

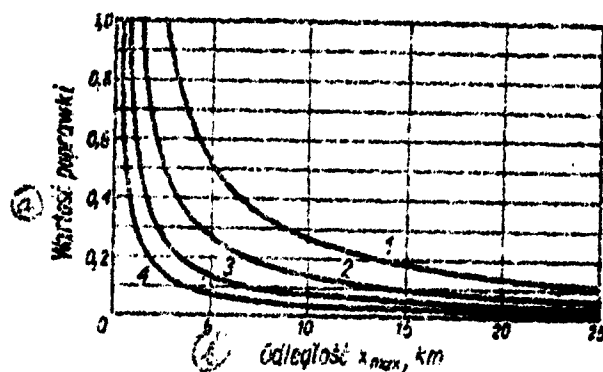


Fig. VI, 28. Values of corrections F' for decrease in the average maximum pollutant concentration or average maximum dustfall as a function of the angle of wind deviation and on x_{max} . 1. Angle of deviation $\pm 0.5^\circ$; 2. $\pm 1^\circ$; 3. $\pm 2^\circ$; 4. $\pm 4^\circ$. a) Correction; b) Distance.

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PART THREE

TESTING OF ATMOSPHERIC POLLUTANTS

Chapter VII

Methods of Measuring Atmospheric Pollution

1. Introductory remarks

The problem of pollution abatement is extremely complex and involved, and the state of knowledge in this field, both theoretical and experimental, cannot be regarded as satisfactory. For this reason, great importance attaches to systematic and widespread measurements of air pollution, as these contribute to a deepening of the knowledge of the problem, and supply practical pointers of value to the technology of pollution abatement.

Atmospheric pollution can be considered in three stages:

1. Emission phase;
2. Dispersion phase;
3. Deposition phase.

The sampling technology embraces all these phases, but it has a different task to perform in each case, and different methods are used.

The measurement of emissions by large industrial sources is relatively the easiest. The results of these measurements give an idea of the degree of responsibility on the part of a given source for the total pollution of the district, in addition to supplying direct pointers as to the necessity of reducing the amount of emitted pollutants.

A little more difficult is the measurement of emissions by numerous small and scattered sources, such as domestic fireplaces and automobiles. The difficulties are not inherent in the sampling techniques, but in the number of sources. Therefore, it is necessary

to measure emissions from single sources, and estimate emissions of the remaining ones.

The measurement of pollution in the dispersion phase is extremely difficult. The strong relationship between dispersion and meteorological conditions, as well as the changes undergone by emitted pollutants as a result of absorption, desorption, coagulation, condensation or mutual chemical or photochemical reactions cause quantitative and qualitative changes in the pollutants with time at given points in the atmosphere. Nevertheless, systematic and continuous sampling in this phase is necessary since it allows:

1. To determine whether intermittent pollutant concentrations attain values which represent danger to human health;
2. To check the degree to which theoretical calculations of pollutant dispersion from a given source correlate with practical conditions;
3. To determine relationships between the individual parameters influencing the degree of pollution.

In addition to sampling techniques, the methods used to analyze the results of measurements are of fundamental importance. For instance, they make it possible to introduce suitable coefficients into equations for pollutant dispersion in a given region, thus making it possible to determine accurately the influence on the existing state of air pollution by the locations chosen for new sources of emission.

As a result of gravity and precipitation, some pollutants, and notably particulate matter and condensed fumes, settle on the surface of the earth. In this connection measurements are conducted to determine the amount of dust settling on the ground. Although the dustfall figures can be re-calculated directly into particulate pollutant concentrations only in a few cases, they do nevertheless constitute a valuable clue as to the degree of pollution.

One of the main virtues of dustfall measurement is the fact that the equipment used for this purpose is relatively cheap and simple. Furthermore, when certain simplifying assumptions are made, dustfall figures can supply data similar to those gathered in the dispersion phase.

2. Choice of monitoring locations

In view of the fact that pollutant concentrations change

strongly with place as well as with time, the problem of the number and location of monitoring points is essential to the procurement of reliable results.

According to J. Pelletier (VII.2), the following criteria determine the choice of monitoring points:

1. Population density;
2. Concentration of industry;
3. Geographical and topographical conditions;
4. Local meteorological conditions;
5. Local microclimatic conditions.

Since the main aim of pollution measurements is to protect human health, it is obvious that the number of monitoring points should be proportional to population density. Similarly, large numbers of monitoring points should be located in the vicinity of large industrial plants.

In urban areas situated in flat locations, monitoring points should be set up at street level, as well as on tops of the tallest buildings. In cities located in valleys, and in general in all places where terrain relief causes considerable turbulence of air flow, monitoring points should be located on as many levels as possible.

If the mean distribution of local winds is known, the concentration of monitoring points downwind from industrial plants should be greater than that upwind. Theoretical calculations of pollutant distribution should be used to a significant degree in establishing the location of monitoring points.

Aspiration of air into sampling instruments should be sufficiently free. Monitoring points should not be placed in densely built-up areas or too near the sources of emission (e.g., factory stacks).

These are, of course, merely general principles for siting monitoring stations, and the matter should receive individual attention in particular cases. Needless to say, the aim should be to establish as many monitoring stations as possible, but technical and financial considerations may militate against this.

This matter receives different treatment in various urban and industrial areas. In London there are 262 monitoring points, 62 of which carry out continuous measurements of particulate matter and SO_2 concentrations. This corresponds to one monitoring point per 5 km² of surface area. In Paris, there are 13 points for continuous measurement of particulate matter and SO_2 concentrations, correspond-

ing to one station per 37 km². It is aimed in France to have at least one monitoring point per 9 km² (VI.3).

In the course of samplings carried out around Bochum in 1950 - 1956, 1,700 dustfall meters were set up over an area of 2,100 km², corresponding to one meter per 1.2 km². According to English data, the result of measurements from one monitoring point may be characteristic of the dustfall over a circle having a surface area of 400 m², and that only if the monitoring point is well situated.

3. Duration of sampling

The frequency of unit samplings of atmospheric pollution depends firstly on the purpose of sampling and on the method of interpretation. Fluctuations in the concentration of atmospheric pollutants are very large at the individual points. The values of pollutant concentrations may alter within a few minutes by several orders of magnitude (usually between 1 and 100) (VII,3). Therefore, if the purpose of sampling is to determine this variation, the duration of unit samplings should be limited to a minimum consistent with concentrations arising at that point, and with the sensitivity of the sampling method. A period of less than one hour is usually sufficient in the case of average pollutant concentrations and prevalent qualitative analytical methods. However, samplings lasting an hour are of interest only in exceptional cases, e.g., in establishing the correlation between the volume of motor traffic and pollutant concentrations. The results of measurements carried out in Paris (VII,3) are given in Fig. VIII,1.

In order to evaluate the air from the hygienic standpoint, average values collected over longer period of time are necessary, and one day is generally chosen as the unit sampling time. This duration is also adequate for most correlative analyses. Monthly and annual averages can be obtained from the results of day-long samplings. An example of monthly fluctuations in pollutant concentration in Paris is shown in Fig. VII,2 (VII.3). In the case of some sampling methods (e.g., in measuring the dustfall by dustfall meters), the duration of sampling is much longer, and amounts to one month.

It should be stressed that, independently of the method and unit time used, the sampling should be done continuously. Only the results of continuous sampling can provide a basis for the evaluation of the general hygienic state of the atmosphere. Of course, spot checks can be carried out at individual points for research and experimental purposes.

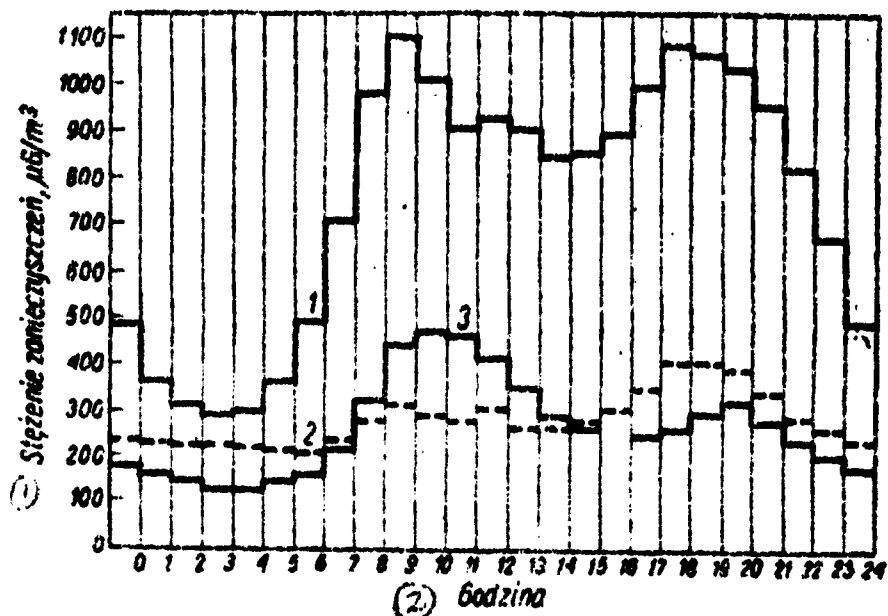


Fig. VII, 1. An example of the daily variation of pollutant concentrations in different towns: 1. Glasgow; 2. Westminster; 3. Paris.

Legend: a. Pollutant concentration; b. Hour.

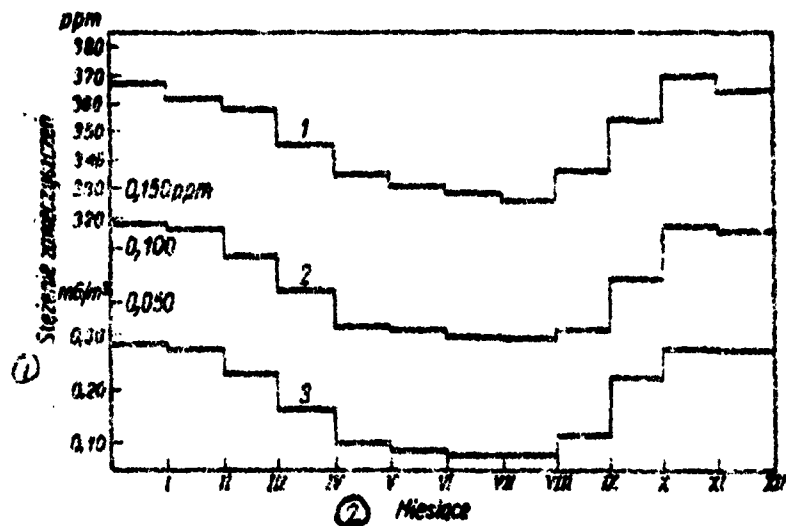


Fig. VII, 2. Average monthly pollutant concentration in Paris. 1. CO_2 concentration; 2. SO_2 concentration; 3. Particulate matter concentration.

Legend: a. Pollutant concentration; 2. Month.

4. Accuracy of measurements

As in other cases, interpretation of the results of pollution measurements is of great importance.

The error in the results of sampling consists of systematic error and random error.

Systematic error of the sampling instrument is determined by calibration, and is then taken into account by the introduction of a suitable correction into the reading. The determination of systematic error in pollution sampling instruments is generally difficult, and in some cases quite impossible. This relates particularly to the instruments for measuring particulate concentrations (0.13). For this reason, all sampling results are arbitrary, and a comparison of results obtained with the aid of instruments working on different principles is essentially impossible. This creates the need for standardization of sampling instruments and methods.

Random error is due to a number of minor causes which are difficult to determine theoretically and experimentally. Estimation of error based on the theory of probability concerns only the random error.

Determination of random error in the results of pollutant concentration measurements is usually also difficult. In the measurement of other physical quantities, a given number of readings is usually taken, and the random error is determined on the assumption of a normal Gaussian error distribution

$$b_s = \frac{\sum (x_i - \bar{x})}{n-1} = \frac{1}{h\sqrt{\pi}} \quad b_m = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} = \frac{1}{h\sqrt{2}} \quad (\text{VII}, 1)$$

where b_s is the mean arithmetical error;
 b_m is mean square error;
 x_i is the result of an individual reading;
 $\bar{x}$ is the arithmetical mean from n readings;
 n is the number of unit measurements;
 h is the index of accuracy.

In the case of pollutant concentration determination, the quantity measured is never constant in time, the nature of its variability depends on a number of parameters, and it has a different form in the individual cases. Thus discrepancies between the consecutive readings taken at the same point at given intervals of time are

caused by the changes in the measured quantity, as well as by random error. Since in this case it would not be indicated to operate with mean error values, standard deviation σ is made use of in calculations

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}} \quad (\text{VII},2)$$

In accordance with the statements made above, and assuming that random error does not depend on the changes in the quantity measured, we can write

$$\sigma = \sqrt{b_m^2 + \nu^2} \text{ or } \nu = \pm \sqrt{\sigma^2 - b_m^2} \quad (\text{VII},3)$$

where b_m is mean square error;
 ν is standard deviation of the measured quantity.

The ratio of b_m to ν should be so small, that it should be possible to determine whether discrepancies between results are caused only by random error, or whether changes have occurred in the measured quantity.

The foregoing relationships show that changes in the measured quantity amounting to 10% can be detected using apparatus whose random error does not exceed 4.5%.

5. Methods of compilation and analysis of results

All results of pollutant concentration measurements are averages for the duration of sampling. As has been mentioned, the minimum duration of sampling is 24 hours. When average values are given for longer sampling periods, arithmetical means of the individual unit measurements are commonly used.

However, the knowledge of the average value of pollutant concentration is not sufficient for establishing the degree of harmfulness of a given pollutant to human health, and graphical methods are best used to this end. Of great convenience is a system of coordinates where pollutant concentrations are plotted on the abscissa, and percentage lengths of time during which concentrations higher or lower than the average occur are plotted on the ordinate. As an example, Table VII,1 shows the results of particulate matter concentrations measured over a period of 30 days. Table VII,2 contains these results in the form ready for use in the graph shown in Fig. VII,3.

Table VII, 1.

Daily particulate pollutant concentrations over a period of one month

Dzień ①	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Średnie ② mg/m³	0,14	0,17	0,20	0,25	0,14	0,16	0,28	0,16	0,13	0,10	0,15	0,16	0,21	0,22	0,12
Dziś ①	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Średnie ② mg/m³	0,26	0,11	0,15	0,16	0,20	0,21	0,15	0,16	0,18	0,22	0,19	0,18	0,16	0,15	0,20

Legend: 1. Day; 2. Concentration.

Table VII, 2.

Percentage duration of time during which concentrations lower than the limit value occur
(From the data in Table VII, 1)

① Średnie mg/m³	0,10	0,11	0,12	0,13	0,14	0,15	0,16	0,17	0,18	0,19	0,20	0,21	0,22	0,25	0,26	0,28
② Liczba odczy- tów jed- nosto- wych	1	1	1	1	2	4	6	1	2	1	3	2	2	1	1	1
Udział czasu ③ %	3,3	6,7	10,0	13,3	20,0	33,3	53,3	56,7	63,3	66,7	76,7	83,3	90	93,3	96,7	100

Legend: 1. Concentration; 2. Number of unit readings; 3. Percentage duration.

Further conclusions can be drawn from the graph drawn on the basis of these data on a probability grid (Fig. VII,4).

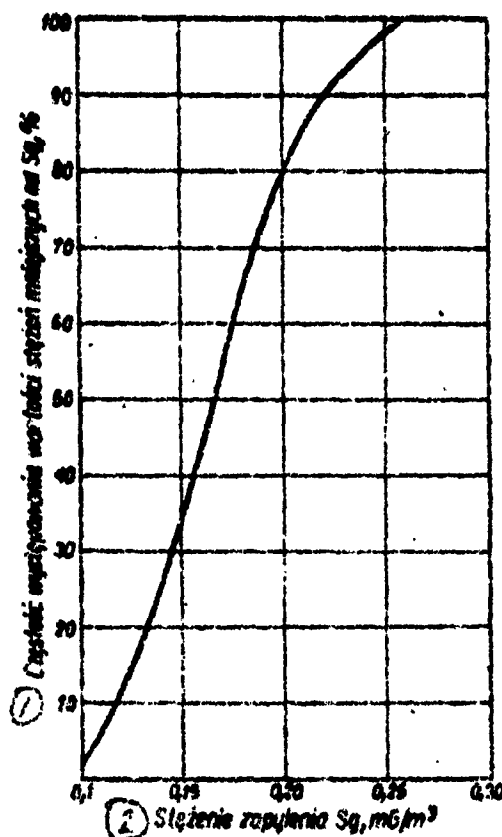


Fig. VII,3. Graph showing the frequency of occurrence of various particulate concentrations

Legend: 1. Frequency of occurrence of concentrations lower than S_g , in %; 2. Particulate concentration.

When comparing a series of readings made at different times at the same point, or those made simultaneously at various points, it should be remembered that the differences between arithmetical mean values do not always reflect the trends of change in the measured quantity. For example, let us consider a case in which pollutant concentrations were measured in the vicinity of a large plant in which highly effective dust arrester devices had been newly installed. This has led to a drop in pollutant concentration at a given monitoring point. At one time, the arrester device was damaged, causing a brief but violent increase in pollutant emission with the resultant increase

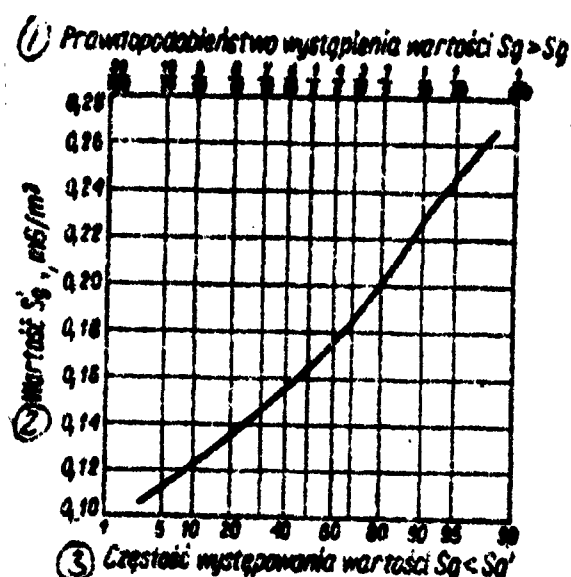


Fig. VII,4. Graph showing the frequency of occurrence of various pollutant concentrations on a probability grid

Legend: 1. Probability of occurrence of $S_g < S_g'$; 2. The value of S_g ; 3. Frequency of occurrence of $S_g < S_g'$.

in the pollutant concentration at the monitoring station. To take this maximum into account in calculating the arithmetical mean would lead to the false conclusion that emission from that source had increased.

Mathematical reasons for discrepancies in the results are dealt with on the basis of the Student significance test t , which takes into account the effect of completely random values of little probability.

Let x_i ($i = 1, 2, 3, \dots, n_1$) and y_k ($k = 1, 2, 3, \dots, n_2$) be the results of the consecutive measurements of two quantities in two series conducted simultaneously, or two series of measurements conducted one after the other. The question is, what is the probability that results x_i and y_k are taken from the same set. The answer to this question can be obtained with the aid of the Student statistics t . Its value for the number of degrees of freedom $n_1 = n_2 - 2$ is given by the relationship

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{\sum(x_i - \bar{x})^2 + \sum(y_k - \bar{y})^2}{n_1 + n_2 - 2}}} \sqrt{\frac{n_1 \cdot n_2}{n_2 + n_1}} \quad (\text{VII,4})$$

Comparing the value of t obtained from the above relationship with t_{α} found in the Student tables of distribution of t for a given number of degrees of freedom, we can determine whether the probability of a difference between the average values of the two series of measurements is greater or smaller than α .

Table VII,3.

Compilation of the results of dustfall measurements in $\text{g.m}^2/\text{day}$

Miesiąc	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Średnia
① Rok I x_i	0,74	0,57	0,96	1,34	0,47	1,04	0,93	1,11	2,38	—	0,66	0,52	$\bar{x} = 0,97$
② Rok II y_k	0,37	0,52	0,53	0,46	0,2	0,19	0,33	0,45	1,07	0,89	0,94	0,37	$\bar{y} = 0,63$

Legend: 1. Month; 2. Year; 3. Average.

A calculated example is given as an illustration. Table VII,3 lists the results of dustfall measurements for two years. It is necessary to find out whether there had been a change in dust concentration after the first year. The arithmetical mean of dust concentration in year I $\bar{x} = 0.97 \text{ g/m}^2/\text{day}$, while that for year II, $\bar{y} = 0.63 \text{ g/m}^2/\text{day}$. It clearly follows from a comparison of the average values that there had been a sharp reduction in dust concentration in year II. The decrease amounts to 35%. Now it remains to be checked if this result is fortuitous. From data contained in Table VII,3 we can calculate further values necessary for the Student test of significance: $\sum (x_i - \bar{x})^2 = 2.9127$; $\sum (y_k - \bar{y})^2 = 1.1064$; $n_1 = 11$; $n_2 = 12$. Therefore, t equals

$$t = \frac{0.97 - 0.63}{\sqrt{\frac{2.9127 + 1.1064}{11 + 12 - 2}}} \sqrt{\frac{11 \cdot 12}{11 + 12}} = 1.86$$

In the tables we find for $t_{\alpha} = 1.86$ a probability of 0.05 to 0.1. This means that the probability of a fortuitous appearance of a difference between average values as large as 35% is 10%, and it cannot be maintained with certainty that there has been a drop in dustfall relative to the previous year.

6. Establishment of correlation between the individual parameters of atmospheric pollution

Among the more important aims of atmospheric pollution measurements is to establish the influence of the individual emission sources on the total level of pollution. This influence can be determined in a fundamental manner only with respect to those large sources whose emission is equal to zero over sufficiently long sampling periods. Thus, for instance, we can determine the influence of emission due to space-heating, since this emission is equal to zero during the summer months.

In general, it is necessary to measure a large number of parameters in addition to the pollutant parameters if the correlation between the source activity and pollutant levels is to be established. How detailed and extensive these measurements have to be is seen from a measurement chart (Fig.VII,5) prepared by the Saar meteorological service (VII.4).

Since the chart is intended for correlative calculations using computers, the values contained in it have been coded in 10 ratings from 0 to 9, and a separate key has been prepared for each of the parameters.

The individual values are recorded by punching a hole in the chart.

The relationship between the values of two different quantities can be determined by statistical mathematics methods. The relationship between two different quantities is expressed by the correlation coefficient r (VII.1) given by the formula

$$r = \frac{\sum_{xy} (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \quad (\text{VII}, 5)$$

where x and y are the results of measurements of two independent quantities X and Y ;
 $\bar{x}$ and $\bar{y}$ are averaged values of results;
 n_{xy} is the number of pairs of measurements of both quantities.

Relationship (VII,4) can be written in different forms which are sometimes more convenient for calculation

$$r = \frac{\frac{\sum xy}{n_{xy}} - \frac{\sum x}{n_{xy}} \cdot \frac{\sum y}{n_{xy}}}{\sqrt{\left[\frac{\sum x^2}{n_{xy}} - \left(\frac{\sum x}{n_{xy}} \right)^2 \right] \left[\frac{\sum y^2}{n_{xy}} - \left(\frac{\sum y}{n_{xy}} \right)^2 \right]}} \quad (\text{VII},6)$$

or

$$r = \frac{\sum xy - n_{xy} \bar{x} \bar{y}}{(\sum x^2 - n_{xy} \bar{x}^2)(\sum y^2 - n_{xy} \bar{y}^2)} \quad (\text{VII},7)$$

In the case of two series of measurements of two different quantities, correlation coefficient r always fulfills the double inequality

$$-1 \leq r \leq 1 \quad (\text{VII},8)$$

If the measured quantities are independent, then we obtain $r = 0$. If, however, it follows from recalculation that $r = 0$, it can only be stated that these quantities are unrelated.

The case where $r = -1$ is the extreme opposite of independence. If $r = +1$, then the direction of change in both these quantities is the same, i.e., greater values of one of the quantities correspond to greater values of the other. If, on the other hand, $r = -1$, then the direction of change is opposite. We can accept, after Gavette (0.14), the following degrees of relationship between measured quantities:

Value of correlation coefficient r	Degree of relationship
< 0.30	virtually nil
$0.30 - 0.50$	medium
$0.50 - 0.75$	considerable
$0.75 - 0.90$	high
> 0.90	very high

If the number of measurements is very small, then the actual correlation coefficient r_c should be calculated from the formula:

$$r_c = \sqrt{1 - (1 - r^2) \left(\frac{n_{xy} - 1}{n_{xy} - 2} \right)} \quad (\text{VII},9)$$

As an example, calculation is shown of the coefficient of correlation between grit emission from a given source and particulate matter concentration at a given monitoring point. The results of simultaneous measurements of emission and particulate matter concentrations are given in Table VII,4. These data were used to calculate the values entering into equation (VII,6):

$$\begin{aligned} \Sigma xy &= 1281,18; \Sigma xy/n = \\ &= 42,706; \Sigma x = 5,17; \Sigma x/n = 0,1723; (\Sigma x/n)^2 = 7165; \Sigma x^2/n = \\ &= 238,83; (\Sigma x^2/n) = 57039,77; \Sigma x^2 = 0,9617; \Sigma x^2/n = 0,03206; \\ \Sigma y^2 &= 1771450; \Sigma y^2/n = 59048,3. \end{aligned}$$

After substituting these values in equation (VII,6), the correlation coefficient was found to be $r = 0.717$. This means that there is considerable relationship between emission intensity and particulate matter concentration.

Table VII,4.

Results of emission and pollutant concentration measurements

Dzień ^①	1	2	3	4	5	6	7	8	9	10
Emission ^② T/godz	190	205	290	210	215	230	350	220	185	160
Stężenie ^③ mg/m ³	0,14	0,17	0,20	0,15	0,14	0,16	0,28	0,16	0,13	0,10

Dzień ^①	11	12	13	14	15	16	17	18	19	20
Emission ^② T/godz	200	210	280	300	200	320	190	215	235	280
Stężenie ^③ mg/m ³	0,15	0,16	0,21	0,22	0,12	0,26	0,11	0,15	0,16	0,20

Dzień ^①	21	22	23	24	25	26	27	28	29	30
Emission ^② T/godz	290	210	225	240	290	270	235	225	200	275
Stężenie ^③ mg/m ³	0,21	0,15	0,16	0,18	0,22	0,19	0,18	0,16	0,15	0,20

Legend: 1. Day; 2. Emission, in tons/hour; 3. Concentration, in mg/m³.

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Chapter VIII

Determination of Pollutant Emission

1. Introductory remarks

A well planned air pollution abatement action should be based above all, on systematic sampling of pollutants emitted by industrial plants. The results of qualitative and quantitative determinations of pollution make it possible to determine whether or not a given plant is following the ordinances with regard to maximum permissible pollutant concentrations, and to what extent it is responsible for the pollution of the surrounding area.

It should be stressed that in view of the considerable difficulties connected with accurate and extensive research into atmospheric pollution, particularly strong emphasis should be placed on the measurement of pollutant emission. This is all the more justified in Poland, where the main sources of pollutant emissions are industrial plants due to the development of electric power and heat generation and a relatively light motor vehicle traffic.

Determination of emissions is essentially confined to particulate matter, CO and oxides of sulfur. An exception to this are chemical plants, where emissions of other gaseous pollutants are sampled.

2. General principles of determining emissions of particulates

The measurement of particulate matter emissions reduces to determination of particulate matter concentrations in gases emitted into the atmosphere. Since these measurements were discussed in detail in J. Juda's previous works (6.13), (VIII.20), the classical methods of determining particulate matter concentrations in industrial gases will be discussed briefly, while automated sampling will be considered more extensively.

The methods of determining dust concentrations in flowing gas can be divided into two groups: 1), direct methods; 2), indirect methods.

Direct determination reduces to the following operations: 1), determining the gas flow in a conduit; 2), aspiration of a gas sample from the gas stream; 3), measurement of the volume of the aspirated sample; 4), precipitation of particulates contained in the

gas sample; 5), determination and characterization of precipitated particulates.

Further sub-division of direct methods follows from the ways of separating the dust from the gas sample. Among the instruments used in these methods are: 1), cyclones and measuring filters; 2), electrostatic filters; 3), thermal filters.

The amount of dust in all these cases is determined by weighing.

The indirect methods can be divided into two sub-groups: 1), with aspiration of gas sample; 2), without aspiration of gas sample.

The first sub-group embraces the following instruments: 1), camograph; 2), electrostatic dustmeters; 3) optical dustmeters; 4) venturi tubes.

Optical dustmeters and venturi tubes can also work without aspiration of gas samples. A schematic representation of the methods used for determining particulate matter concentrations in industrial gases is given in Fig. VIII, 1.

Regardless of the method employed, the following conditions must be observed in order to assure that the results are indicative of the actual particulate matter concentration in industrial gases: 1), point at which sample is taken from a conduit must be chosen so that it represents the average particulate matter concentration in that conduit; 2), the characteristics of particulate matter present at the sampling point should be representative of the average characteristics of particulate matter in the conduit; 3), the sampling device should be constructed, and the conditions of aspiration chosen so, that the sample taken preserves the dust concentration and characteristics of the mass of gas under study.

It can be accepted with good approximation that the above conditions will be observed if the sampling point in a straight vertical conduit is located between five and ten diameters away from the source of flow turbulence (0.12). It should be explained that by sources of flow turbulence we understand not only mechanical obstacles such as changes in cross-section, branches, knees, flaps, fans, etc., but also abrupt changes in gas temperature, local heating or cooling of the conduit's walls, etc.

Since in determining the concentration of particulate matter in gases emitted into the atmosphere the sampling usually takes place

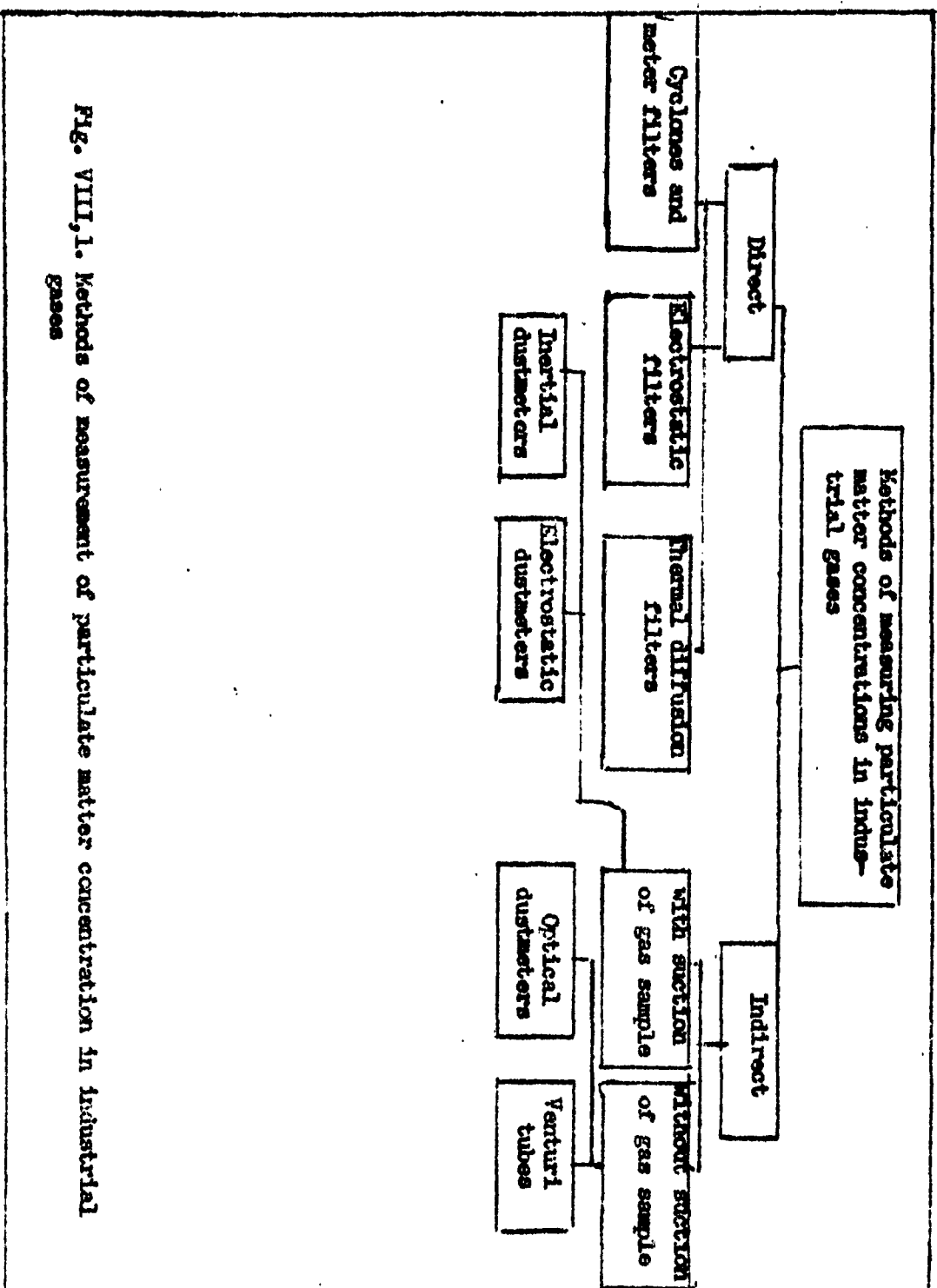


Fig. VIII,1. Methods of measurement of particulate matter concentration in industrial gases

in the stack, the above conditions are fulfilled if the sampling point is located at a height equal to between five and 10 stack diameters above the flue gas inlet (given an average stack diameter, between 15 and 30 meters above the gas inlet). This statement is of importance in selecting the type of sampling instrument to be used, since it must be remembered that the access to the sampling point will be difficult, and so the sampling instrument must not require frequent inspection, calibration, etc.

It is much more difficult to fulfill the condition concerning the method of aspiration of the sample of dust-laden gas. It follows from the works of W. Allner (VIII,1), K. Guthmann (VIII,9), P. Noss (VIII,13), E. Zimmerman (VIII,18) and others, that the correct sampling of dust laden gas is a fairly complicated matter.

In order to aspirate into the probe a sample of dust laden gas having characteristics unchanged from those of the gas stream, the following conditions must be observed:

1. The direction of aspiration must be the same as that of the gas stream;
2. The placing of the probe in the gas stream must be such as not to cause any disturbances in the flow of gas which might cause changes in the characteristics of particulate suspension at the probe inlet;
3. The rate of aspiration must be equal to that of the gas stream in the conduit.

Various designs of probes exist for the aspiration of particulate suspensions which assure the observance of the above conditions. Among these, the most popular are the so-called zero probes and rapid probes.

In the zero-type probes, the isokinetic conditions are preserved through simultaneous measurement of static pressure in the lead and in the probe itself. This type of probe has lately been strongly criticised (VIII.14), and rapid-type probes are now generally used with high gas flow rates. A diagram of such a probe (made by Babcock) is shown in Fig. VIII,2. Four small tubes (1) for measurement of the total gas pressure at the sampling point are placed symmetrically around the probe proper. Along the periphery of the probe there are orifices (2) for the measurement of static pressure in the tube. Tubes (1) lead to a chamber (3), while orifices (2) connect with chamber (4). Chamber (3) which is under total pressure, and chamber (4) which is under static pressure are connected by means of tubes

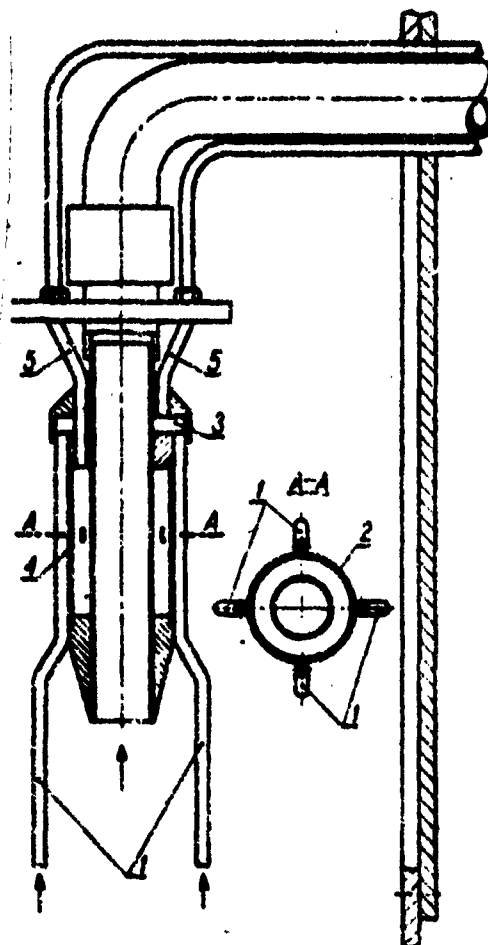


Fig. VIII,2. Rapid Babcock probe. 1. Stacked tubes for measurement of the total pressure; 2. Orifices for measurement of the total pressure; 3. Collecting chamber under total pressure; 4. Collecting chamber under static pressure; 5 and 6. Leads to micromanometer.

(5) and (6) with a micromanometer which reads the dynamic pressure. Thus this system permits the reading of the gas flow velocity directly at the point of sampling.

Due to the placing of the orifices, (2), the indicated values of static pressure are too low. The latest modification of the rapid probe (Fig. VIII,3) overcomes this objection by the use of stacked concentric rings.

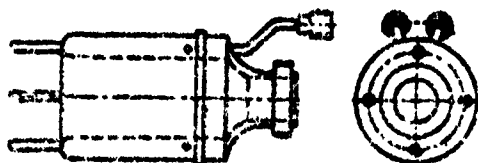


Fig. VIII,3. Modification of rapid probe with a stacked ring

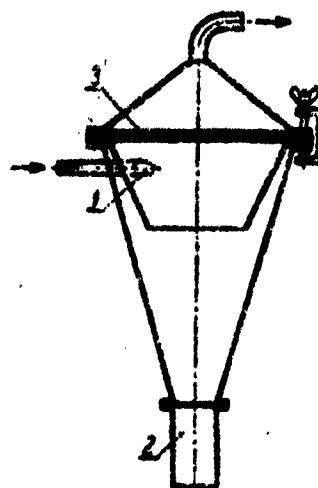


Fig. VIII,4. A measuring cyclone. 1. inlet tube; 2. dust container; 3. paper filter.

A set of rapid probe heads manufactured by Babcock consists of six heads having probe diameters of 38, 46, 55, 65, 77 and 92 mm at a maximum gas flow rate of 100 m³/hour.

Precipitation of dust from the aspirated gas sample takes place in special cyclones. A diagram of a typical cyclone design is shown in Fig. VIII,4. The gas is led in through a tube placed at a tangent to the cyclone wall. Coarse particulates are precipitated in the cyclone and settle in the container (2). The remainder of dust is retained on the filter paper (3).

The Babcock sampling system is shown in Fig. VIII,5 (VIII.14). Gaseous particulate suspension is sucked into the probe (1) with the aid of an injector (5) operated by steam or compressed air. The gas flow velocity at the point of sampling is measured directly by the probe, and is calculated from micromanometer (7) readings. The volume of gas aspirated into the probe is calculated from the readings of micromanometer (6) connected to a venturi tube (4).

Gas aspirated into the probe passes into the cyclone where coarse particulates are deposited, and then through a filter on which the remaining particles are retained. In order to prevent condensation of water vapor, the tube connecting the probe with the cyclone, and the cyclone with the filter, are electrically heated. Knowing the

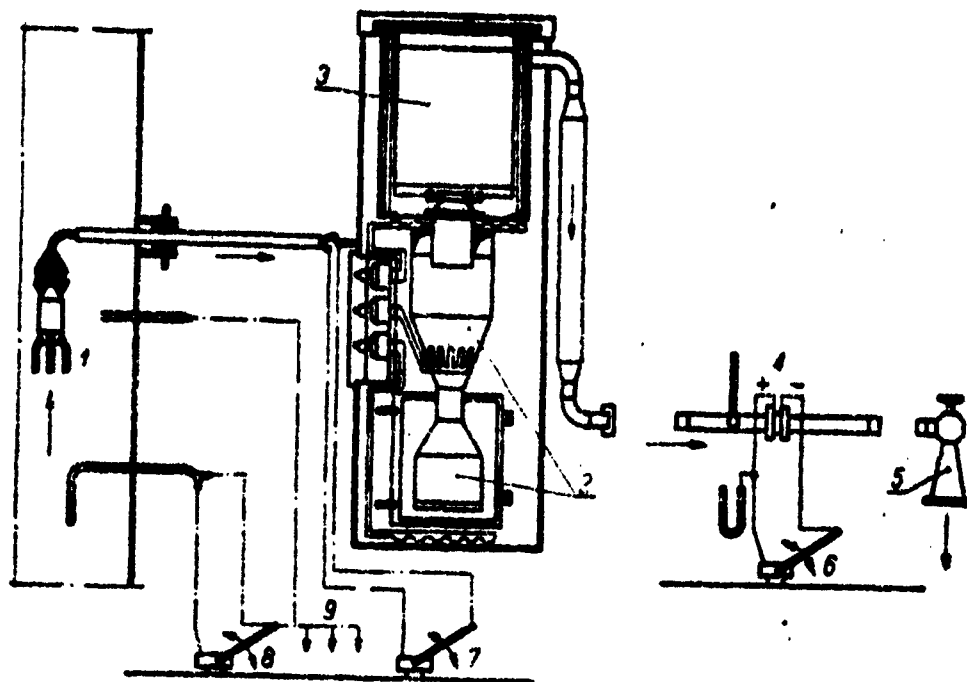


Fig. VIII,5. The Babcock sampling system. 1. Rapid probe; 2. Cyclone; 3. Filter; 4. Venturi tube; 5. Injector; 6, 7 and 8. Micro-manometers; 9. Gas temperature monitor.

amount of gas aspirated into the probe, and the amount of particulate matter deposited in the cyclone and on the filter, we can calculate the concentration of particulate matter in gas from the following equation:

$$S_g = \frac{G}{V_p} \quad (\text{VIII},1)$$

where S_g is particulate matter concentration, in g/Nm^3 ;

G is the weight of dust collected in the cyclone and on the filter; in kilograms;

V_p is the volume of air aspirated during the sampling, reduced to NTP.

Knowing particulate matter concentration, we can calculate particulate emission E

(VIII,2)

where k is the coefficient for recalculating S_g , in g/Nm^3 , into the value expressed in g/m^3 under the conditions of sampling;

v is the average velocity of the gas stream in the conduit (stack), in m/sec;

F is the cross-section of the conduit (stack), in m^2 .

The average gas flow rate in the conduit is measured by the stacked tube connected with micromanometer (8). In order to reduce the volume of gas to NTP with the aid of the measuring terminal (6), the gas temperature is measured with the aid of a thermoelectric or resistance thermometer, and the gas is aspirated for chemical analysis.

Each determination of particulate matter concentration in industrial flue gases should have a duration equivalent to three full production cycles of the plant, and not less than eight hours.

The particulate matter collected in the cyclone and on the filter is subjected to analytical processes, the most important of which is the fractional analysis of the particulates. As is known, the knowledge of the particle size analysis is necessary for calculating the dispersion of particulate emissions in the atmosphere.

3. The possibility of automatic sampling of particulate matter concentrations in industrial gases

Constant control of particulate emissions is possible only when a certain amount of automation is introduced into determination of particulate matter concentration, and when continuous recording of results is available. Despite a great deal of research and experimental work done in this field, no satisfactory answer to this problem has been found to date.

It appears that the solution to the problem of automatic sampling should be sought among the indirect methods of particulate matter concentration measurements. However, this presents a difficulty in the shape of the lack of a quantity which would be univocally dependent on particulate concentration. The unequivocality of this relationship means that neither the physical and chemical properties of particulate matter such as its specific gravity, particle size, chemical composition, etc., nor the properties of the gas, its temperature, humidity, and its impurities in the form of vapors or liquid droplets should distort the results.

One of the first indirect automatic samplers is the carnograph (Fig. VIII,6), which has been used in the smelting industry since



Fig. VIII,6. The carnograph

1910 (VIII.9). Dust laden gas is aspirated at a rate of 10 -- 20 litres/min through a nozzle whose outlet faces a paper tape driven by a clockwork mechanism. White tape is used for dark-colored particulates, and black tape is used with light-colored dusts. Dusts exhibiting low adhesive power are trapped on a tape coated with an adhesive composition. Particulate matter concentration of the gas is estimated on the basis of the color of the tape. Obviously, this method cannot be regarded as being sufficiently accurate.

Optical dustmeters such as the Siemens smoke density gage, have found a wider application. These instruments utilize the principle of light absorption or scattering by dust particles. A number of works have been devoted to both these phenomena. Among them are those of Berek, Bahnchen and Schaffer (VIII.2), Roseg (0.17), Statter (VIII.19), and others.

If a beam of light having a cross-section area F is passed through a medium supporting suspended particulate matter, then the drop in light intensity over a distance Δl will be

$$\Delta J = k \sum_{i=0}^n C \cdot N \cdot d_i^2 \quad (\text{VIII},3)$$

where K is the shape coefficient of the particle dust;
 C is the coefficient of light absorption by dust particle;
 N is the number of particles having the size d_1 in a volume $F \times \Delta l$.

The above formula is valid only for a length Δl of the light ray path in which it passes through only one dust particle. Furthermore, the measured quantity depends on K and C in addition to being dependent on particulate matter concentration. In determining particulate concentrations in industrial gases, where particulate mixtures undergo a constant change, it is difficult to assume, albeit theoretically, any sort of constant light absorption or shape coefficients for dust particles. In addition, light absorption can also be caused by liquid droplets contained in the gas, leading to further error.

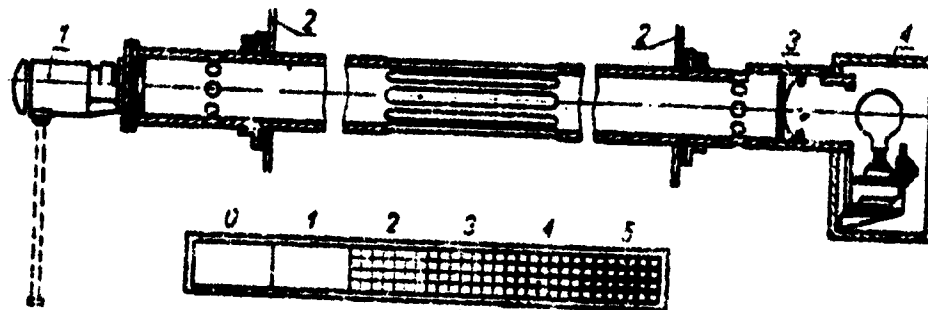


Fig. VIII,7. Siemens optical dustmeter. 1. Photocell; 2. Channel walls; 3. Lens; 4. Light source. The Ringelmann scale is shown at the bottom of the Figure.

These shortcomings notwithstanding, dustmeters working on the light absorption principle are widely used in England and the USA as a result of the acceptance in these countries of the Ringelmann scale as the smoke density standard.

Fig. VIII,7 shows a Siemens optical dustmeter. After passing through particulate suspension in gas, the light beam impinges upon a photocell or a thermoelement connected to an indicator which gives readings of results in the Ringelmann units (standards 0 -- 5).

More widely used are the instruments based on the principle of light scattering. In accordance with Rayleigh's theory, intensity of scattered light J is expressed by the following formula:

$$I = I_0 \frac{\pi^2 \cdot V^2}{R^2 \lambda^4} \cdot \left[\frac{3(n^2 - n_0^2)}{n^2 + 2n_0^2} \right]^2 \cdot (1 + \cos^2 \alpha) \quad (\text{VIII},4)$$

where I_0 is the intensity of incident light;
 V is the volume of a dust particle;
 R is the distance between the point of observation and the particle scattering light;
 λ is the wavelength of light;
 n is the refractive index of the particle;
 n_0 is the refraction coefficient of light in the gas;
 α is the angle between the direction of observation and that of illumination.

The above formula is valid only on the assumption that dust particles are much smaller than the wavelength of light. According to G. Stetter (VIII.19), the Rayleigh equation can be used only for particles $< 0.1 \mu$. For particles between 0.1 and 1μ , G. Mie (0.14) derived a complicated relationship for the total scattering S

$$S = \frac{\lambda^2}{2\pi} \sum_{v=1}^{\infty} \left(\frac{s_v^2 + p_v^2}{2v+1} \right) \quad (\text{VIII},5)$$

where $s_v = f_1(2\pi r/\lambda)$,
 $p_v = f_2(2\pi r n/\lambda)$,
 r is the particle radius.

Since the above relationship cannot be solved in an ordinary manner, use must be made of the tables compiled by Mie.

After transforming equation (VIII,5), D. Sinclair introduced the concept of the scattering coefficient K

$$K = \frac{2}{(2\pi r/\lambda)^2} \sum_{v=1}^{\infty} \left(\frac{s_v^2 + p_v^2}{2v+1} \right) \quad (\text{VIII},6)$$

Checking the relationship $K = f(r)$ for various particulates, D. Sinclair obtained for $n = 2$ and $n = 1.5$ the relationship shown in Fig. VIII,8. As can be seen, the course of this relationship does not exhibit any order, so that it is practically impossible to establish a dependence between the intensity of scattered light and the particulate concentration in a gas.

R. C. Tolman (VIII,2) gave a simple equation for the intensity of scattered light valid for particle size range of $1 - 5 \mu$

$$J = K N d^2 \quad (\text{VIII},7)$$

where K is a constant dependent on the type of particulate matter.

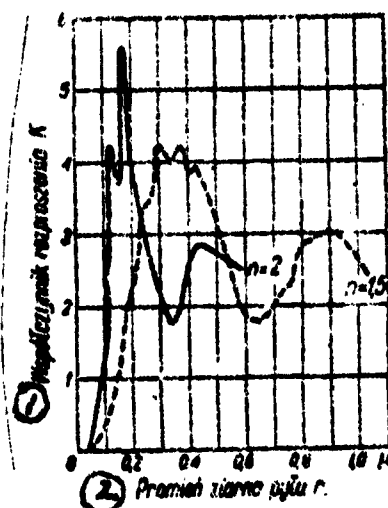


Fig. VIII,8. Relationship between light scatter coefficient K and particle radius for a light wavelength $\lambda = 0.524$

Legend: 1. Light scatter coefficient K ; 2. Particle radius, r .

It can be concluded on the basis of the above formulas that: 1), it is impossible to derive a theoretical relationship between particulate concentration (regardless of particle size) and the intensity of scattered light; 2), within certain particle size ranges, the intensity of scattered light depends on the particle size and the optical properties of particulate matter, particularly on the refractive index.

It should be added that a spherical particle shape was assumed in all the foregoing theoretical considerations. If the particles are not spherical, the relationships become more complex. Furthermore, liquid droplets (water and tars) dispersed in air also cause light scattering.

Dustmeters for use with industrial gases designed by R. Melden (0.16) and M. Dorleyn (VIII,4) are also based on the principle of light scattering. They differ from the Siemens instrument in that the intensity of light is not measured in its original axis inclined with respect to the former at a certain angle.

In 1955 E. Feifel and R. Prochaska (VIII.10) designed a dustmeter

working on the principle of electrification of particulates as a result of friction. Dust particles rub against the walls of a tube made of some material having appropriate dielectric properties. As a result of friction, a charge arises on the outer wall of the tube. The charge is led off through a galvanometer.

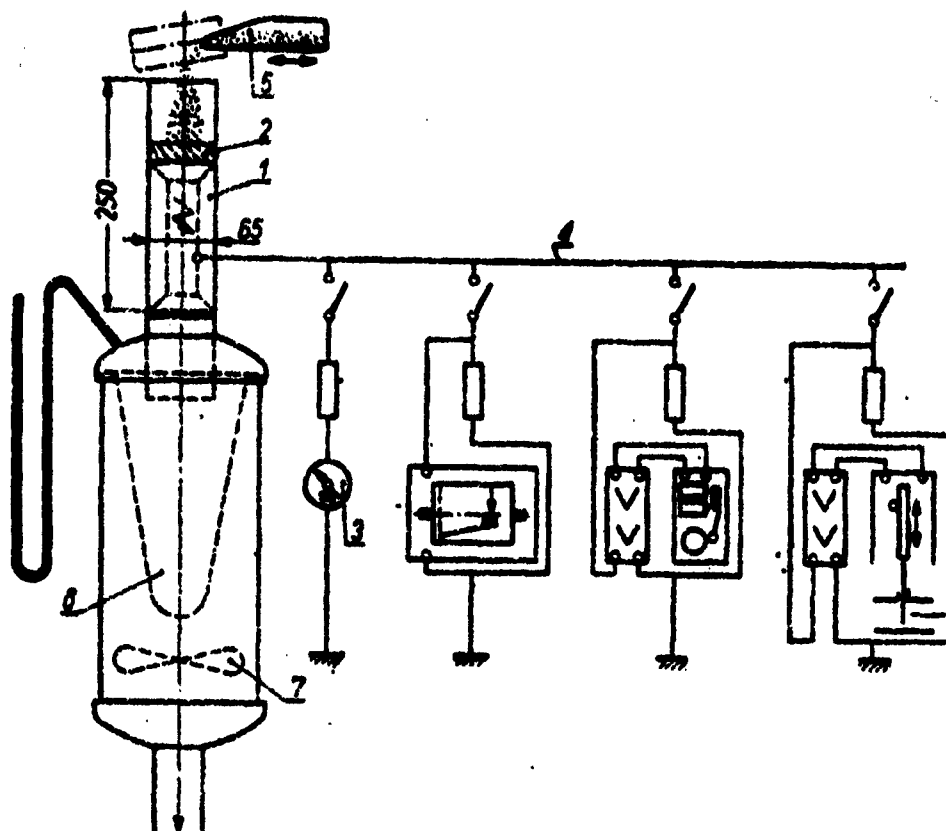


Fig. VIII,9. The Feifel electrostatic dustmeter^{ex}, as constructed in the laboratory. 1. The measuring section of the tube; 2. Deflectors; 3. Galvanometer; 4. Electric amplification and recording devices; 5. Particulate matter dispenser; 6. Absolute filter; 7. Aspirator fan.

A schematic diagram of the Feifel dustmeter as constructed in the laboratory is shown in Fig. VIII,9. The dust is fed from a dispenser (1). Dust laden air passes through deflectors (4) which ensure that the particles come into contact with the walls of the excitation tube. Next, the dust laden air passes through an absolute filter (6)

fixed in the housing, and is pumped out through a pipe. The flow of air is accomplished by means of a fan (7).

The electric charge arising on the walls of the tube can be grounded either through a galvanometer (11), or through a recording electric compensator. Independently of the above, the design provides for alarm (13) and control (14) devices. The individual devices can be switched on using switches (15) by way of resistors (16).

The dust dispenser makes it possible to vary the concentration of particulate matter between 10 and 50 g/m³, and the air flow rate can be varied between 0 and 10 litres/sec. In the latter case the flow pressure, as measured by a manometer, is around 600 mm H₂O.

Feifel's studies have shown that if all the particles flowing through the tube come into contact with its walls, the resultant electric charge is proportional to the concentration of particulate matter. Unfortunately, this charge is also a function of pressure and gas flow rate and, probably, of the dielectric properties of the dust, the particle size, and liquid droplet impurities.

In order to partly overcome these shortcomings, Feifel proposed the use in industrial sampling devices of an absolute filter, for instance one made of glass wool, located beyond the excitation tube (Fig. VIII,10), or a twin probe (Fig. VIII,11) for the simultaneous aspiration of gas into the electrostatic sampler and the filter. Of course, when this is the case, it is necessary to change or clean the filter at least once every 24 hours, and to weigh the particulate matter trapped on it.

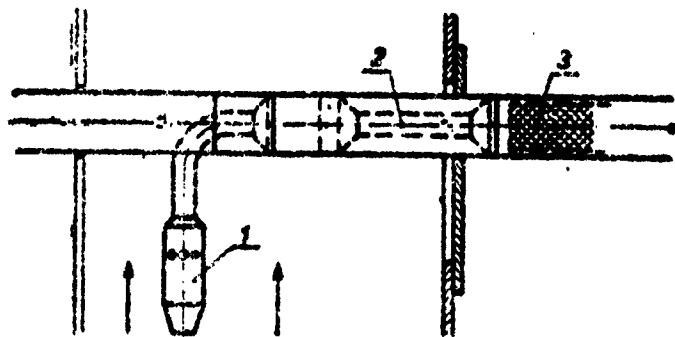


Fig. VIII,10. The Feifel sampler with a filter. 1. Probe head; 2. Excitation tube; 3. Absolute filter.

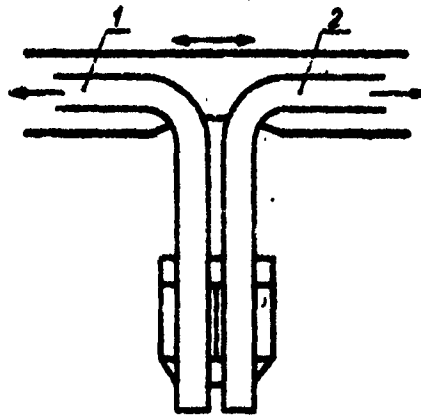


Fig. VIII,11. Twin probe. 1. Aspiration into the electrostatic sampler; 2. Aspiration into the filter.

An automatic dust sampler designed by Feifel and Prochaska, and now manufactured by I. C. Eckhardt A. G. of Stuttgart under the name of Konitest makes it possible to determine particulate concentrations between 0 and 0.1 g/m³, and between 0 and 10 g/m³. The head and amplifier of this instrument are shown in Fig. VIII,12.

It seems that this instrument can give a relatively accurate indication of the fluctuation in particulate emission values when used in conjunction with a source emitting particulates of relatively constant characteristics, and following the calibration with respect to that source. However, a shortcoming of the instrument is the absence of an automatic device for aspiration and recording of the amount of dust laden gas sampled.

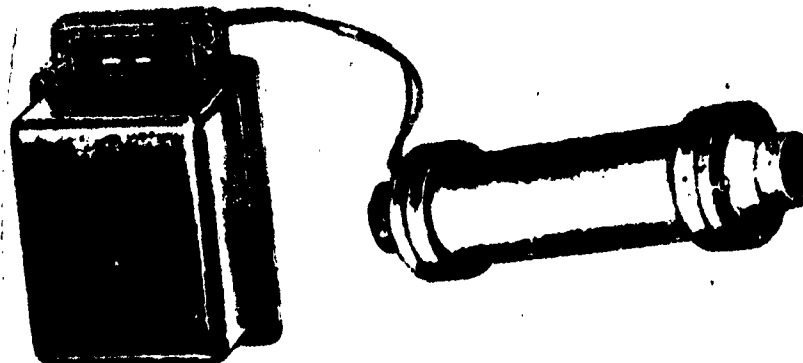


Fig. VIII,12. Automatic Konitest dustmeter

A relatively high degree of automation in measuring particulate concentrations in the gas stream is assured by the design developed by T. Gast (VIII.5), (VIII.6), (VIII.7).

Automatic devices for sample aspiration while preserving isokinetic conditions are shown schematically in Fig. VIII,13. Tubes (1) for the measurement of static pressures are placed both in the conduit through which the gas stream flows, and in the probe. Tubes (1) connect with regulator (2) controlling a servomotor (3) which determines the setting of the valve (4). Gas is sucked in with the aid of a constant-rate fan. The amount of aspirated gas, as well as the gas flow rate in the probe depend on the amount of air sucked in by the by-pass tube in which the valve (4) is located.

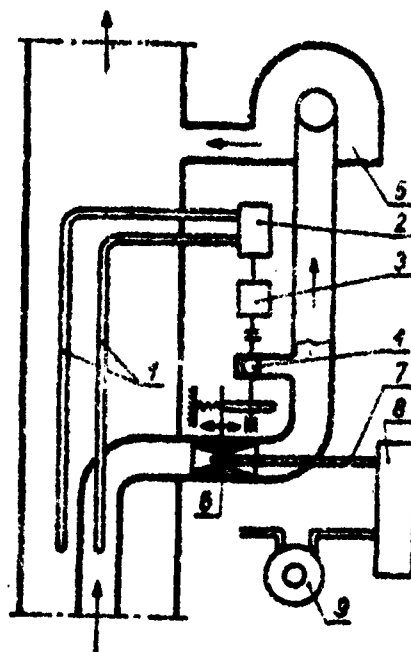


Fig. VIII,13. Automated aspiration of dust-laden gas. 1. Tubes for measuring static pressure; 2. Regulator; 3. Servomotor; 4. Valve; 5. Fan; 6. Venturi; 7. Conduit; 8. Device for precipitation of particulate matter; 9. Blower.

In this system, the flow rates in the conduit and the probe are similar at equal static pressures. Therefore, the principle on which the instrument is based is identical with that of the zero-type probes. Zero-type probes are now receiving strong criticism (VIII.14), not on theoretical premises, but because of the difficulty of measuring accurately the static pressure in the conduit by means of large-

-diameter probes. It seems that the criticism levelled at zero-type probes does not apply to the device described above.

The following design solution was applied in the system shown in Fig. VIII,13 in order to enable it to aspirate isokinetically still smaller volumes of gas sample. The duct (7) which leads the aspirated gas to the precipitating device (8) is located in a venturi constriction (6). Different flow rates prevail in that cross-section of the venturi in which the gas is aspirated, depending on the surface area of the cross-section. The rate at which gas is aspirated into the duct (7) is constant due to the fact that the blower (9) has a constant output. Equalization of rates is attained by an appropriate positioning of the venturi in relation to the inlet of duct (7). Changes in the position of the venturi are dependent on the settings of the valve (4).

A diagram of the Gast sampler (Sartorius Werle A. G. Cottingen) for use in measurement of particulate matter concentrations in air is shown in Fig. VIII,14. The blower (1) causes the aspiration of dust-laden gas into the chamber (2). The blower has a constant number of revolutions, and is switched on intermittently. In this way, equal volumes of gas are aspirated, the actual volume being dependent the particulate matter concentration in the sampled medium.

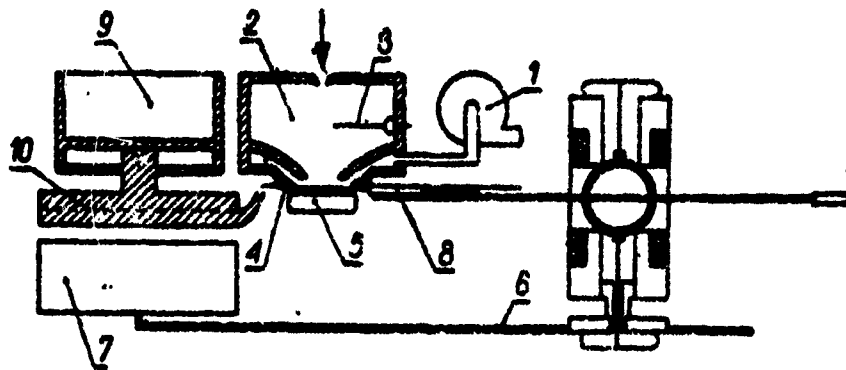


Fig. VIII,14. The Gast sampler for measuring particulate matter concentrations in air. 1. Blower; 2. Chamber; 3. Negative electrode; 4. Diaphragm; 5. Collecting plate; 6. Arm of recorder; 7. Recording tape; 8. Plate with brush; 9. Auxiliary blower; 10. Paper filter.

Dust precipitation occurs as a result of the ionizing action of the negative electrode (3) whose potential difference is 10,000 volts. Dust particles are deposited on the collecting plate (5) which constitutes the positive electrode. The time of coarse particulates settling on the collecting plate is 50 seconds, while that of fine particulates is 250 seconds. Following the precipitation, the collecting plate, which is attached to an automatic electric balance, is weighed. The balance readings are recorded by the recording pen (6) on revolving tape (7).

Following the determination, the collecting plate is swept clean by means of a travelling plate to which a brush is attached. The sweepings are sucked up by the auxiliary blower (9) and settle on the filter paper (10). After the collecting plate is cleaned, its zero point is checked by another weighing operation, and the next measurement can be proceeded with.

The balance operates on the principle of automatic compensation. A small revolving coil is suspended on two fine wires. A beam of thin glass or quartz is fastened to the coil. A counter-weight is attached to one end of the beam, while the other end supports the collecting plate. A pair of compensating Helmholtz coils generates a constant magnetic field. Dust settling on the collecting plate causes the coil to rotate by a given angle. The return of the rotating coil to its original position occurs as a result of the flow of current in the compensating coil. The current intensity is proportional to the angle subtended by the revolving coil and, therefore, proportional to the weight on the collecting plate. The flow of current through the compensating coils is automatically regulated by an oscilloscope connected to an amplifier system. The balance readings are recorded by an automatic electric recorder.

The Gast electrostatic sampler enables determinations to be carried out of dust concentrations ranging from 0 to 1,000 mg/Nm³. The time of particulate concentration determination in the range of up to 200 mg/Nm³ is six minutes, while concentrations up to 1,000 mg/Nm³ are determined in ten minutes. The balance reads in mg/Nm³ with an accuracy to 0.1 mg/Nm³. Two points are determined for each reading: the zero point, and the point corresponding to the weight of particulate matter on the balance. The suction pump aspirates air at the rate of between 1 and 5 dm³/min, and its run durations can be set at between one and ten minutes.

The precipitation chamber has been somewhat modified in the instrument for particulate concentration determination in hot gases (Fig. VIII, 15). In order to avoid condensation of vapors contained in the gas, the whole chamber is heated electrically by a heating

coil (1). The shape of the emitting electrode (2) has also been altered. The chamber housing (3) is made of metal, while the chamber itself is constructed of heat-resistant plastic (teflon). The collecting plate which also constitutes the balance pan is introduced into the chamber through a slit. The plate is fastened with the aid of an electromagnet. Although the Gast electrostatic sampler is one of the best designs available, it suffers from two shortcomings: a very high cost of construction, and the fact that only very small gas samples are aspirated by the present models.



Fig. VIII,15. The chamber of the Gast electrostatic sampler for industrial gases

4. Measurement of gaseous pollutant emissions

Measurement of pollutants emitted with flue gases extends essentially only to the following gases: CO_2 , CO, SO_2 , SO_3 , and H_2S .

Determination of the CO_2 content in flue gases is taken care of in all power generating stations within the framework of combustion control. In the case of periodic measurements, the popular Orstat analyzer is used. The result gives the content of CO and CO_2 in volume percent.

Knowing the basic chemical composition of the fuel, it is possible to calculate the CO content in flue gas with adequate accuracy. The graphical methods, and especially the Ostwald graph, are exceptionally convenient. When variations in the chemical composition

are small, the CO content can be calculated in this manner with an accuracy to 0.5%. A similar order of accuracy is obtained with the Orsat apparatus employing exhaustive combustion.

As a rule, automatic flue gas analyzers, such as the Duplex-Mono, Renarex or Siemens, are installed in the larger power generating stations [See note]. These serve to determine the CO₂ content, and in some cases, the content of CO + H₂.

(Note: See Poradnik Techniczny Mechanik (Mechanic's Technical Guide) 1/3).

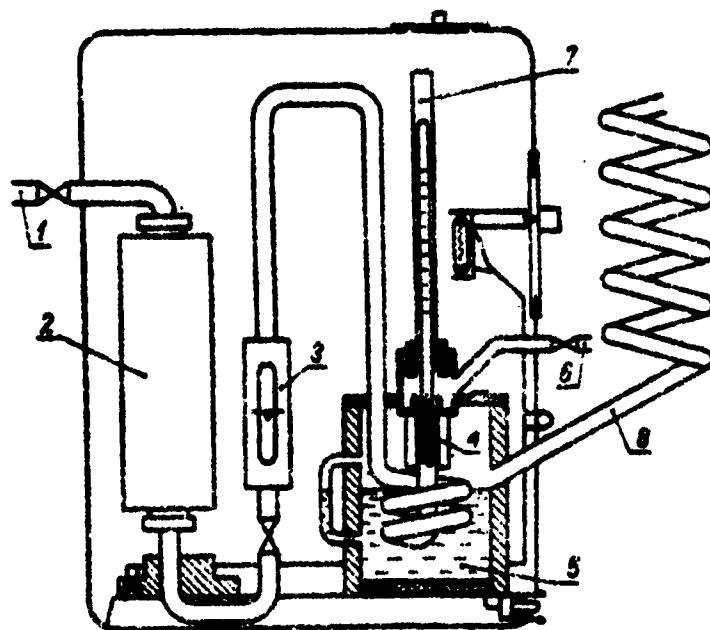


Fig. VIII,16. A schematic diagram of the Drager CO analyzer. 1. Inlet valve; 2. Filter; 3. Rotameter; 4. Catalytic combustion chamber; 5. Water bath; 6. Outlet valve; 7. Thermometer; 8. Condenser.

The accuracy of CO determination by the above methods is adequate for the control of combustion processes, and is generally sufficient for the determination of CO emission. In particular cases, use is made of automatic analyzers characterized by a greater accuracy, such as the Drager analyzer shown in Fig. VIII,16 (VIII.21).

Determination of the CO content in flue gases with the aid of the Drager instrument is based on the amount of heat evolved in

the catalytic combustion of CO. The instrument functions as follows: The gas to be analyzed enters the instrument through a valve (1), passes through a filter (2) on which the compounds of chlorine and sulfur are retained, and then is led through the rotameter (3) into the combustion chamber (4) which is packed with a catalyst (most frequently the so-called Hopkalite). As a result of passing the gas through a coil immersed in a water bath, the gas enters the combustion chamber at the constant temperature of 100°C. The CO is burned catalytically, and CO₂ is led out of the instrument through valve (2).

The amount of CO contained in the sample is determined by the amount of heat evolved in catalytic combustion, which is manifested in an increase in the chamber temperature. This temperature can be measured with a thermometer (7) or a system of thermo-couples, and the scale can be directly calibrated in terms of the percentage of CO.

In technology, CO measurements are carried over the range 0 — 0.5% or 0 — 1%, or 0 — 0.3% in exceptional cases. The smallest amount of CO capable of detection by this method is 10 ppm. The hydrogen present in the sample does not affect the result if its concentration does not exceed 0.3%.

Between 75 and 80% of the sulfur present in fuels is burned to SO₂ and SO₃, and is emitted into the atmosphere together with flue gases. Certain amounts of H₂S can also be formed in the process of combustion. As a rule, the SO₃ and H₂S content in flue gas does not exceed 1% of the SO₂ content. Therefore, the SO₂ emission can be accurately determined on the basis of the chemical analysis of the fuel.

In particular cases, or in order to carry out control measurements, a number of chemical analytical methods can be used to determine the SO₂ content in flue gases. The W. Radmacher and K. Hadicke method will be described by way of an example.

The basis of determination is as follows. The gas sample is passed through an 80% solution of isopropyl alcohol, which absorbs SO₃ and small amounts of SO₂. The next two wash-bottles filled with a 15% solution of hydrogen peroxide absorb SO₂. The amount of SO₃ is determined gravimetrically after precipitation with barium chloride. The amount of SO₂ can also be determined gravimetrically in the wash-bottles filled with hydrogen peroxide on the basis of the amount of sulfuric acid produced.

Apparatus for determining the SO₃ and SO₂ content in gases is shown in Fig. VIII, 17. The gas sample for analysis is taken from

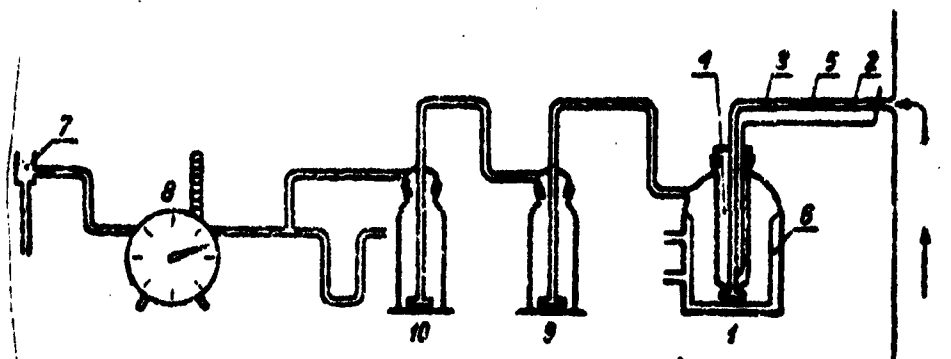


Fig. VIII, 17. Apparatus for determining the SO_2 concentration. 1. Wash-bottle with isopropyl alcohol; 2. Inlet tube; 3. Heating coil; 4. Thermoelement; 5. Glass wool filter; 6. Water jacket; 7. Water pump; 8. Gas gage; 9 and 10. Wash-bottles containing hydrogen peroxide.

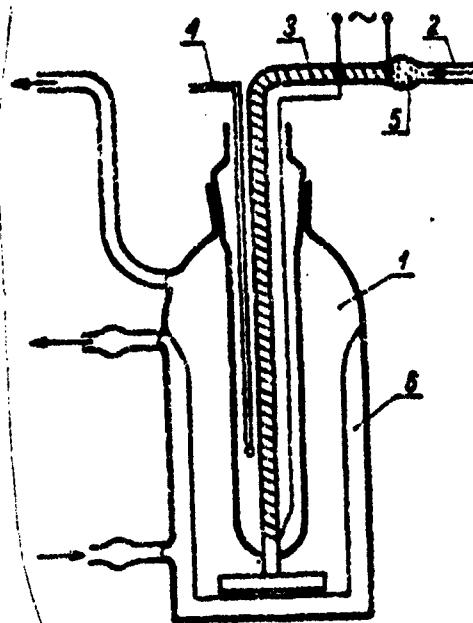


Fig. VIII, 18. Schematic diagram of a wash-bottle. 1. Vessel filled with isopropyl alcohol; 2. Inlet tube; 3. Heating coil; 4. Thermoelement; 5. Glass wool filter; 6. Water jacket.

the wash-bottle (Fig. VIII, 18). The inlet tube is heated to a temperature of $160^{\circ} - 180^{\circ}$ with the aid of coil (3) in order to prevent the condensation of water vapor or possibly of the formed sulfuric acid on the vessel walls. A thermoelement (4) serves to control the inlet tube temperature. The glass wool filter (5) prevents solid impurities from entering the wash-bottles. Wash-bottle (1) is cooled by means of water jacket (6). Before the determination is carried out, it is necessary to raise the temperature of the inlet tube to $160^{\circ} - 180^{\circ}$, and to regulate the water pump to the required suction rate. The amount of gas is passed through the wash-bottles, the inlet tube should be disconnected, and air should be passed through the apparatus for about 30 minutes (at the rate of about 1.5 liters/minute). This is in order to carry the SO_2 dissolved in wash-bottle (1) to wash-bottles (9) and (10) containing hydrogen peroxide. At the end of air aspiration the apparatus is disconnected, the contents of the wash-bottles poured into beakers and evaporated to a volume of 40 cc, and the absorbed SO_2 precipitated by the addition of a solution of barium chloride. The resultant precipitate is then filtered off and calcined. The BaSO_4 is weighed and re-calculated to SO_2 .

The contents of wash-bottle (1) are also transferred into a beaker, evaporated to a volume of 40 cc, 0.3 ml of 0.1 N solution of H_2SO_4 are added, and the SO_2 ions are precipitated by the addition of BaCl_2 . The amount of BaSO_4 due to the solution of H_2SO_4 added should be subtracted from the total weight of precipitate, and the difference is then re-calculated to SO_2 .

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(Abatement of smoke pollution)

Chapter IX

Estimation of Dustfall

1. Introductory remarks

As is known, one of the indicators of particulate matter concentration in air is dustfall over unit surface area in unit time, expressed in $\text{g/m}^2/\text{day}$, $\text{kg/m}^2/\text{month}$, and $\text{ton/m}^3/\text{year}$.

Sometimes the value of dustfall is taken to be an index of the concentration in air of the mechanically disintegrated particulate matter only. This is justifiable insofar as colloidal particulates may remain suspended in air over long periods of time without settling on the surface of the earth. On the other hand, even the smallest particles are deposited on the surface of the earth as a result of the vertical movement of air masses, condensation of vapors on particles of all sizes, and precipitation. Therefore a division into particulates which do or do not settle on the surface of the earth is not possible, especially since the value of dustfall depends on the method of measurement used.

The harmfulness of particulate matter can be determined by additionally carrying out chemical or mineralogical analyses.

In order to determine the range of distribution of the particulate matter emitted from a given source, or to settle legal questions arising from litigation about damage caused by grit pollution, it is desirable to determine the source of origin of particulate matter at a given monitoring point.

The instruments currently in use for determining dustfall values can be divided into the following three groups:

1. Dustfall meters (dust cans);
2. Collecting plates;
3. Directional dustmeters.

Each of these groups has its own range of applications, and the results obtained are not generally comparable. Therefore, as in the case of all determinations of pollutant concentrations, the results should be accompanied by a detailed identification of the measuring instrument.

2. Dustfall meters

Dust cans were first used in England in 1912. Now they are among the most widely known and used instruments for the estimation of dustfall.

A classical design of a dust can is shown in Fig. IX,1. It consists of a glass funnel (2) whose stem is connected by rubber tubing with a bottle (3), usually 10 liter capacity. It is mounted on a stand (5) and enclosed by wire netting (1).

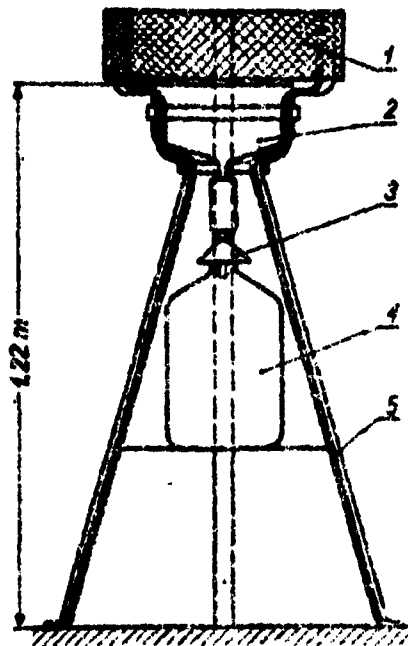


Fig. IX,1. A dust can.
1. Protective wire netting;
2. Glass funnel; 3. Rubber
tubing; 4. Bottle; 5. Stand.

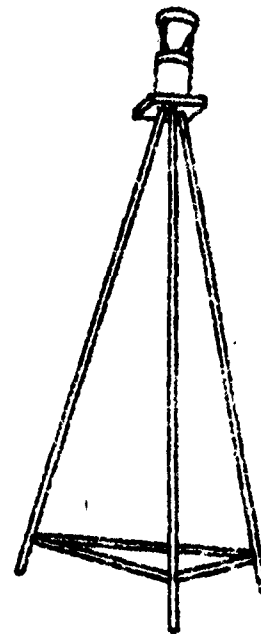


Fig. IX,2. A dust can mounted
on a stand

Particulate matter settling in the funnel is washed by rain into the bottle whose contents are subsequently subjected to a detailed physical and chemical analysis. The sampling period is usually one month. A new bottle is installed on the first day of the month, and taken off on the next month, when a fresh bottle is again installed.

Dust cans are usually placed on roofs of buildings. A rooftop of the highest building which is not partly sheltered by the wall of

another building should be selected. If the sampling is done in an open space free of buildings, the instrument should be placed on a stand between three and five meters above ground level (Fig. IX,2). Thus the collection of secondary dust blown off the surface of the earth is prevented.

There are a number of modifications of this instrument, consisting chiefly in different dimensions and shape of the funnel. British Standard glass funnel (0.15) is shown in Fig. IX,3. In addition to the latter, International Joint Commission (Fig. IX,4) and Toronto Study (Fig. IX,5) types are used in the United States (IX.5).

Funnels used in the English-speaking countries are calibrated in inches, which presents difficulties in re-calculating dustfall figures into the metric equivalents. For this reason, the funnels used in Europe are mainly 305 mm or 252 mm, in diameter. The use of 252 mm diameter funnels is particularly convenient, since it corresponds to a surface area of the opening of 0.05 m².

The construction of the Liesegang-Lobner dust can is shown in Fig. IX,6. Both the funnel and the bottle are made of transparent plastic (e.g., of polymethyl methacrylate), and housed in a structure also made of plastic, which has a door for manipulating the bottle.

There are a number of shape varieties of the 305 mm diameter funnel. These are shown in Fig. IX,7 (IX.9). The design shown in the bottom right corner seems to have the advantage that the upward narrowing of the funnel periphery partly prevents the blowing out of the collected dust. The 252 mm diameter Hibernia-type funnels come in a similar variety of shapes, as illustrated in Fig. IX,8 (IX.12).

In view of the high cost of dust can funnels, use is occasionally made of the Weck-type glass funnels for scouting determinations of dustfall. Precisely this type of funnel is most frequently used in Poland. In the large-scale investigation carried out between 1950 and 1956 in the Bochum district involving 1,700 monitoring points, the Weck-funnels placed in a wire cage were also used (Fig. IX,9) (IX.6).

The use of dust cans is essentially restricted to the seasons of the year when the temperature does not fall below 0°C. Furthermore, the error of measurement increases during periods devoid of precipitation as a result of the settled dust being blown out of the funnel. Therefore, it is advisable to sprinkle the funnel with distilled water every third rainless day wherever possible.

Although it would seem that the shape and diameter of the funnel should have no significant effect on the results, comparative measurements carried out using several different types of funnel show

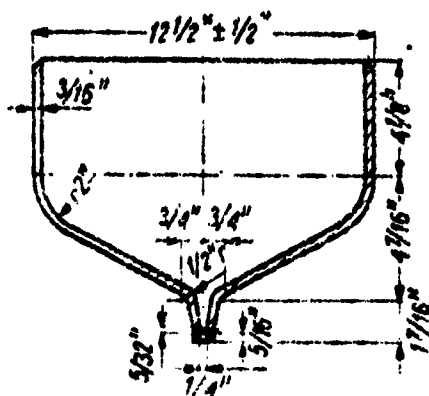


Fig. IX,3. British Standard funnel

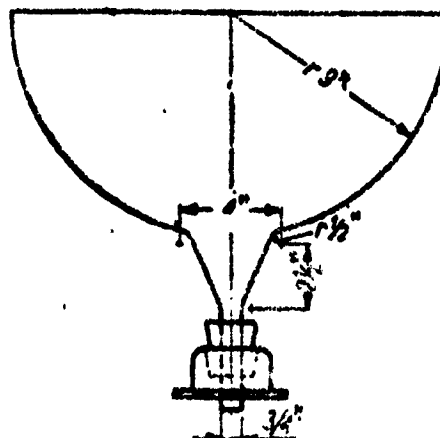


Fig. IX,5. "Toronto Study" type funnel

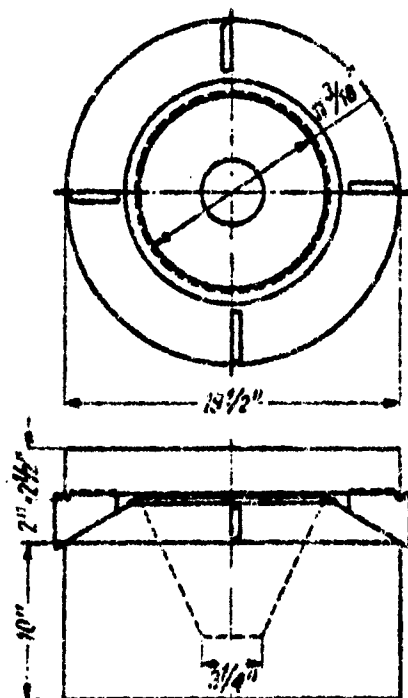


Fig. IX,4. International Joint Commission" type funnel

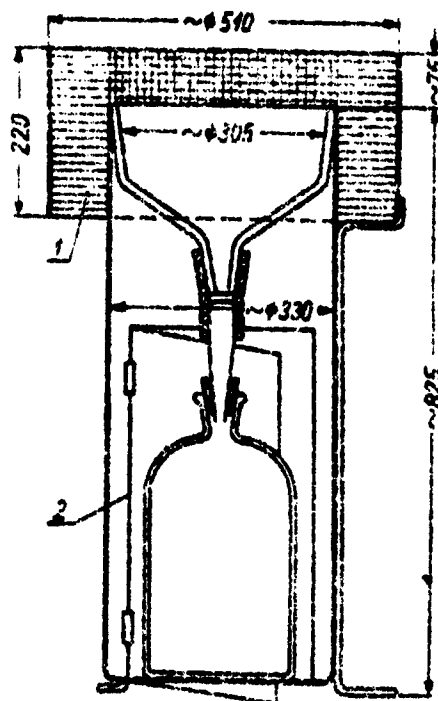


Fig. IX,6. The Liesegang-Lobner dust can. 1. Protective netting open at the top; 2. Door.

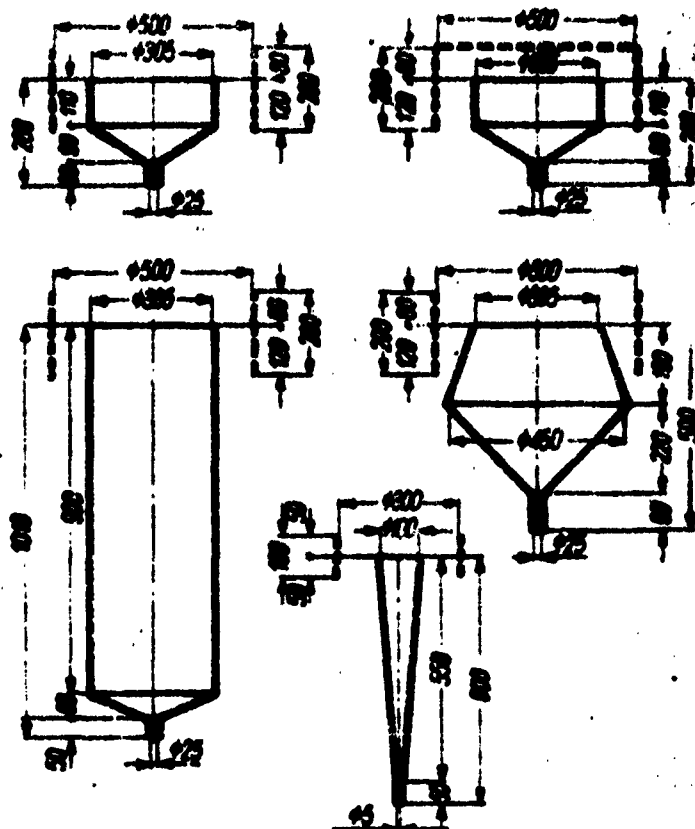


Fig. IX,7. Various shapes of funnels for dust cans

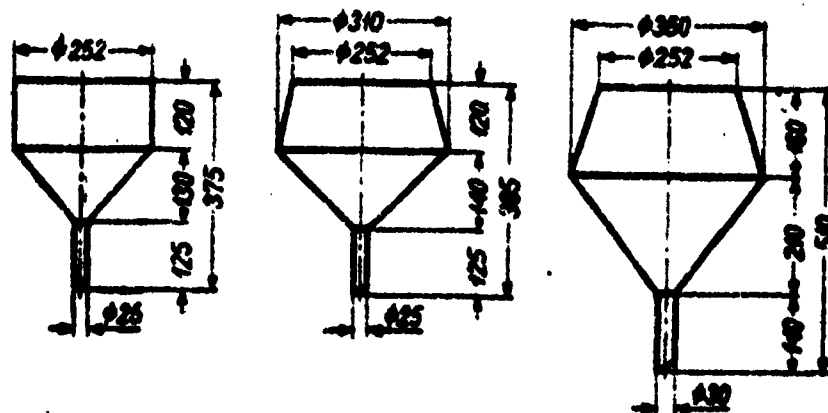


Fig. IX,8. Various shapes of funnels of the "Hibernia" type

that the differences are considerable. It follows from the studies of A. F. Fisher (IX.5) that whereas the results obtained from two identical funnels placed side by side do not exceed $\pm 5\%$, discrepancies in the results obtained using the funnels shown in Fig. IX,5 alongside those in Fig. IX,6 amount to between 60 and 220%.

Similar conclusions were reached by A. Lobner, who compared the results obtained using the funnels shown in Fig. IX,7. In long-range samplings (from four to 26 months) the following average ratios of readings were obtained: $I/I = 1.2$, $II/I = 1.33$, $II/I = 1.66$.

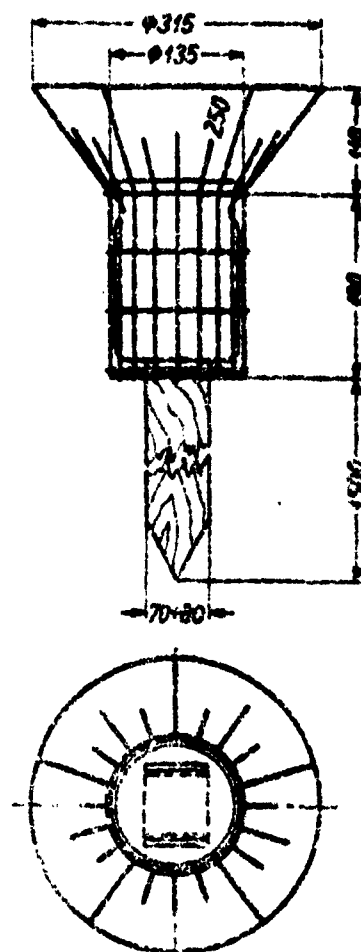


Fig. IX,8. Holder for the "Weck" type dustfall meter. a. Sampling foil grip; b. Protective netting.

Similar discrepancies between the readings obtained using the various types of instrument point to the necessity of standardizing the shape of dustfall meter funnels on the international scale. At the present state of affairs, it is difficult to obtain comparable results.

3. Collecting plates

Independently of the universal application of dust cans, attempts are made at developing rapid methods of measuring the amount of dustfall.

R. R. Paxton (IX.11) introduced the use of glass plates measuring 250 x 125 mm for determining dustfall. After a thorough cleaning, the plates are coated with hot petroleum jelly (about 1 g per plate) and placed high above ground level (a practice analogous with that followed in the case of dust cans). The average exposure time is 10 days. After removing trapped insects and bird droppings, plates are washed in carbon tetrachloride. The suspension is filtered through a filter paper which is subsequently dried and weighed. The proportion of combustible particulates can be determined by incinerating the filter paper. Non-combustible particulates can be tested by other methods. The advantage of these plates resides in the fact that the dust settles on them in an unaltered form, while the disadvantage is that they cannot be used on rainy days.

A similar method for using collection plates was developed by M. Dien (XI.1). Instead of glass plates, he used aluminum foil 0.07 mm thick and measuring 50 x 84 mm. The working surface of the foil is 39 x 84 mm, giving a surface area of 0.33 dm². The foil is placed in a holder shown in Fig. IX,10a, and protected from the birds by a wire guard (Fig. IX,10b).

The foil is covered with petroleum jelly (about 50 mg per foil) spread uniformly over the surface with a finger, and then heated to obtain a layer of uniform thickness. All the subsequent manipulation of the foil is done with the aid of pincers.

The coated foil is weighed with an accuracy to 0.1 mg. The value of dustfall is determined by noting the increase in weight due to dust deposition. As a rule, exposures at the monitoring point last seven days. This period ought to be shortened if the weight increase is more than 30 mg. The layer of petroleum jelly does not provide a sufficient degree of adhesiveness for greater amounts of particulate matter.

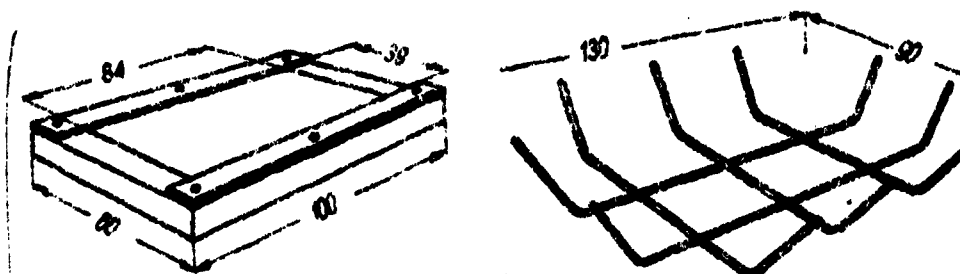


Fig. IX,10. Foil holder and wire guard

Table IX,1.

Results of dustfall measurements at various elevations above ground level

Wysokość ① m	1.5	3	6	12	24	31
Opad ② G/m ²	8.2	6.0	4.5	2.7	2.2	1.6

Legend: 1. Elevation; 2. Dustfall.

Stands bearing the foil are usually set up on tops of buildings. Stands set up in open spaces should be 1.20 meters high. M. Diem recommends the setting of between two and seven stands per square kilometer. Comparative measurements have shown that no perceptible differences in results are obtained at elevations of up to 2.5 meters. At higher elevations of foil exposure, the results can differ significantly. Table IX,1 shows the results of comparative measurements lasting 46 days.

Moderate rainfall does not prevent dustfall measurements using the foil method. In this case, the foil should be dried at 40°C prior to weighing. Violent rains or hailstorms cause definite damage to the layer of petroleum jelly. Similar damage and a loss of weight can occur during periods of strong insolation.

The great advantage of the foil method lies in the possibility of carrying out large numbers of measurements in a relatively short period of time, permitting the characterization of dust pollution.

of a given region. Being rather troublesome, this method is not so suitable for determining average dust concentrations over long periods of time.

4. Directional dustfall meters

Directional dustfall meters are used for rapid and short measurements lasting from a few minutes to one day. The main aim of the measurements done using these instruments is to determine the source of origin of particulate matter at a given monitoring point, or to define the range of pollution by emissions from a given source.

Among the best known instruments of this type is the dustfall meter developed by H. Liesegang (IX.10) shown in Fig. IX,11. The dust settles on glass plates (1) and (2) coated with petroleum jelly. Plate (2) is always set against the direction of wind due to a rotational setting of the plates and the use of a direction vane (3). The device secures a simultaneous measurement of air temperature and humidity by means of a thermometer and hygrometer (4) and wind velocity with an anemometer (5). A wind compass is engraved on the base, which permits determination of the wind direction. The sampling lasts from a few to several tens of minutes. Dustfall, expressed in particle count, as well as the origin of particulate matter, are determined by microscopic observation of the plates.

Fig. IX,12 shows a similar type of dustfall meter designed by R. Kroeber (IX.7). A shaft (1) supports a circular plate (2) fastened by a wedge (3) with a slot for collecting foil (4) held in place by springs (5). Small scoops may be used instead of foil to collect larger amounts of particulate matter. Above the permanent plate which supports the collecting foil, a plate (6) is placed in a bearing (7). This plate has a slot for accommodating large collecting foils. Thanks to a direction vane (8) and counter-weight (9) attached to this plate, it always positions in a given way with respect to the direction of the wind.

Thus the above instrument makes it possible to determine the relationship between dustfall and wind direction.

A design intermediate between directional dustfall meter and some gages for determining particulate concentrations is exemplified by the instrument shown in Fig. IX,13 (IX.7). The instrument is placed on bearings on a stand (1) so that the direction vane (4) always places the inlet of the sampling cyclone (2) in a direction perpendicular to that of the wind. The aspiration of polluted air into the cyclone is accomplished by means of an air vacuum pump (3). Particulate matter precipitated in the cyclone is collected in a

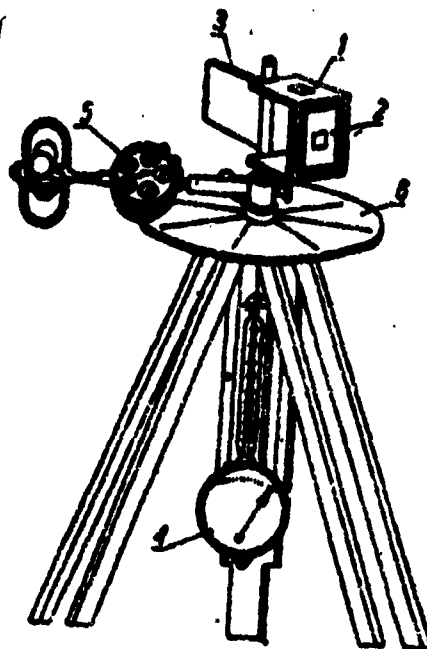


Fig. IX,11. Li-segang directional dustfall meter

container (5).

This design does not permit the measurement of particulate matter concentration in mg/m^3 since the volume of aspirated air is not measured. Thanks to the fact that this instrument can collect large amounts of particulate matter, it is possible to characterize accurately the composition of the latter, as well as the dependence of its concentration on the direction of the wind at the monitoring point.

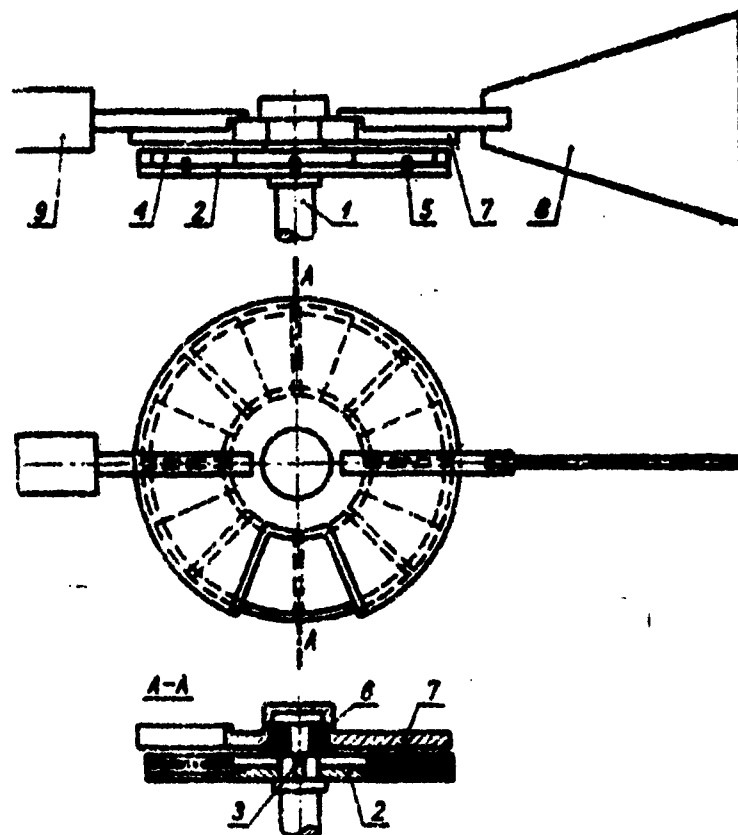


Fig. IX,12. The Kroner directional dustfall gage. 1. Shaft; 2. Plate with slots; 3. Wedge; 4. Foil; 5. Holding springs; 6. Bearing; 7. Cover plate; 8. Direction vane; 9. Counter-weight.

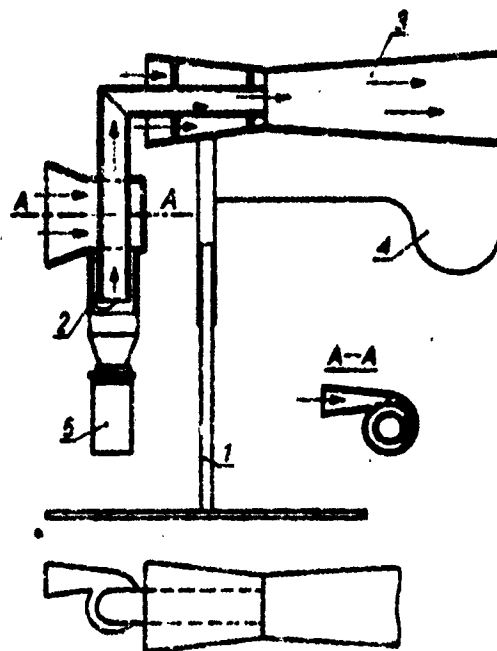


Fig. IX,13. Directional smoke gage (US patent No 2386282).
1. Stand; 2. Sampling cyclone; 3. Air vacuum pump; 4. Direction vane;
5. Dust container.

5. A comparison of the various methods of dustfall measurement

Because of its specific characteristics, each of the dustfall gages described above has its range of applications. For this reason, efforts have been made to establish a relationship between dustfall readings obtained with different instruments. E. Effenberger (IX.3), (IX.4) carried out a large number of comparative measurements using the Lobner, Diem and Effenberger instruments (the latter is described in Chapter X).

The first series of measurements (IX.4), lasting one year, was done using 15 sampling foils spaced symmetrically on a rooftop measuring 5 x 60 meters. The following conclusions were drawn on the basis of an analysis of the results:

1. Correlation between results obtained from single sampling foils and an average value based on the results from 15 foils is not statistically assured;

2. In order to assure statistically verifiable correlation at each sampling point, simultaneous measurements using at least five sampling foils should be carried out.

3. The differences in readings of the individual foils are smaller than the fluctuations in dustfall at a given monitoring point.

On the basis of the last conclusion, E. Effenberger recommends the establishment of a larger number of monitoring points in a given area rather than increasing the number of sampling foils at the individual monitoring points.

The results of a year-long measurement using dustfall meter, foil, and Effenberger dustmeter showed that there is no statistical correlation between the readings of a dustfall gage and those of a sampling foil (Fig. IX,14).

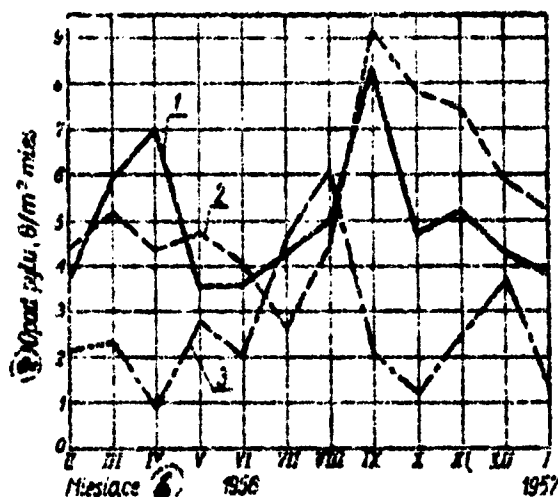


Fig. IX,14. Comparison of the results of dustfall measurements by different methods. 1. The Effenberger automatic konimeter; 2. Sampling plates; 3. Lobner dustfall gage.

Legend: a. Dustfall; b. Month.

It is possible to draw the following general conclusions on the basis of the study in question:

Results of dustfall measurements done by different methods, or even by different instruments within the same method are not mutually comparable. Until the methods of measurement become stan-

standardized, results of measurements must be accompanied by a detailed description of the method and equipment used.

6. Determination of the source of origin of particulate matter

In industrial districts where there are many sources of emissions, it is very important to be able to determine the source of particulate matter, since only this can supply the basis for preparing smoke pollution maps of a given district by the individual plants, and for deciding about the necessity of improving the efficiency of dust arrester equipment or the possibility of expansion of a given plant. It also serves to settle disputes arising out of damage caused by grit.

Identification of source is facilitated by a description of characteristic and easy to identify particulates emitted by the individual plants. For instance, A. R. Meetham (O.15) states that grit from powdered fuel burners clearly differs from that emitted by fixed grate fireboxes. At the high temperatures encountered in powdered fuel burners, the mineral components are fused, forming characteristic spherical granules (condensation products) not encountered in emissions from grate fireboxes.

The characteristic particulates emitted from iron and non-ferrous metal smelters may be metal oxides (IX.8) which can be easily identified in microscopic examination by their characteristic shapes and color. It is also relatively easy to pick out particulates characteristic of the individual chemical plants. For instance, soda ash and apatite dusts are characteristic of the production of superthomazine.

R. Moldau recommends that samples should be taken from the stacks of the individual plants and microscopic slides prepared for the purpose of characterizing emissions from the individual sources.

The results of such procedure are shown in Figures IX.15 and IX.16 (after K. Schwartz (IX.12)). The photographs were taken from sampling foils. The first one shows grit from a grate firebox, while the second one shows dolomite dust generated in the manufacture of refractory materials.

Identification of the source of grit emission by this method may not always be possible, as the individual sources may not show differences in characteristics sufficient to form a basis for identification. In such cases it is recommended to use artificial standard grits, e.g., cobalt glass, uranium oxide, rock salt, metal oxides,



Fig. 14, 15. Grit from a grate
fireclay

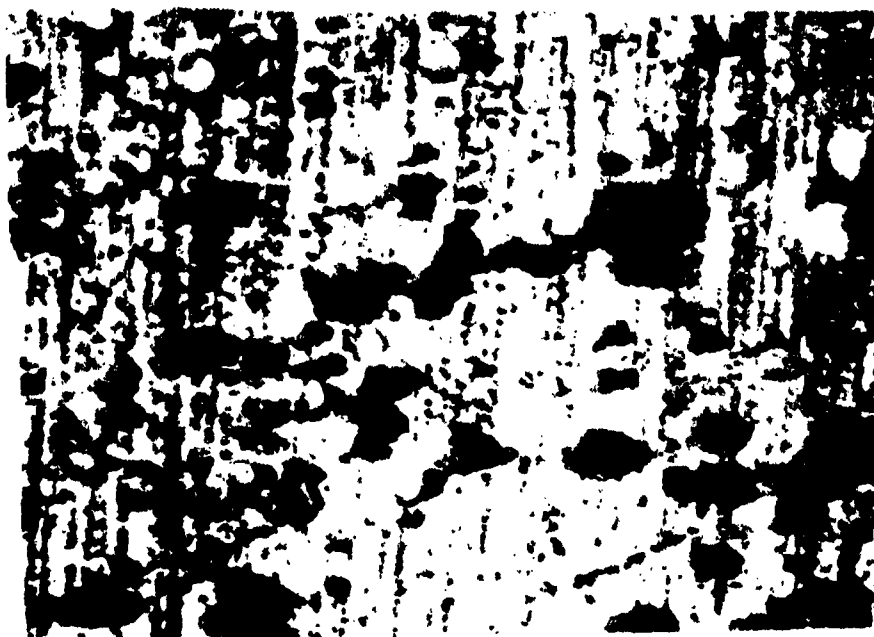


Fig. 16. Dust from the manufacture of
refractories

etc. (0.16).

R. R. Paxton points out the fact that the standardization or addition of artificial standards does not provide a complete solution of the problem, since the lead particulates should span the entire particle size range encountered in the emissions from a given source. Evidently, the matter is quite complicated and each problem requires individual attention.

7. Physical and chemical testing

a. Physical tests. In the case of methods using sampling plates, the microscopic methods described above may be applied.

b. Chemical tests. This embraces the determination of soluble and insoluble fractions, combustible components, ash content, and the determination of calcium, chlorides, sulfides and, sometimes, of the concentration of carbonates, phosphates, sodium ions, etc.

Determination of insoluble fraction

This method depends on the separation and weighing of the particulate fraction insoluble in water.

Accumulated dustfall in water suspension is allowed to stand until the supernatant liquid becomes clear. Then the latter is syphoned off, and the residue is filtered through a retentive quantitative filter of known weight. The filtered residue on the filter is placed in a weighing dish and dried at 105°C. Simultaneously a similar operation is carried out using only distilled water to determine the amount of water absorbed by the filter.

The insoluble matter content in milligrams is determined from the following formula:

$$W = (a - b - p)$$

where a is the weight in mg of the weighing dish, filter and residue after drying;
b is the weight of the weighing dish plus filter, after drying and prior to filtration;
p is the correction, in mg, for water absorption by the filter. It is equal to the difference between the weight of the weighing dish plus filter before and after saturation with distilled water (dried to a constant weight in both cases).

Determination of soluble matter

The water-soluble components of dustfall are determined using the filtrate from the accumulated dustfall and rainwater following the determination of the insoluble content. The method reduces to evaporating a known volume of filtrate to dryness and weighing the residue. Evaporation is best carried out using platinum or quartz dishes previously heated to constant weight.

Following evaporation, the dish with residue is dried at 105°C to constant weight.

The soluble content R, in mg, in dustfall is calculated from the formula

$$R = \frac{1,000 V(a - b)}{v}$$

where a is the weight of the evaporating dish plus residue, in mg;
b is the weight of empty dish, in mg;
v is the volume of liquid used for evaporation, in ml;
V is the volume of accumulated precipitation, in liters.

Total dustfall

After the soluble and insoluble matter content is determined, the total amount of dustfall per day O, in g/m²/day can be determined from the following formula:

$$O = \frac{1,000 (W + R)}{Ft}$$

where O is the amount of dustfall, in g/m²/day;
W is the weight of insoluble fraction, in mg;
R is the weight of soluble fraction, in mg;
F is the surface area of the collecting funnel;
t is duration of sampling, in days.

Determination of tars

Tars are determined by extracting the water-insoluble fraction of dustfall with carbon disulfide in a Soxhlet extractor. Tars are dissolved in CS₂ and are collected in the flask of the extractor. After evaporating CS₂, the flask is weighed at 105°C to constant weight. The tar content is equal to the weight difference of the flask before and after extraction.

Determination of ash

Ash is defined as the incombustible fraction of dustfall remaining after extraction of tars and following calcining. After extraction with CS_2 , the dustfall residue is placed in a tarred crucible and calcined until nearly constant weight is reached.

The ash content is equal to the difference of weight before and after roasting.

Content of combustible matter

This is calculated as follows:

$$X = (W - B) - c \text{ mg}$$

where W is the weight of insoluble fraction;
B is the weight of tars.

Determination of pH

pH meters are used for this purpose. The measurement is done using the clear filtrate after insoluble matter had been filtered off. The latter does not affect the value of pH.

The measurement is carried out by immersing the meter electrode in the liquid.

In view of the fact that the pH of the liquid may change on standing, the reading must be taken immediately after filtering off the insoluble fraction.

Colorimetric indicators are also frequently used for determining the pH of dustfall supernatants. These depend on adding an indicator to the sample, and comparing the resultant color with a standard. Brom phenol blue, whose range is 5.8 - 6.0 pH, is most frequently used. Lower values of pH are determined with methyl red, and those above 8.0, with phenolphthalein. If pH fluctuations are large, the Janady universal indicator with a range of 4.0 - 10.0 is used.

Universal indicator strips can also be used, but the values indicated by these differ considerably from the actual.

Determination of chlorides

Chlorides are determined volumetrically (by the Mohr or Volhard method). The most frequently used Mohr method depends on

titrating the chloride solution with silver nitrate solution in the presence of potassium chromate as an indicator. White silver chloride is precipitated first, followed by the red precipitate of silver chromate.

The chloride content X , in mg, is calculated as follows:

$$X = \frac{1.000 V m n}{V_1}$$

where V is the silver chloride titre, in ml;
 V_1 is the volume of sample used;
 m is the number of mg of silver nitrate per liter of solution;
 n is the volume of accumulated precipitation.

Determination of sulfur compounds

The method depends on the determination of sulfur in all the compounds present in dustfall, and really amounts to the determination of total sulfur. Sulfur compounds are oxidized by bromine water in an alkaline solution, barium sulfate is precipitated by addition of barium chloride in an acid solution.

The sulfate content X_{SO_4} is calculated from the formula

$$X_{SO_4} = \frac{0.4114 a 1000 n}{V} = \frac{411.4 a n}{V}$$

where a is the weight of barium sulfate in mg;
 V is the volume of precipitation tested in mg [sic];
 0.4114 is the coefficient for re-calculating $BaSO_4$ into SO_4 ;
 n is the volume of accumulated precipitation, in liters.

Table IX,2 shows an example of the results of month-long sampling described by the method of A. R. Metham.

Table IX,2.

Item	Results	
Total volume of dustfall and rain precipitation pH	2.73 dm^3 7.1	
	G	ton/ km^2 /month
Insoluble matter	0.1873	2.540
Tars	0.0043	0.058
Ash	0.1098	1.480
Combustible matter	0.0732	0.990
Soluble matter	0.0546	1.150
Chlorides	0.0173	0.023
Sulfates	0.0415	0.585
Calcium	0.0096	0.012
Dustfall	0.2719	3.690

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Chapter X

Determination of Particulate Matter Concentration in Air

1. Introductory remarks

In foreign literature, the apparatus for measuring particulate concentrations in air is referred to as "smoke" samplers or gages. In view of the classification scheme given at the beginning of the present work, this would mean that the measurements concern only particulate matter of colloidal origin. However, this would not be strictly accurate, and a closer consideration of the conditions of sampling is required to define the scope of the measurement of particulate matter concentrations in air.

Colloidal particulates may remain airborne for long periods of time, and they are deposited on the earth's surface mainly as a result of atmospheric precipitation. In addition to colloidal particulates, there are in the atmosphere also mechanically disintegrated particulates in sedimentation phase.

As a result of the differences in settling velocities, there is a considerable increase in the percent concentration of fine particulates in the air.

A characteristic of all the methods of smoke sampling is that the measurement consists in aspirating a given volume of particulate laden air and precipitating the particulate matter. If the aspiration of a sample of air were to be accomplished without changing the characteristics of the air-borne particulate matter, the determination would embrace both colloidal and mechanical particulates, always remembering that as a result of the larger particle size of mechanical particulates, their concentration in the air aspirated into the sampler would be smaller.

However, aspiration of a two-phase system such as an aerosol usually results in changed characteristics of the system, manifested in a reduced content of the coarser particulates.

Although a theoretical definition of the limiting particle sizes would be very difficult, it can be stated that smoke sampling essentially concerns colloidal and very finely divided mechanical particulates.

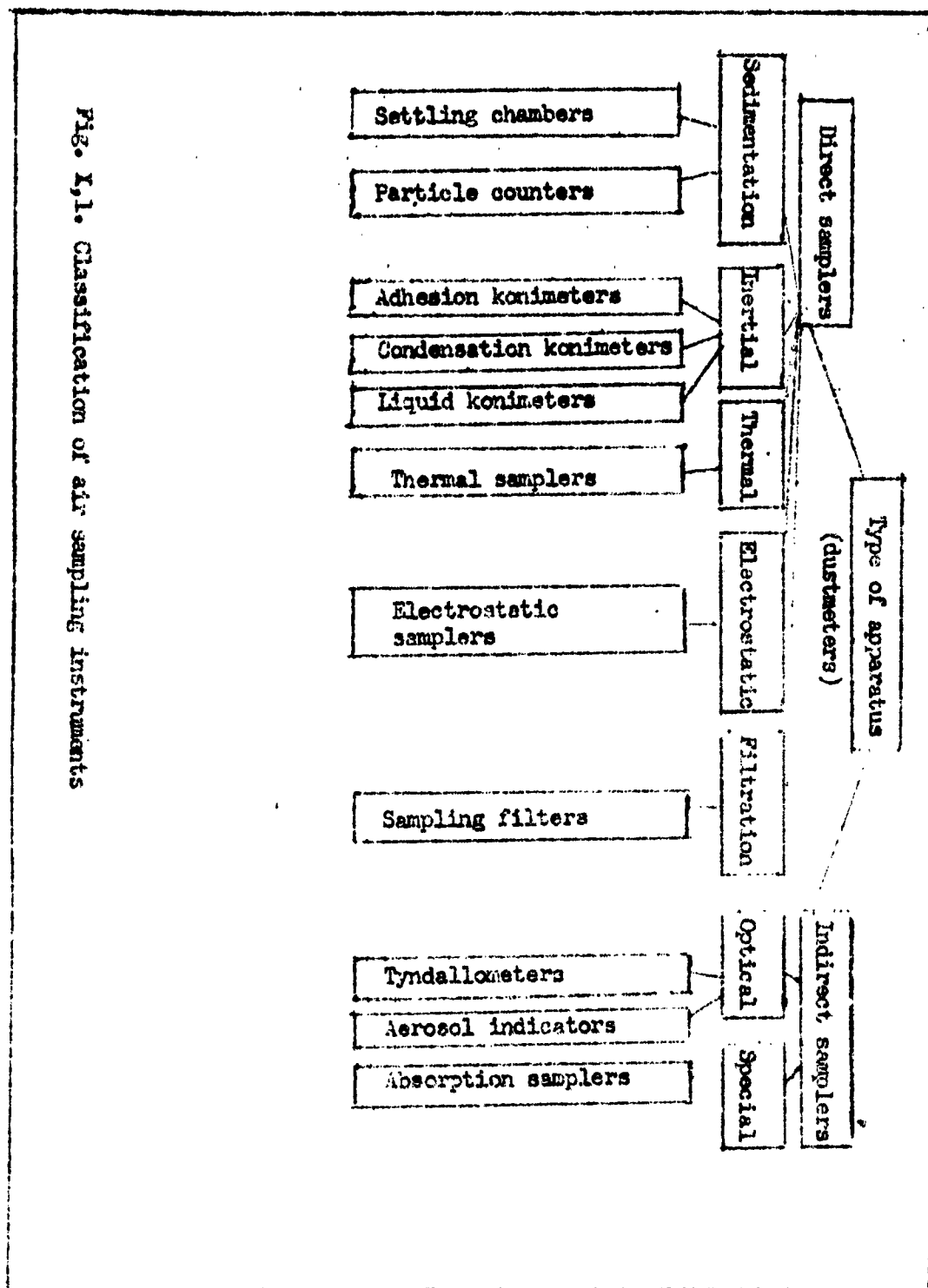


Fig. 1,1. Classification of air sampling instruments

In principle, all the sampling devices used for determining particulate concentrations in enclosed space can also be used in open air. A general schematic representation of the methods and apparatus in present use is given in Fig. I, 1. A detailed description of the individual smoke samplers is given in (0.13).

Only some of the available types of smoke samplers are used in view of the specific conditions of sampling in the case of continuous systematic pollution control.

Smoke samplers reading in Z/cm^3 have a very limited application, being used only in isolated cases in research.

Particulate pollutant concentrations are most frequently expressed in mg/m^3 or $\mu g/m^3$. As in every problem of measurement, it is necessary first to determine the range of the measured quantity and the order of accuracy that can be expected.

According to the Soviet norms, maximum concentrations of non-toxic particulates vary between 0.15 and 0. mg/m^3 . Assuming that the upper limit can be exceeded ten-fold, and that the lower limit can be taken as 1/10 of the minimum value, we have a range of measurements between 0.015 and 5 mg/m^3 . According to J. Pelletier (x.5) the mean value with respect to which accuracy requirements should be established is 0.05 mg/m^3 .

For sufficiently accurate results, the amount of particulate matter collected should be at least 50 mg. Therefore, in view of the expected range of measurements, the sampler must aspirate between 10 and 3,300 m^3 of air.

Since the average time reference unit in pollution control is one day, the aspiration rate should be between 0.4 and 130 m^3 /hour. Therefore, in the case of instruments using filters offering even moderate resistance to flow, relatively large surface area filter must be used.

As can be seen, measurement of particulate matter concentrations in terms of mg/m^3 is very troublesome. Therefore, comparative methods are sometimes used. These methods usually depend on estimating the degree of soiling of the filter material, and the units are established arbitrarily.

2. Measuring filters for the direct determination of particulate matter concentrations

Because of the relatively high air flow rates possible, the

Staplex Hi-Volume Air Sampler (Staplex Company, Brooklyn) is very convenient to use. This instrument, shown in Fig. X,2 (X.7) can aspirate air at a rate of $1.8 \text{ m}^3/\text{Min}$, which corresponds to $2,600 \text{ m}^3$ of air passed through the filter in 24 hours. Ordinarily, the instrument is designed for service with a filter of about 10 cm in diameter, but suitable adapters may permit the use of other filter sizes. The following sizes are used: $15.2 \times 23 \text{ cm}$ (6" x 9"), $20.3 \times 25.4 \text{ cm}$ (8 x 10"), and $30.5 \times 30.5 \text{ cm}$ (12 x 12") depending on the flow resistance of the filter material used and on the particulate matter concentration.

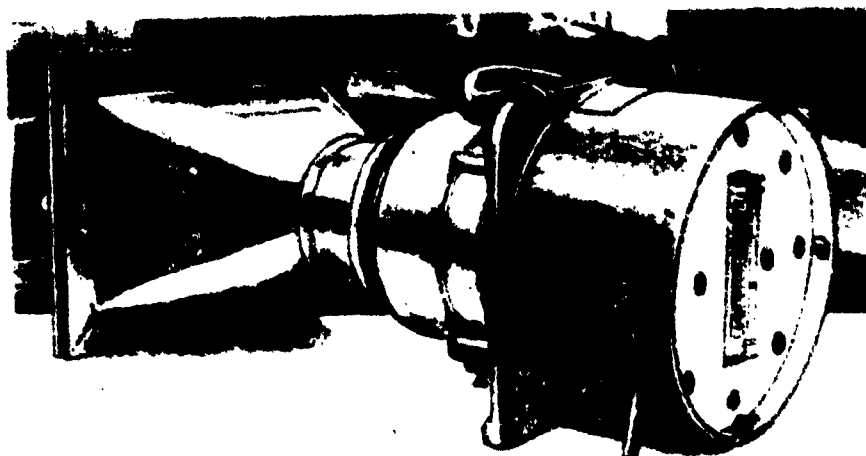


Fig. X,2. Staplex Hi-Volume Air Sampler

Filter paper and board manufactured in a number of grades by the Staplex Co. is used with the instrument. The manufacturer states that particles of up to 0.01μ diameter can be retained by selecting filter material.

As in all filtration methods, the filter should be first dried to constant weight and weighed with an accuracy to 0.1 mg prior to use (if the weight of particulate matter collected is of the order of several tens of milligrams. The procedure is repeated after sampling.

The troublesome business of taking into account the humidity changes of the filter can be avoided by using soluble filter materials such as tetrachloronaphthalene, developed by A. P. Ivy (X.1). The filter is formed directly on a frame equipped with a metal mesh. After sampling the filter is dissolved in ether, and the solution is placed

in a test tube. The solution is centrifuged, the supernatant liquid decanted, and the residue is dried at 105°C and weighed, or subjected to chemical and microscopic analysis.

3. Electrostatic samplers

Electrostatic samplers are also used for determining the concentrations of particulate matter in air. An example of such an instrument, manufactured by Sartorius-Werke A. G. Gottingen, is shown in Fig. 1,3 (I.7).

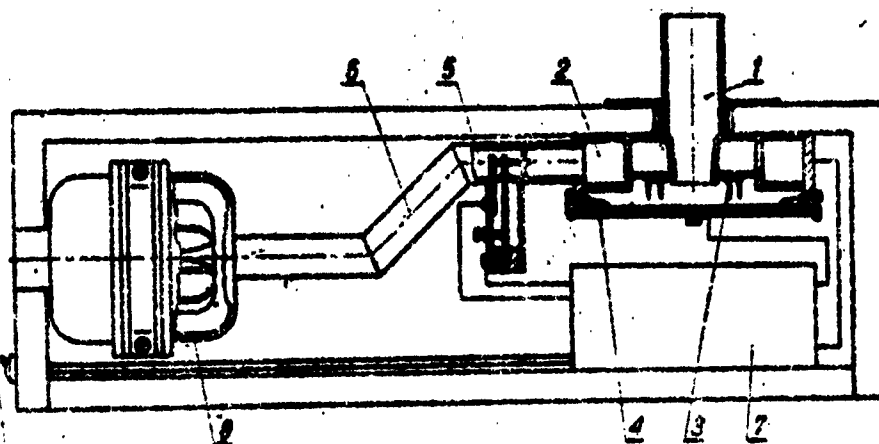


Fig. 1,3. Sartorius-Werke electrostatic air sampler. 1. Inlet; 2. Collection chamber; 3. Emitting electrodes; 4. Collecting electrode; 5. Electric regulator; 6. Connecting tube; 7. High voltage generator; 8. Fan.

Dust laden air is aspirated through the intake (1) into the chamber (2). There the particulate matter is ionized as a result of the coronal discharge by the emitting electrodes (3) fed by a device for generating high voltage (7). The particles settle on the collecting electrode (4) made of thin steel plate under the influence of electrostatic forces. Clean air is sucked by fan (8) through tube (6). The air flow rate is regulated by an automatic regulator.

The air flow rate is 3.6 m³/hour. According to the manufacturer's data, the sampler assures dust precipitation with an efficiency of 90% ± 4%. The maximum amount of dust allowed to accumulate on the collecting plate is 60 grams. After sampling, the collecting plate is

removed, and weighed on an analytical balance together with the accumulated dust.

The Gast electrostatic sampler (chapter VIII) is also used for determining particulate concentrations in the atmosphere.

4. Filters for the indirect estimation of particulate matter concentrations

In view of the aforementioned difficulties associated with the direct methods of determining particulate concentrations through weighing the filter, a number of automatic samplers have been designed in which particulate concentrations are estimated by comparing the degree of dirtying of the filter material. Despite their lower accuracy, they have found wide application because of the ease of service, and also due to the fact that they make it possible to record hourly fluctuations in particulate concentrations.

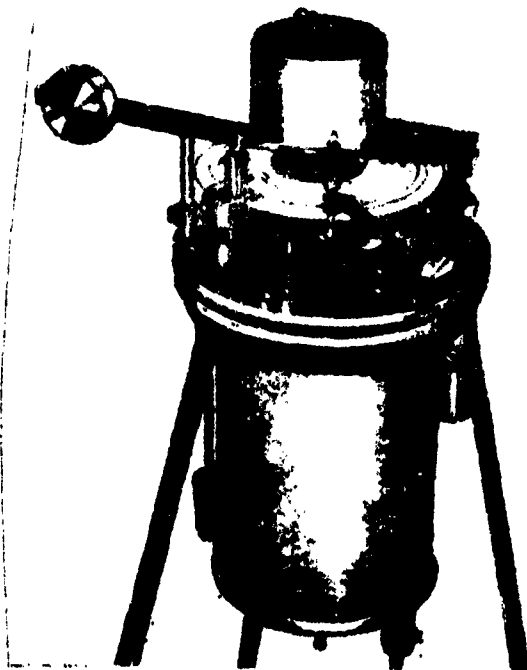


Fig. X,4. General view of the J. S. Owens automatic sampler

The automatic sampler developed by J. E. Owens (O.15) is very convenient for measuring particulate concentrations over 24 hour

periods. A general view of the instrument is shown in Fig. X,4, and a simplified schematic diagram is shown in Fig. X,5.

The instrument works as follows:

Water from the mains is led into a two-liter tank (3) through a pipe (1) equipped with a cock (2). The water flows through a valve (4) connected to a timing device not shown in the diagram. The valve (4) is opened at hourly intervals. After attaining level a-a, the water overflows through a syphon (5), causing the aspiration of two liters of air into the tank. A filter paper is fastened in the intake tube (6) having a diameter of 0.32 meters. This retains the particulate matter contained in the aspirated volume of air. A clockwork mechanism shifts the filter paper while the tank is being filled with water. The filter paper is a circle with an overprinted scale corresponding to 24 hours. Fig. X,6 shows the filter paper along whose periphery there are blackened spots caused by the aspiration of dirty air. The concentration of particulate matter is estimated by comparing the intensity of spots on the filter paper with a standard calibrated from 0 to 20. The results can be arbitrarily re-calculated to mg/m^3 by multiplying the rating by 0.032.

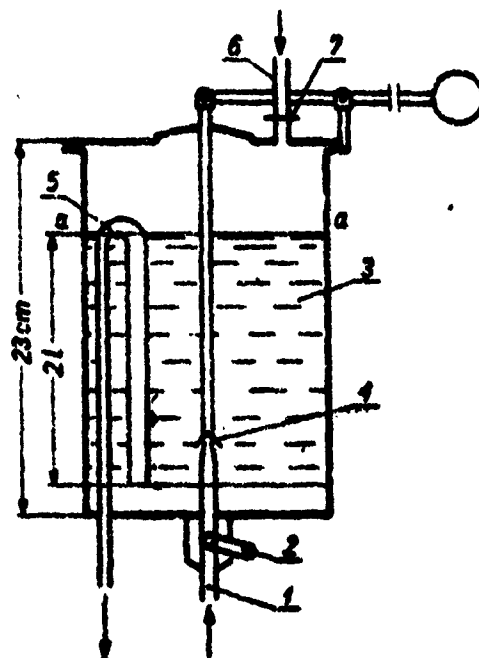


Fig. X,5. A schematic diagram illustrating the action of the J. S. Owens automatic sampler. 1. Inlet water pipe; 2. Cutoff cock; 3. Tank; 4. Valve; 5. Syphon tube; 6. Air intake; 7. Filter paper.

In the case of low pollutant concentrations, another tank of any desired capacity can be set on the same level, and connected by two pipes: one near the bottom of the vessel, and the other above the upper bend of the syphon pipe. Thus the air intake is increased, resulting in a larger amount of dust being retained on the filter, with a corresponding increase in the degree of blackening. In this case the arbitrary concentration in mg/m^3 is obtained as the product of the rating and expression $\frac{0.32 \times 2}{V}$ where V is the volume of the additional tank.

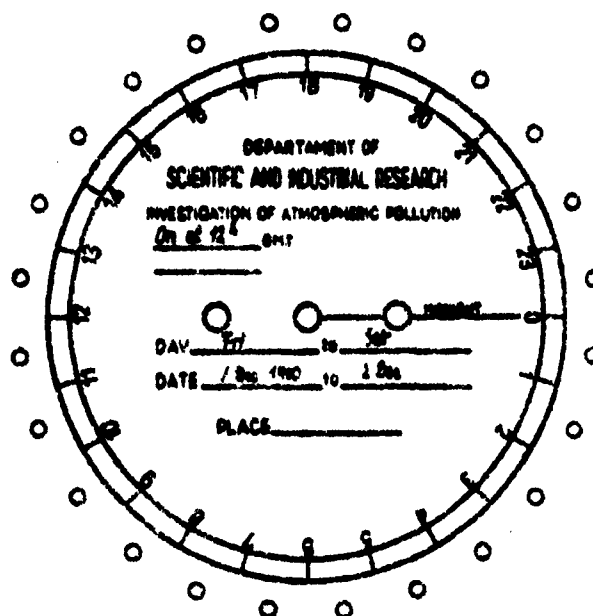


Fig. X,6. Filter paper used in the J. S. Owens automatic sampler

It should be explained that the above method of re-calculating the degree of blackening into mg/m^3 is merely to obtain a rough estimate. Furthermore, standards of blackening must be established daily for each sampling area.

The ALS1 Automatic Smoke Sampler manufactured by the Research Appliance Co. (X.7) also works on the filter principle. Its general view is shown in Fig. X,7. The air is aspirated at a rate of about seven liters/min through a filter with a working area of 4.7 cm^2 . The

filter has the form of a tape which can be transported automatically. The unit sampling time can be set at between 0.5 to 24 hours. The degree of filter blackening is measured with the aid of a special photometer. The results are given in Coh units per 1,000 feet. The Coh unit is the amount of dust causing a change in the optical density of air by 0.01. The amount of dust retained on the filter is determined with the aid of a special device which measures the intensity of transmitted light.

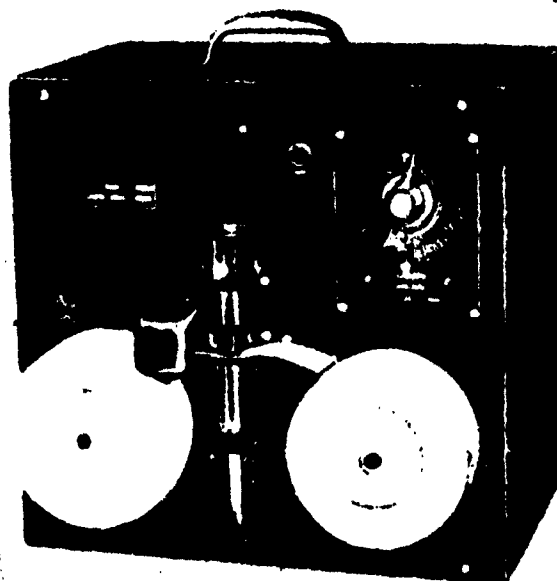


Fig. X,7. ALS1 Automatic Smoke Recorder

Another improvement of the above instrument is the Hi-Flow Tape Sampler manufactured by the same company, and shown in Fig. X,8 (X.4). The basic difference between the two is that the latter instrument uses a membrane filter in the form of a tape, and it can regulate the air flow rate between five and 32 liters/min. Control of the aspiration rate is accomplished by measuring the vacuum forming beyond the filter, when the characteristics of the filter material are known. The length of tape loaded into the instrument permits the execution of 60 consecutive readings. Depending on the length of the individual samplings, the tape can last between 30 hours and 60 days. While the tape is being shifted between the samplings, the suction pump is automatically cut off. Fig. X,9 shows a section of the tape before and after sampling.

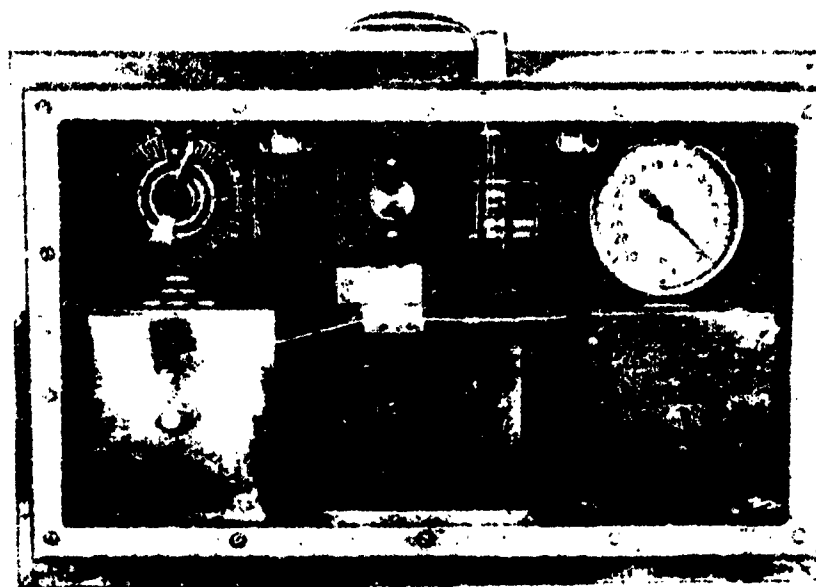


Fig. X.8. Hi-Flow Tape Sampler

The Automatic Air Pollution Recorder, made by Fleming Radio Ltd (X.7) and illustrated in Fig. X.10, works on a similar principle. Atmospheric air is aspirated through a filter paper in the form of a tape at a rate of about $15 \text{ m}^3/\text{hour}$. The instrument can be additionally equipped with a flow rate regulator and with electronic equipment for determining the degree of blackening of the tape. The degree of blackening is estimated as follows. After each sampling the tape is shifted so that the dirtied spot is placed under one of the photocells. The other photocell is trained at that time on a clean section of the tape. The photocell voltages, which are proportional to the amount of light passing through the respective sections of the filter tape, are amplified by a DC amplifier and then led to two branches of a bridge consisting of a double triode. The degree of imbalance of this bridge is the measure of the amount of particulate matter collected on the filter. In this way, changes in the intensity of the light source and the optical properties of the filter tape are eliminated. The bridge output can be connected directly to a recording device calibrated in suitable units.

A type of instrument designated by the symbol SF (Soulre-fumes) for the simultaneous determination of particulate matter and SO_2 concentrations in air are very popular in France and England (Fig. X.11; (0.15), (X.5)).

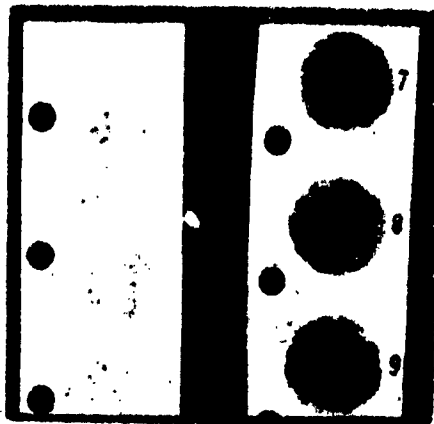


Fig. X,9. A section of filter tape from Hi-Flow Tape Sampler before and after sampling

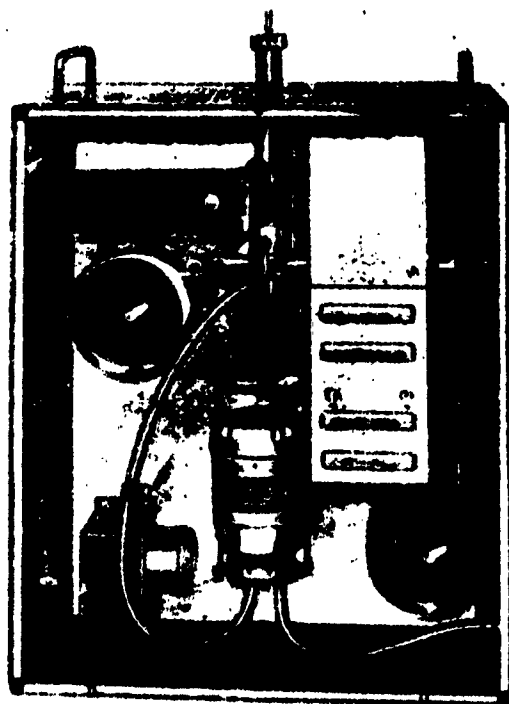


Fig. X,10. Automatic Air Pollution Recorder

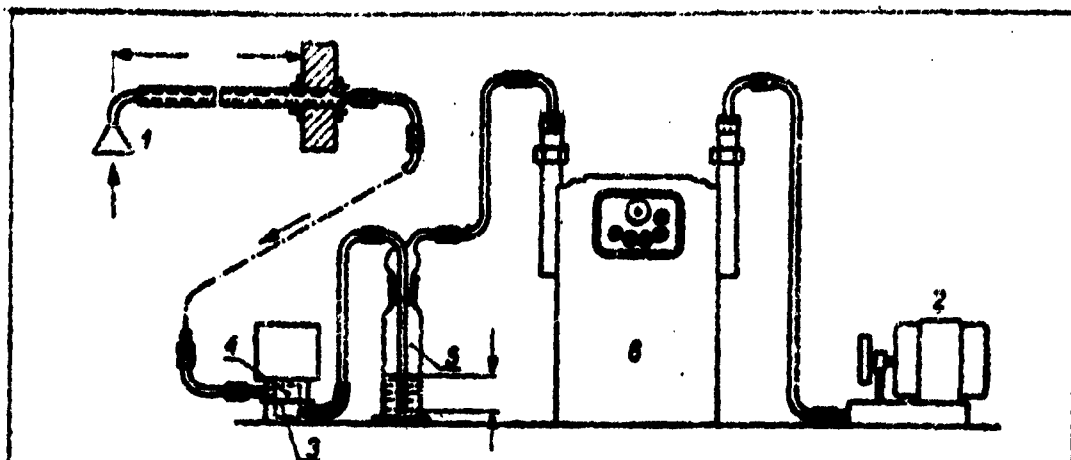


Fig. X,11. Diagram of the "SF" type instrument. 1. Intake funnel; 2. Compressor; 3. Filter paper; 4. Filter chamber; 5. Wash-bottle with hydrogen peroxide solution; 6. Gas gage.

Air is aspirated through a funnel (1) which excludes atmospheric precipitation by means of compressor (2), and passes through a filter paper (3) fastened in the filter chamber (4), a wash-bottle (5) filled with hydrogen peroxide solution, and then through a gas gage (6). Particulate matter concentration is estimated by determining the degree of blackening of the filter paper by comparison with a suitable standard.

Filters having diameters of 2.5 or 5 cm are used, depending on smoke density in the air. The SO_2 concentration is determined as described in chapter VII on the basis of the amount of H_2SO_4 formed in the wash-bottle.

The paper and the wash-bottle are changed daily and analyzed in a central laboratory.

5. Automatic konimeters

In Germany and Austria particulate matter concentrations are also determined using samplers based on the adhesive konimeter principle. They differ from the classical Zeiss or Sartorius konimeter designs (X.7) in that aspiration of air and rotation of the sampling glass are done automatically.

One of the first designs of this type, introduced in 1938 by F. Lowe (X.3), was an automatic konimeter capable of continuous operation over 24 hours. It was produced by Zeiss Co. under the name of "Registrierender Konimeter". The nozzle and glass are of the same

size as those in the ordinary konimeter.

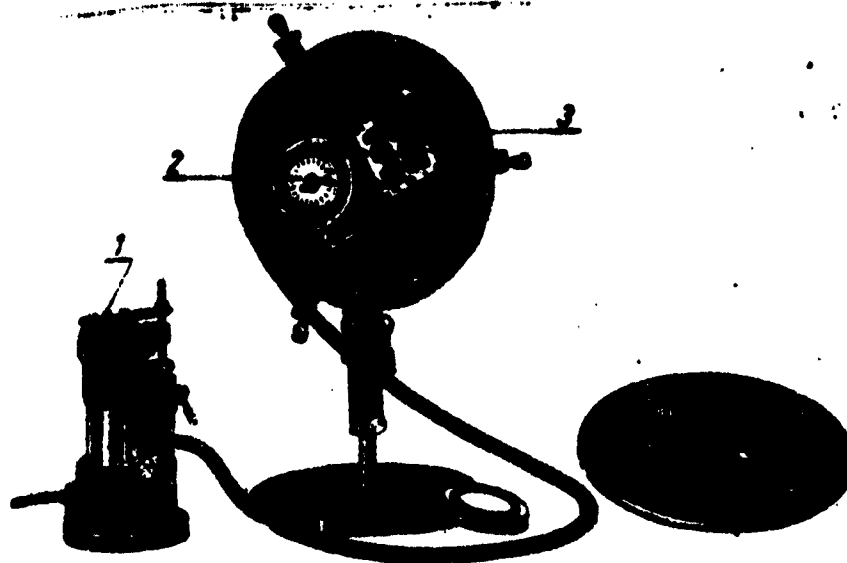


Fig. X,12. Automatic Zeiss konimeter. 1. Vacuum pump; 2. Sampling glass; 3. Clockwork mechanism.

The instrument is shown in Fig. X,12. Air is aspirated by means of a vacuum pump (1) driven by an electric motor. The konimeter glass is continuously rotated by a clockwork mechanism. A 360° revolution of the glass is accomplished in 24 hours, so that a continuous ring of deposited dust is obtained on it.

For intermittent sampling, J. A. Schedling (X.6) has developed a konimeter shown in Fig. X,13. As in the former case, the Zeiss konimeter was the starting point for the design of this instrument. Aspiration of air occurs at predetermined intervals of time. The pump (1) has the same dimensions and characteristics as the one in the standard konimeter. The tensioning and release of the spring is obtained by rotating a cam (3) driven by a synchronous motor. This motor simultaneously drives the sampling glass (4) so that it rotates by one sampling field between the samplings. The entire assembly is controlled by a mercury switch (5), and the intervals between the individual samplings can be set at between four and 60 minutes.

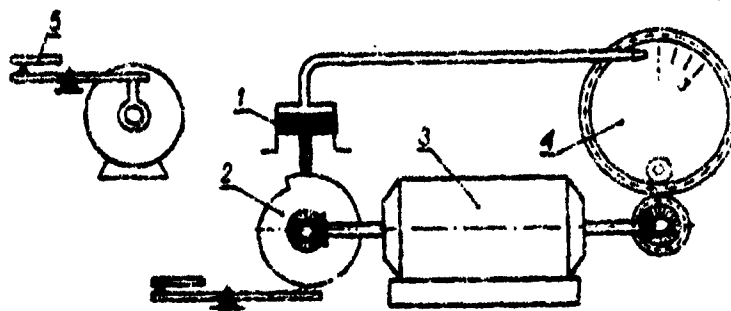


Fig. X,13. Diagram of the Schedling automatic sampler. 1. Suction pump; 2. Can; 3. Synchronous motor; 4. Sampling glass; 5. Mercury switch.

Yet another sampler based on the konimeter principle has been designed by E. Effenberger (X.2). Its diagram is shown in Fig. X,14. Air is continuously pumped out from the housing (1) through nozzle (1). Due to the resultant vacuum, dust laden air is aspirated through intake (3). After passing through nozzle (4), the air impinges on a specially treated paper fastened on a drum (5). As a result of revolution of the drum and travel of the nozzle, the dust particles precipitated on the paper form darkened spiral lines. The degree of blackening indicates the amount of particulate matter in the aspirated air. The circumference of the drum is 24 cm, which at one revolution per 24 hours gives an advance of one cm/hour. The transverse travel of the nozzle is caused by a screw (6), and amounts to 2 cm per 24 hours. Both the drum and the screw are driven by a synchronous motor with suitable transmission. At the stated velocities, the instrument can work for about two weeks without changing the paper. Various nozzle diameters (0.5, 0.75, 1.0 and 1.5 mm) can be used depending on pollutant concentrations. The air flow rate can also be altered. The paper used in the instrument should have the greatest possible resistance to humidity. The grade of paper used in recording meteorological instruments meets this condition. The paper is coated with a layer of petroleum jelly in order to secure better adhesion of dust particles.

The degree of blackening is compared with a standard rated between 0 and 6. Effenberger claims that it is possible to evaluate a degree of blackening of the order of 0.1 that of the standard.

In view of the very small volumes of air aspirated, the results obtained with the Lowe and Schedling konimeters cannot be

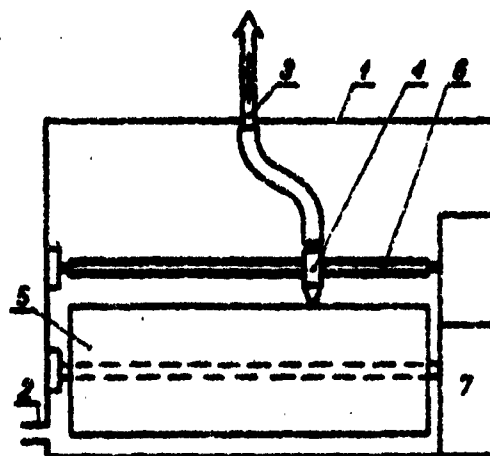


Fig. X,14. Schematic diagram of the Effenberger automatic konimeter. 1. Housing; 2. Outlet; 3. Intake tube; 4. Nozzle; 5. Recording drum; 6. Screw; 7. Synchronous motor and transmission.

considered sufficiently accurate. However, they do give an idea of the fluctuations in particulate matter concentrations.

Due to the fact that the efficiency of konimeters drops with the particle size of pollutants, the accuracy with regard to particles less than 1μ in diameter is inadequate, they should be used only for determining the concentration of mechanically disintegrated dusts.

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Chapter XI

Determination of Gaseous Air Pollutants

1. Introductory remarks

One of the basic problems to be solved by the air pollution in engineer planning the determination of gaseous pollutant concentrations in the atmosphere is the selection of characteristic pollutants. For technical reasons, the number of these pollutants cannot be too large.

As has been mentioned at the beginning of the present book, the oxides of carbon, sulfur or nitrogen are taken as the characteristic pollutants.

The next problem to be solved is the choice of a suitable sampling method. The factors influencing this choice are the levels of pollutant concentrations and the variations in them.

Fluctuations in the concentration of gaseous pollutants at a given monitoring point are greater than those of particulate matter concentrations. Fig. X,1 shows the results of SO_2 concentration measurements at one point over a period of 30 minutes according to Schwartz (XI.6). The graph shows that the SO_2 concentrations may vary between 0.02 and 0.85 ppm within a few minutes. It is possible to record such rapid changes only when automatic apparatus is used. This, of course, is the ideal solution not always attainable in practice. At any rate, determination of gaseous pollutants should be done using continuous-action apparatus. A period of 24 hours may be regarded as adequately long for determining average concentration values.

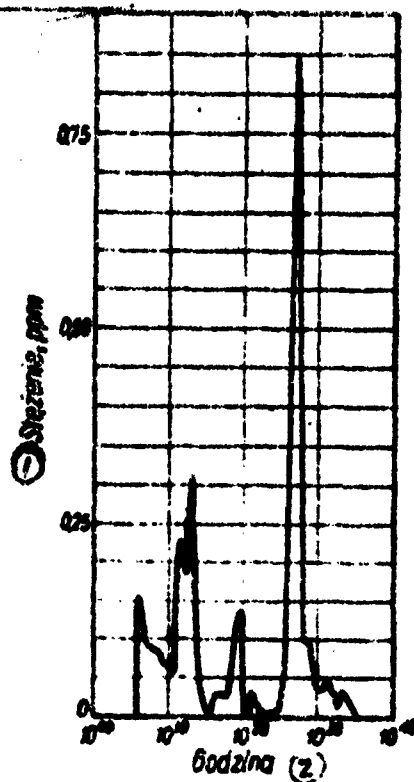


Fig. XI,1. Variations in SO_2 concentrations with time

Legends: 1. Concentration, in ppm; 2. Hour.

2. Classification of sampling methods

Numerous physical and chemical methods are at one's disposal when it comes to determining gaseous pollutant concentrations. The basis of selection of the most appropriate method lies in the possibility of continuous recording, and in the accuracy attainable.

Fig. XI,2 gives a general classification of the methods of identification of the individual gaseous components.

The optical methods are based on the phenomena of absorption, scattering, refraction, birefringence, polarization, etc. Both the ultraviolet and infrared regions can be used.

The infrared techniques have found the widest application in gas analysis. The infrared absorption strongly depends on the molecular structure. Virtually all gases can be identified on this basis. A typical design based on this principle is exemplified by the instru-

ment called the URAS (Ultrarotabsorbtionsschreiber). Its minimum range is between 0 and 500 ppm, and it works with an accuracy of $\pm 2\%$ in the upper end of the scale.

The paramagnetic method is based on the relationship between the magnetic constant and the type of gas. The fault of this method lies in the fact that it can be used for determining only one component of a gas mixture, i.e., only when all the remaining components remain constant. It is used mainly for determining oxygen concentrations in the range between 0 and 200 ppm.

The static and dynamic density methods rely on the utilization of differences in the densities of various gases. Their application is limited to determination of one component only on the assumption that the other components remain constant. In view of its low accuracy (of the order of 0.4%), the method is not used for determining gaseous air pollutants.

The methods based on the measurement of heat conductivity make use of large differences of the conductivity coefficient of various gases. In view of their low accuracy (of the order of 1%) they find no application in determination of gaseous air pollutants.

Among the methods depending on the measurement of the heat of reaction we have: 1. Catalytic combustion method, applied in the range between 0 and 3,000 ppm with an accuracy of about 10 ppm; 2. Methods based on chemical reaction between a given gas and a suitably chosen liquid, applicable in the range between 0 and 500 ppm with an accuracy of 5 ppm (Thermoflux).

The electrolytic methods are based on the phenomenon of changes in the conductivity of an electrolyte as a result of the absorption of a gas. The range is between 0 and 5 mg/m³, with an accuracy of 2% in the upper part of the scale. Methods based on a reduction in the volume of a gas as a result of absorption by a liquid are not used because of their low accuracy.

The chemical absorption methods depend on the absorption of a gas by a liquid and on determination of concentration by the gravimetric, nephelometric or colorimetric methods. These methods find a wide application in the determination of gaseous air pollutants, but only in the case of non-automatic sampling.

Adsorption methods are based on the adsorption of gases on solid reagents and the determination of the resultant color change.

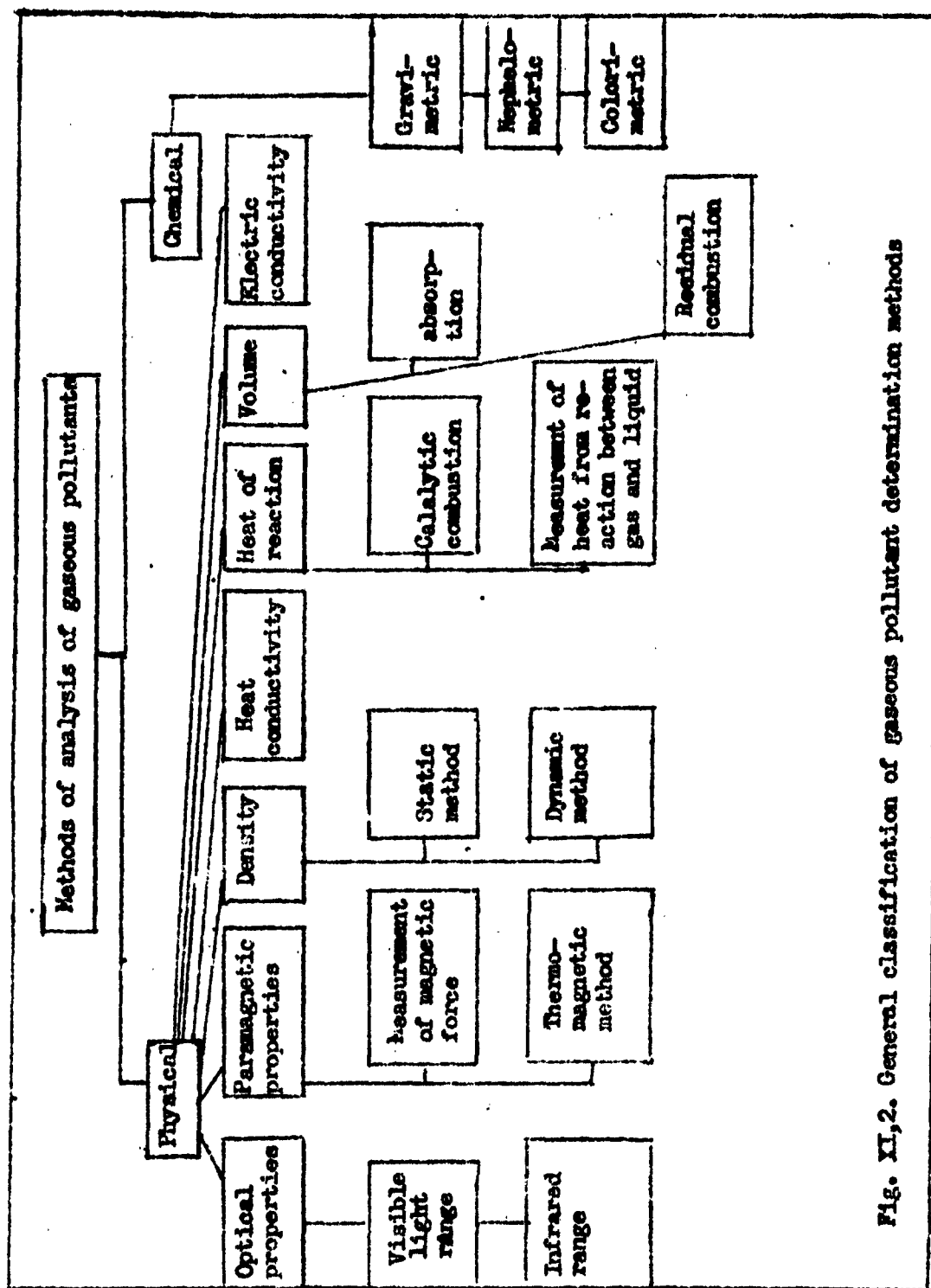


Fig. XI,2. General classification of gaseous pollutant determination methods

3. Determination of the individual gaseous pollutants

3. 1. Sulfur compounds

Sulfur as an air pollutant is present in many forms, but mainly as SO_2 , H_2S , SO_3 , H_2SO_4 , and various metal sulfides.

Sulfur dioxide under normal conditions is a colorless gas with a suffocating odor. Its density is 2.927 g/litre; and its melting and boiling points are -72.7° and -10.0°C respectively.

In concentrations of between six and 12 ppm ($7.2 - 14.4 \text{ mg/m}^3$) it immediately causes irritation of nose and throat. The maximum permissible single concentration of SO_2 in air is 0.5 mg/m^3 . Small amounts of SO_3 (comprising between 1 and 5% of total sulfur) escape into the atmosphere with flue gases. However, this is not the only source, since SO_2 is oxidized to SO_3 in the atmosphere. This reaction is very slow in dry air, but is speeded up in the presence of water droplets (fog), and in particular, in the presence of manganese compounds. SO_2 dissolves in water droplets, and is readily oxidized to H_2SO_4 , which in turn become hydrated and yield sulfuric acid mist. The latter can react with metal oxides present in air, giving sulfates.

Mainly colorimetric methods are used for determining the SO_2 concentrations in air. The method developed by West and Gacke (XI.7) is particularly sensitive. It makes use of a liquid which assumes a purple-red color upon absorbing SO_2 . The SO_2 concentration is determined by comparing the sample with standard color tubes. The accuracy of this method is about 0.05 ppm.

The methods for SO_2 determination are less satisfactory. This compound may be determined by the Kanter method (XI.3), in which SO_2 is simultaneously determined. This method depends on titration of sulfuric acid with a standard sodium hydroxide solution, oxidation of the SO_2 with bromine, acidulation, and precipitation of barium sulfate.

For the purpose of continuous determination of SO_2 in air, universal use is made of recording devices which are based on the measurement of the heat of reaction or the conductivity of an electrolyte. Typical examples of this type of apparatus are the Thermoflux, Autometer, Jonoflux and Titri-log instruments.

A schematic diagram of the Thermoflux is shown in Fig. XI,3 (XI.2). Its mode of action is as follows.

The gas sample is aspirated at a constant rate into a chamber

through which a reagent capable of reaction with one of the gas components (in this case, SO_2) flows also at a constant rate. A given amount of heat is evolved as a result of chemical reaction. The resultant increase in the temperature is measured by means of thermoelectric thermometers which can be calibrated directly either in % or in ppm.

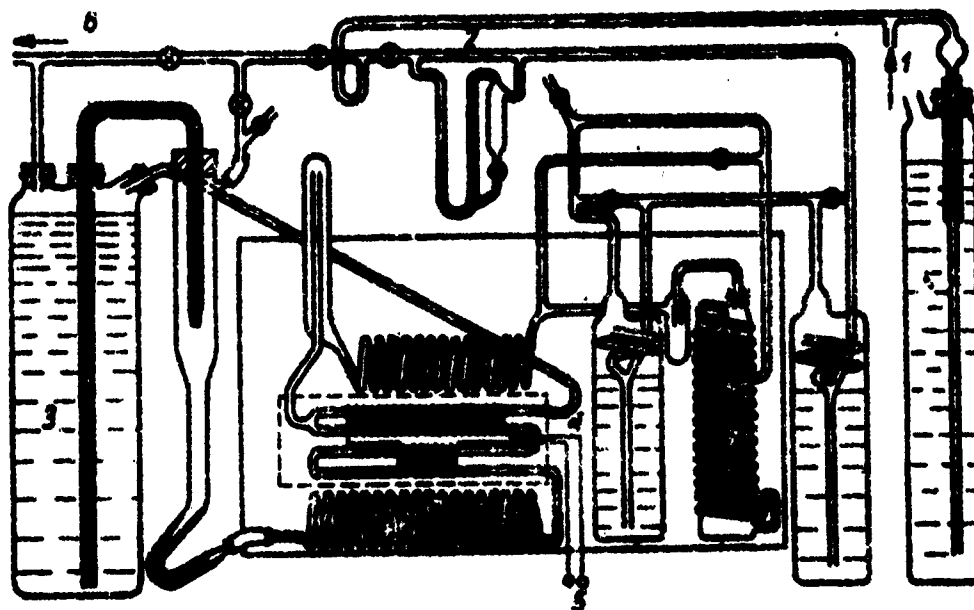


Fig. XI,3. A diagram of the Thermoflux. 1. Intake; 2. Gage; 3. Container with reagent; 4. System of thermocouples; 5. Reading terminals; 6. Gas outlet.

The diagram of the Autometer instrument (0.9) is shown in Fig. XI,4. It works on the principle of measurement of the conductivity of sulfuric acid formed by the oxidation of SO_2 obtained from a given volume of air. Sulfur dioxide is absorbed and oxidized in a slightly acidic solution of hydrogen peroxide. The sampling time is 30 minutes, while the conductivity measurements are made every two minutes. After 30 minutes, the solution is automatically pumped out and replaced by fresh solution. The absorbing solution must not absorb other gases capable of forming electrolytes.

An instrument called the Jonoflux (Fig. XI,5) (XI.4) works on a similar principle, but depends on a constant flow of the absorbing liquid. The liquid is fed from two parallel sections of the tube, one of which receives the gas under investigation. The difference in conductivity between the two sections of the tube indicates the

concentration of the component reacting with the solution. Using a suitable solution, this instrument can also be used for determining other atmospheric pollutants.

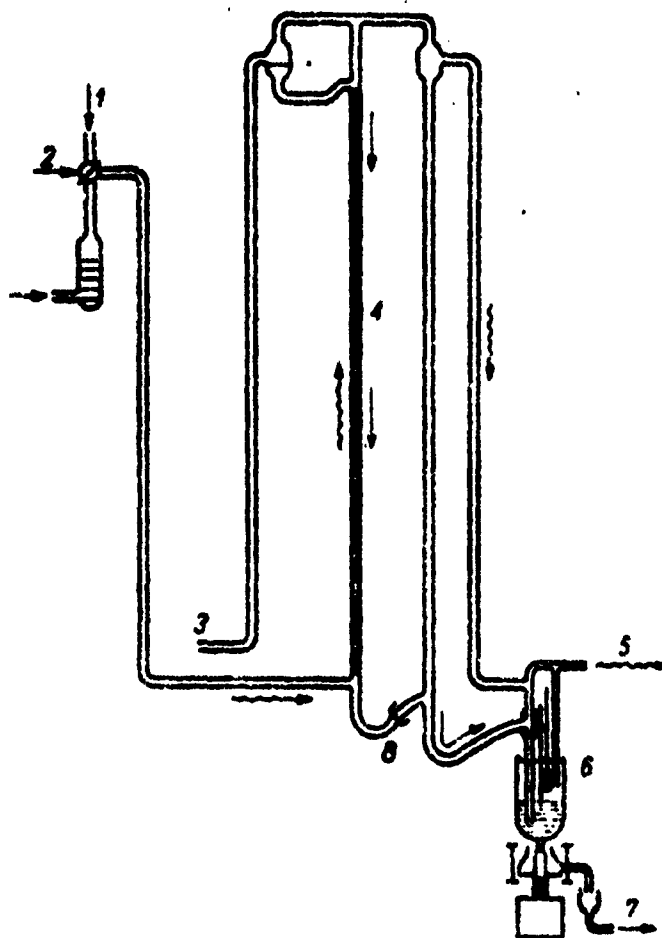


Fig. XI,4. A diagram of the Autometer instrument. 1. Air intake; 2. Valve; 3. Liquid feed; 4. Absorption column; 5. Air outlet; 6. Solution container; 7. Spent solution outlet; 8. Site of conductivity measurement.

Fig. XI,6 shows a diagram of the Titrilog instrument (XI.1). In this instrument the SO_2 contained in the gas stream is absorbed in a dilute solution of bromine in a vessel called the electrolyzer.

A popular method of simplified determination of the SO_2

concentration in air depends on the phenomenon of SO_2 absorption on PbO_2 with the formation of the insoluble lead sulfate. The amount of lead sulfate formed is proportional to the active surface area of PbO_2 and exposure time, and can provide the measure of the SO_2 content in air.

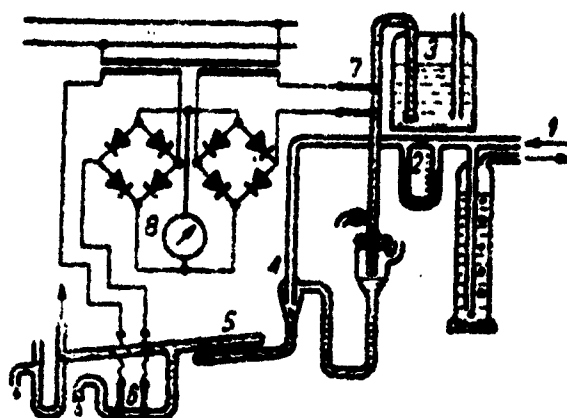


Fig. XI,5. A diagram of the Jonoflux instrument. 1. Air intake; 2. Gage; 3. Vessel with solution; 4. Mixing chamber; 5. Section of tube in which the reaction takes place; 6. Measurement section; 7. Control section; 8. Electric indicating or recording section.

The sampling using this method is carried out by periodically exposing porcelain cylinders coated with a PbO_2 paste to the action of air. After exposure, the amount of absorbed SO_2 is determined in the following manner. The paste stripped from the cylinders is boiled in a solution of sodium carbonate, converting lead sulfate to the soluble sodium sulfate. After filtering off the insoluble lead oxide, the solution is acidified with HCl and the sulfate is precipitated with barium chloride. Then the solution is filtered off, the filter with barium sulfate is dried and calcined, and the BaSO_4 is determined gravimetrically and re-calculated into SO_2 . The SO_2 content is expressed in $\text{mg/cm}^2/\text{day}$.

The results obtained by the PbO_2 method can be approximately recalculated in terms of the absolute mean SO_2 concentration in air, and expressed in mg/m^3 , but the recalculation coefficient varies with meteorological conditions. The ability of SO_2 to react with PbO_2 depends on the method of preparation of the latter, on atmospheric humidity, and on wind velocity.

Hydrogen sulfide is a very toxic gas with an unpleasant odor.

Its boiling point is -61.8°C .

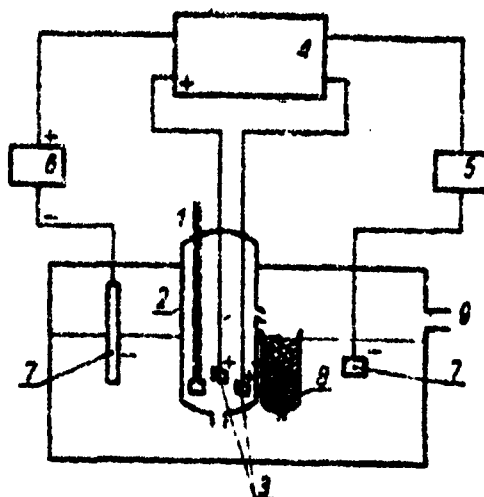


Fig. XI,6. A diagram of the Titrilog instrument. 1. Air intake; 2. Electrolyzer; 3. Positive electrodes; 4. DC amplifier; 5. Recording milliammeter; 6. Voltmeter; 7. External negative electrodes; 8. Charcoal filter; 9. Outlet tube.

The maximum permissible single concentration of H_2S in air 0.03 mg/m^3 . It is partly oxidized in air to SO_2 .

Hydrogen sulfide can be determined colorimetrically. A sample of gas is passed through a 1% solution of zinc oxide. After adding p-aminodimethylaniline and ferric chloride, the solution assumes a blue color in the presence of the sulfide ion. Hydrogen sulfide can also be determined by the automatic methods used for the determination of SO_2 .

3.2. Hydrogen Fluoride

Fluorine as an air pollutant is present mainly in the form of HF and fluorides. HF is a poisonous liquid with strongly corrosive properties. In view of its low boiling point (19.4°C), it is readily emitted into the atmosphere as a vapor. Its maximum permissible concentration is 0.03 mg/m^3 , but such concentrations are never found in the atmosphere. Hydrogen fluoride is particularly dangerous because it is a cumulative poison.

Sensitive analytical and colorimetric methods must be used because of the low concentrations of HF in air.

Fluorine can be determined automatically using the Autometer instrument.

3.3. Chlorine and compounds

Chlorine is present in the atmosphere in the free form (Cl_2), as well as in the form of organic (perchloroethylene) and inorganic (HCl) compounds. Under normal conditions, the chlorides are solid and are present in the atmosphere as particulates. The other compounds are gaseous.

The main harmful action of chlorine and its compounds is in the irritation of the respiratory tract and in acceleration of metal corrosion.

The maximum permissible concentration is 0.1 mg/m^3 chlorine and 0.05 mg/m^3 of HCl . The concentrations of chlorine and compounds in the atmosphere vary between 0.016 and 0.1 ppm . Some compounds of chlorine are dangerous even in low concentrations. Among these are the lachrymators (chloroacetophenone) and poison gases (phosgene). The lachrymatory properties of some compounds are so strong that they are manifested at concentrations of 0.001 ppm .

Free chlorine in the atmosphere can be determined colorimetrically in a solution of o-toluidine. Chlorine and water-soluble chlorides can be determined by passing the gas through a dilute solution of sodium hydroxide, followed by a gravimetric or volumetric determination.

3.4. Oxides of nitrogen

Theoretically, seven oxides of nitrogen can be present in the atmosphere: N_2O , NO , NO_2 , NO_3 , N_2O_3 , N_2O_4 and N_2O_5 , in addition to two acids: HNO_2 and HNO_3 . Only some of these oxides, namely: N_2O , NO , NO_2 and N_2O_5 are encountered in significant amounts in the atmosphere.

Nitrous oxide is one of the normal components of the atmosphere, and its concentration has been estimated at about 0.5 ppm . It is probably formed in the upper parts of the atmosphere as a result of the reaction of nitrogen with atomic oxygen or ozone. Since nitrous oxide is a gas of low activity, it is not considered as a pollutant in the above concentration.

Nitrogen oxide and dioxide, on the other hand, are dangerous pollutants. In air pollution analysis, they are usually described as the sum of nitrogen oxides. Their average concentrations vary between 0.10 and 3.48 ppm . The atmosphere may contain nitrates which

are formed through the oxidation of nitrogen oxide to nitrogen pentoxide which reacts to form nitric acid with water vapor, and then reacts with various metal compounds. Analysis shows the presence of nitrates at concentrations varying between 0.7 and 14.4 mg/m³.

The method most frequently used for determining nitrogen oxide is that based on phenolsulphonic acid. This method determines the total nitrogen (with the exception of N₂O) regardless of the type of compound.

Nitrogen dioxide can also be determined colorimetrically by passing a gas sample through the Griess reagent (XI.5). The sensitivity of this method is of the order of several 0.001 ppm at a flow rate of 0.4 liters/min maintained over 10 minutes.

Nitrogen oxides can also be determined spectrographically. UV spectrophotometers are used for determining nitrogen dioxide, while infrared spectroscopy determines the concentrations of nitrous oxide.

3.5. Carbon monoxide

Carbon monoxide is a colorless and odorless, strongly poisonous gas. It is the product of incomplete combustion of carbon and its compounds. In view of its strong affinity for haemoglobin, it has been classified as a suffocating gas. Its maximum permissible concentration in air is 1 mg/m³. Analysis of air samples from city streets and motor traffic tunnels has revealed CO concentrations of 90 ppm.

Carbon monoxide in the atmosphere is determined by colorometric methods. In one of the most common methods use is made of pure silica gel saturated with ammonium molybdate and a solution of palladium sulfate. The blue-colored molybdenum is formed in the presence of CO. There are also infrared spectrophotometers for determining CO.

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