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INDUSTRIAL DUST

*Hygienic Significance, Measurement,
and Control*

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INDUSTRIAL DUST

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PREFACE

Control of the dust hazard in industry is the joint duty of the physician and the engineer. In the preparation of this book we have emphasized the cooperative nature of the problem and have devoted considerable space to such of the medical aspects as may help the engineer to understand the manner in which hygienic requirements affect engineering design and operation of dust-control equipment.

So far as possible, only the basic principles are considered. The book is written from the engineer's standpoint but we hope it will be of some value to physicians who wish to understand more fully the engineering aspects of the problem. Design of dust control apparatus is an engineering matter, but it is often the physician who finally appraises the success of the control system.

Unfortunately, current practice in the field of industrial hygiene permits the indiscriminate mixing of British and metric units. Thus, fans are rated in cubic feet a minute but dust particles are measured in microns. We do not support these inconsistencies but have merely followed the usual nomenclature and practice in this book.

Many friends and colleagues in this country and abroad have helped us with this second edition. At our request some of them read critically various parts of the manuscript and others supplied technical material. We extend to them our sincere thanks for their help.

PHILIP DRINKER
THEODORE HATCH

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CHAPTER 1
PHYSICAL PROPERTIES OF DUSTS, FUMES,
AND MISTS

Suspensions of finely divided particles in air in the form of fogs and mists are common natural phenomena. Not so well-known, because it is generally not visible, is the dispersed system of atmospheric dust that extends over the face of the earth. It is only during unusual climatic conditions, such as those of 1935 in the Middle West, when atmospheric dust concentrations reached staggering levels (Fig. 1), or in the more recent Donora, Pa.,

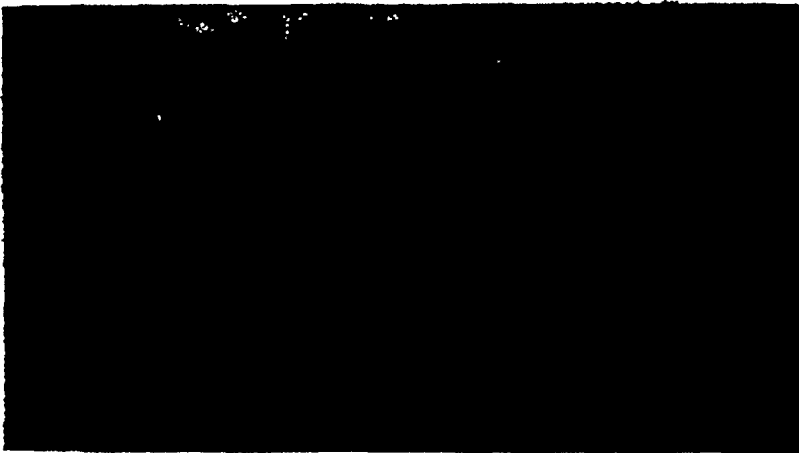


Fig. 1. Kansas dust storm, April, 1935. (Courtesy Boyce.)

incident (371), that the public becomes concerned with this phenomenon in a practical way. Within certain industries, on the other hand, contamination of the atmosphere with dust has long presented a problem, if not as a health hazard, then as a costly damaging agent against plant machinery or products. Even without producing measurable damage, dust constitutes a nuisance and creates poor working conditions.

In recognition of the hazards and cost of such contamination,

¹ Numbers in parentheses refer to corresponding items in the Bibliography on pp. 347-371.

the high levels of pollution of an earlier day have been largely reduced in the dusty trades. But the potential hazards remain, and the control of industrial dust continues as a never-ending battle. Beginning with empirical but common-sense measures, the dust-control program has now the benefit of considerable insight into the nature of dust hazards and is aided by quantitative methods for the measurement and evaluation of dust exposures. An understanding of the physical behavior of dust provides an increasingly sound engineering basis for the design of dust-control measures.

Some of the physical properties of dusts, fumes, and mists, which are important in a consideration of hazards, in the sampling and analysis of such materials, and in their control, are discussed in the present chapter. The subject is a large one and, in its theoretical aspects, has engaged the attention of physicists and chemists for many years. The application of the theoretical and experimental findings to the solution of practical problems, such as the subject of this volume, however, is relatively new. An outstanding contribution of a quarter century ago which brought together much scattered material was *Clouds and Smokes*, by W. E. Gibbs (183), now unfortunately out of print. This was followed in 1932 by *Smoke, A Study of Aerial Disperse Systems*, by Whytlaw-Gray and Patterson (442), and in 1943 DallaValle's *Micromeritics* (93) appeared. During World War II, as in World War I, extensive research added enormously to our understanding of the physical properties of finely divided matter in air, with direct and useful application to the study of industrial-dust problems. Much of this work has found its way into technical handbooks (245, 335). We shall have occasion to refer many times to these and other sources of basic information and shall be satisfied, here, to discuss the physical properties of dusts, fumes, and mists in only the briefest outline form.

Definitions. To all the various disperse systems in air, such as dust, fog, clouds, mist, fumes, and smoke, Gibbs (183) gave the general name *aerosol*, which is analogous to the accepted term *hydrosol* denoting disperse systems in water.

Dust is formed by reducing earthy materials to small size. Processes like grinding, crushing, blasting, and drilling produce dust particles of sizes from the submicroscopic to the visible, their composition being the same as that of the parent material.

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Common examples are the mineral dusts derived from the disintegration of rock and the organic dusts like wheat and flour.

Fumes are formed by processes such as combustion, sublimation, and condensation. Typical examples are the fumes from burning lead or the zinc oxide produced from zinc vapor. Particle size is generally below 1 μ . In contrast to dusts, fume particles often flocculate vigorously.¹

Smoke "presupposes a certain degree of optical density" (442). Generally it is of organic origin, but it may include systems consisting "of particles of low vapor pressure which settle slowly under gravity." We shall use the word with reference particularly to systems that are organic in origin, such as the smoke from burning tobacco, wood, oil, or coal. In general, smokes are characterized by a particle size below 0.5 μ .

Mists or *fogs* are formed by the condensation of water vapor upon suitable nuclei or by the atomization of liquids. Particle or droplet size varies widely depending on the conditions prevailing.

General Properties of Dusts, Fumes, and Mists. Disperse systems of dusts or other finely divided matter in air occupy a position with respect to size properties between the colloidal and the macroscopic regions. The particles are larger than those in colloidal systems; yet they are small enough to exhibit some of the properties of colloids and also to have properties not possessed by large masses of the substances from which they are generated.

When a solid or liquid is broken up into finely divided particles and is dispersed in the air, two important changes take place: (1) the surface area is greatly increased, and (2) the space occupied by the dispersed material is expanded many times over the volume of the original mass. Thus, if 1 cc of quartz is crushed into particles of 1 cu μ in size, there will be 10^{12} particles with a total surface area of 6 sq m as compared with 6 sq cm for the original block. Assuming a dust concentration of 100 million particles per cubic foot of air, the 1 cc of material will be dispersed in an air volume of 10,000 cu ft.

The effect of these changes is to intensify the chemical and physical activity of the material. The rate of oxidation is increased so much that substances like soft coal and aluminum

¹ It is usual to speak of acid *fumes* as denoting a mixture of gas and mist. Throughout this book, however, we shall use the word to designate only solid particles.

powder burn in air with explosive violence. Rates of evaporation and solubility are also increased, and the phenomena of adsorption and electrostatic activity are intensified. The adsorption of a gas film on the particle surface may accelerate or retard chemical reactions, and it also interferes with physical phenomena such as wetting. Since the physiological effect of dust particles always is intimately associated with their physical and chemical activity, small particles generally are of more physiological importance than large ones.

Similarity between Dusts and Liquids. Owing to the large amount of air adsorbed upon the surfaces of fine dust particles, a mass of such particles assumes some of the properties of liquids and gases. The mass can be compressed, and it splashes like a liquid when being carried in a pail. It can be poured through a pipe, and ripples are formed when a stone is dropped into a tank of dust.

Dust can be "distilled" by passing air through it; the amount carried over varies with the air velocity. A fixed rate of air flow will "evaporate" a constant amount, and the air will become "saturated." When the air speed reaches a certain critical value, the whole body of dust will be carried over, *i.e.*, the dust "boils." In these examples air velocity corresponds to temperature (293).

PARTICLE DYNAMICS

Like any other body, a microscopic particle is attracted toward the earth, but because of its relatively great surface area per unit of mass and the consequent high air resistance, an air-borne particle does not fall with increasing velocity according to the ordinary law of gravity. Almost immediately after it starts to fall, the air resistance imposed upon the particle balances the gravitational force, thus preventing further gain in speed. The particle then settles at its constant terminal velocity, which for microscopic particles is low, being measured in centimeters and even millimeters per hour. As a consequence, dust suspensions in air have considerable stability and may persist for long periods. Because of the great air resistance it is difficult to project microscopic particles through air and equally difficult to remove them from the air. In a sense, the finest particles become a part of the air itself.

The dynamic properties of microscopic particles are thus of the

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greatest importance in a consideration of dust hazards and their control. The characteristics of dust dispersion into the air, the spread of dust away from its source of generation or release, the control of dusty processes, and the problems of air cleaning are all intimately related to the dynamic behavior of air-borne dust. Physiologically, these properties are also of major concern for they largely determine the depth of penetration and degree of retention of inhaled dust in the respiratory tract and, hence, limit the lung-dosage rate in relation to air concentration and with it the dust hazard.

General Law of Resistance. Resistance to the travel of a particle through air varies with the size and shape of the particle, with its velocity, and with the fluidity of the air. These factors are combined in the following general equation:

$$R = \frac{C\rho Au^2}{2}$$

where R = resistance

C = coefficient of resistance

A = projected area of particle

u = particle velocity relative to air

ρ = air density

The drag coefficient C is not constant for all conditions of motion but varies systematically with the dimensionless Reynolds number $Re = ud\rho/\mu$, μ being the viscosity of the air and d the particle diameter. C also varies with the shape of the particle, the effect being different for different values of Re .

The relationship $C = f(Re)$, further simplified from the curves of Lapple and Sheppard (275), is shown for spheres in Fig. 2 for a range of Re from 10^{-4} to $>10^6$. The relationship has been divided into three zones according to the nature of dependence of C upon Re . For high values of Re ($>10^3$), C is reasonably constant and for spheres has an average value of 0.44. This is the zone of turbulent motion where the viscosity of the air has no effect. For this region, resistance varies with the squares of particle diameter and velocity (Newton) thus:

$$R = k\rho d^2 u^2$$

For spheres, $k = 0.44 \times \pi/8$. When $Re < 3.0$, however, C varies inversely with Re :

$$C = \frac{24}{Re}$$

and

$$R = k\mu u$$

For spheres, $k = 3\pi$. Here, resistance varies directly with particle diameter and velocity and with viscosity of the air but is independent of air density. It is the zone of streamline motion for which Stokes developed the foregoing equation.

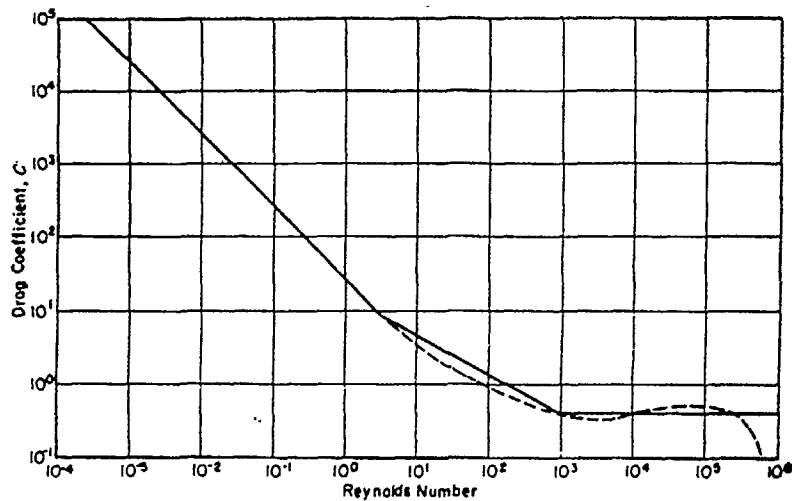


FIG. 2. Drag coefficient for spheres vs. Reynolds number. (Adapted from Lapple and Sheppard.)

In the intermediate zone, the C vs. Re relationship is a complex one, involving both μ and ρ as well as exponential values of d and u . The function has not been described mathematically except in an empirical way (5). An extensive treatment of particle dynamics is given by Lapple and Sheppard (275) in which the zone of intermediate motion is considered more precisely. Approximate relationships, however, with rounded exponents, are

$$C = \frac{14}{Re^{0.4}}$$

and

$$R = 5.5\rho^{1/2}\mu^{1/2}d^{3/2}u^{3/2}$$

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Terminal Settling Velocities. When a free-falling particle has attained its terminal velocity, the air resistance is just balanced by gravitational attraction. Consequently, for spheres,

$$\mathcal{R} = F_g = \frac{\pi}{6} d^3 (\sigma - \rho) g$$

where σ is the density of the particle and g the gravitational constant. For spherical particles, the terminal velocities in the three zones of motion are derived by equating resistance \mathcal{R} to the particle weight, as above (neglecting the unimportant buoyancy of air):

I. Streamline motion: $u_t = \frac{\sigma g d^2}{18\mu}$

II. Intermediate motion: $u_t = \frac{20(\sigma g)^{1/2} d}{(\rho \mu)^{1/2}}$

III. Turbulent motion: $u_t = \left(\frac{3\sigma g d}{\rho} \right)^{1/2}$

Simplifying these equations for spherical particles falling in air at ordinary temperature, $\rho = 1.2 \times 10^{-3}$, $\mu = 1.8 \times 10^{-4}$, we get, for velocity in centimeters per second and size expressed in microns,

I. Streamline motion:

$$u_t = 0.003 \sigma d_m^2 \quad \left(d_m < \frac{115}{\sigma^{1/2}} \right)$$

II. Intermediate motion:

$$u_t = 0.34 \sigma^{3/2} d_m \quad \left(\frac{115}{\sigma^{1/2}} < d_m < \frac{2130}{\sigma^{1/2}} \right)$$

III. Turbulent motion:

$$u_t = 16 \sigma^{1/2} d_m^{1/2} \quad \left(d_m > \frac{2130}{\sigma^{1/2}} \right)$$

The graph in Fig. 3 is for crushed-quartz particles which, owing to their irregular shapes, fall with lower velocities than do spheres of the same diameter. The settling velocities and certain other size properties of microscopic particles are further summarized in the chart (after W. G. Frank) in Fig. 4. For irregular mineral particles obeying Stokes' law it is convenient to recall this rough rule: the terminal velocity for a 10- μ particle is about 1 fpm

($\frac{1}{2}$ cm/sec) and for other sizes is given by the ratio $V_{\text{rpm}} = \frac{d_m^2}{100}$, where d_m is in microns.

Zone Limits. The turbulent zone extends down to $Re = 10^3$ which, for spheres of unit density, corresponds to a lower limiting size of about 2 mm; this also applies roughly to irregular mineral particles settling in air.

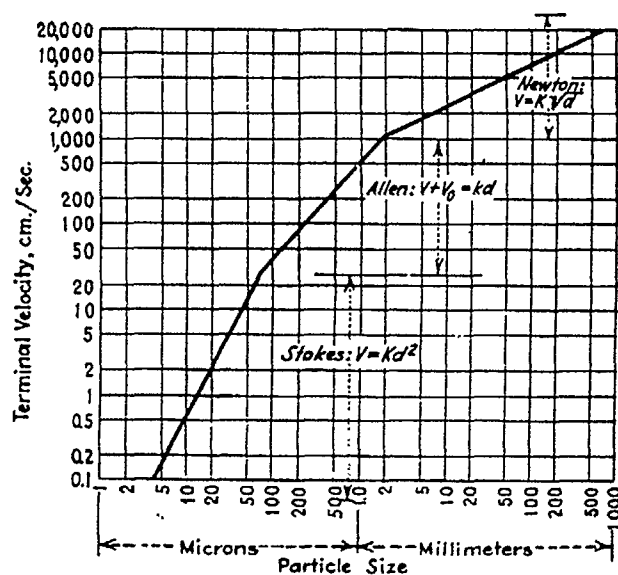


FIG. 3. Terminal velocity for quartz particles in air. (Adapted from Martin.)

The upper limit for the zone of streamline motion is defined by $Re = 3.0$, giving d for spheres of unit density a limiting value of 115μ ; for irregular mineral particles the upper limit is about 85μ . Thus, the intermediate zone for mineral particles falls between the approximate limits 85 to 2000μ .

The zone of Stokes' law also possesses a lower limit, for when the particles become small compared with the mean free path of the gas molecules, it is evident that resistance will decrease and, consequently, the terminal velocity increases over the calculated value from Stokes' equation. A suitable correction was developed by Cunningham, see Gibbs (183), thus:

$$u_c = u_s \left(1 + 1.7 \frac{\lambda}{d} \right)$$

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DIAM. OF PARTICLES IN MICRONS	SCALE OF ATMOSPHERIC IMPURITIES	RATE OF SETTLING IN F.P.M. FOR SPHERES OF DENSITY 1 AT 70° F.	NUMBER OF PARTICLES IN ONE CU. FT. OF AIR CONTAINING 0.0001 GRAMS OF IMPURITIES PER CU. FT. (DENSITY=1)	SURFACE AREA IN SQUARE INCHES	LAW OF SETTLING IN RELATION TO PARTICLE SIZE (LINES OF DEMARCATION APPROX.)
8000		1750			PARTICLES FALL WITH INCREASING VELOCITY
6000					
4000					$c = \sqrt{\frac{2gd_s}{3Ks_2}}$ c- Velocity cm/sec. C- Velocity ft./min.
2000		790	0.075	0.000365	
1000					$C = 24.9V\sqrt{D_s}$ d- Diam. of particle in cm. D- Diam. of particle in microns
800		555	0.6	0.00073	
600					STOKES LAW
400					
200		59.2	75	0.00365	$c = \frac{2r^2g}{9\eta} \frac{s_1 - s_2}{s_1}$ r- Radius of particle in cm. g- 981 cm./sec. ² acceleration s ₁ - Density of particle s ₂ - Density of Air (Very small relative to s ₁)
100		14.8	600	0.0073	
80					FOR AIR AT 70° F.
60		0.592	75000	0.0365	
40					$c = 300,460s_1d^2$ $C = 0.00592s_1D^2$ s ₂ - Density of Air (Very small relative to s ₁) η- Viscosity of air in poises = 1814 x 10 ⁻⁷ for air at 70° F.
20		0.148	600,000	0.073	
10					CUNNINGHAM'S FACTOR
8		0.007-5	75 x 10 ⁶	0.365	
6		0.002-4	60 x 10 ⁷	0.13	$c = c'(1 + K \frac{\lambda}{r})$ c'- c OF STOKES LAW K= 0.8 to 0.86 λ= 10 ⁻⁵ cm. (Mean free path of gas molecules)
4		0.0007-2	75 x 10 ⁹	3.65	
2		0	60 x 10 ¹⁰	7.3	PARTICLES MOVE LIKE GAS MOLECULES
0.8					
0.6					BROWNIAN MOVEMENT
0.4					
0.2					$A = \sqrt{\frac{RT}{N}} \frac{t}{3\pi\eta r}$ A- Distance of motion in met. R- Gas constant = 8.316 x 10 ⁻⁷ T- Absolute Temperature N- Number of Gas molecules in one mol = 6.06 x 10 ²³
0.1					
0.01					
0.001					

FIG. 4. Size properties of air-borne particulate matter. (After W. G. Frank.)

where u_c is the corrected velocity, u_s is calculated by Stokes' equation, and λ is the mean free path of the gas molecules (about 10^{-5} cm, under ordinary atmospheric conditions). For particles above $1/2 \mu$, the correction is negligible; there is a fivefold increase in settling velocity, however, for $0.05\text{-}\mu$ particles.

In free-air dust suspensions, the gravity settlement of sub-microscopic particles is of little importance and their movement is conditioned more by natural air currents in space. Diffusion is generally the controlling factor in the removal of submicroscopic particles from the air onto collecting surfaces.

Particle Acceleration during Free Fall. Microscopic particles falling in air accelerate from rest up to the terminal velocity within a very short distance. There is little interest, therefore, in considering the acceleration phase in an analysis of behavior of such particles during free fall. The terminal velocity may be applied to the entire height of fall. Larger particles, however, undergo acceleration over significant distances, and this zone must be properly described in many practical problems dealing with falling particles.

Acceleration in Laminar Zone of Motion. Particle acceleration at any instant equals the difference between the gravitational constant and the particle resistance per unit of mass, as derived from a balance of forces. Thus,

$$\frac{du}{dt} = \frac{u}{dh} = g - \frac{R}{M} = g \left(1 - \frac{u}{u_t} \right)$$

Integration leads to the following equation:

$$\frac{u}{u_t} = 1 - e^{-(gh + u_t u)/u_t^2}$$

where u is the particle velocity after falling distance h and u_t is the terminal velocity of the particle. This equation applies only to particles whose terminal velocities are in the streamline zone ($< 85 \mu$ for mineral particles falling in air).

Acceleration in Turbulent Zone of Motion. Coarse particles will pass through the streamline and intermediate zones of motion in the course of acceleration in a short distance, and for practical purposes the behavior of such falling bodies may be considered only in relation to the drag coefficient imposed in turbulent motion. Since the coefficient is taken as a constant (0.44), the velocity increases with distance according to the following equation:

$$\frac{u^2}{u_t^2} = 1 - e^{-h/h_t}$$

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where u , u_t , and h are as above and $h_t = u_t^2/2g$. In this equation it is assumed that the distance of fall required to reach $Re = 10^3$, the point of transition from the intermediate into the turbulent zone, is negligible. A more exact form of the equation recognizes the distance h_0 and corresponding velocity u_0 , which mark the beginning of turbulent motion:

$$\frac{u_t^2 - u^2}{u_t^2 - u_0^2} = e^{-(h-h_0)/h_t}$$

Acceleration in Intermediate Zone of Motion. Since the drag coefficient varies in a complex manner with Re throughout the intermediate zone of motion, a convenient statement of the relationship between velocity and falling distance cannot be written. Lapple and Sheppard (275) developed a method for constructing the u vs h curve over this zone based upon graphical integration of differential relationships. By this method a fraction k is derived which corrects the time of fall to reach any velocity, calculated on the assumption of streamline motion, to yield the actual time for any particle size and velocity.

The Lapple and Sheppard procedure makes use of the following equation:

$$\frac{3\mu}{4\sigma d^2} t = \frac{k}{C Re} \cdot \ln \frac{1}{1 - Z^2}$$

where

$$Z = u \sqrt{\frac{3\rho C}{4\sigma g d}} = Re \sqrt{\frac{C}{\phi}}$$

$$\phi = \frac{4\sigma g d^3 \rho}{3\mu^2}$$

The factor k has the values given in Table 1 for different values of Z^2 and ϕ as indicated. In use, a series of velocities are taken over the desired range up to the terminal velocity and the corresponding values of Re are calculated. Values of C are then obtained by reference to the chart, Fig. 2, and $C Re$ is determined. Finally, Z^2 is calculated for each velocity and corresponding values of k are obtained from Table 1. These serial values of $C Re$, Z^2 , and k together with the appropriate constants are then entered in the equation to calculate the time required to develop each of the successive velocities. From the time vs velocity

curve thus constructed, the relationship between u and h is readily obtained by graphical integration, keeping in mind that

$$h = \int u dt$$

Calculations of velocity of fall of a 3-mm particle are given in Table 2 in accordance with the Lapple and Sheppard procedure, and results are plotted in Fig. 5 together with a similar curve calculated for a 1-mm particle. For comparison with these

TABLE 1. VALUES OF k FOR FREE-FALLING SPHERICAL PARTICLES

Z^2	Values of k at the following values of ϕ							
	10	50	100	1000	10^4	10^5	10^6	10^7
0.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.10	1.00	1.000	0.998	0.995	0.990	0.987	0.985	0.982
0.20	1.00	0.999	0.995	0.990	0.983	0.976	0.970	0.964
0.30	1.00	0.995	0.990	0.982	0.975	0.963	0.952	0.945
0.40	1.00	0.991	0.984	0.973	0.965	0.947	0.933	0.924
0.50	1.00	0.987	0.976	0.961	0.950	0.930	0.912	0.900
0.60	1.00	0.982	0.967	0.947	0.933	0.907	0.886	0.872
0.70	1.00	0.976	0.955	0.928	0.909	0.880	0.857	0.840
0.80	1.00	0.968	0.941	0.905	0.877	0.845	0.821	0.801
0.85	1.00	0.964	0.934	0.890	0.858	0.826	0.799	0.778
0.90	1.00	0.960	0.924	0.875	0.835	0.800	0.770	0.748
0.95	1.00	0.953	0.913	0.856	0.807	0.768	0.734	0.708
0.98	1.00	0.948	0.905	0.841	0.785	0.743	0.700	0.668
0.99	1.00	0.946	0.902	0.836	0.775	0.730	0.680	0.645
1.00	1.00	0.943	0.900	0.830	0.760	0.700	0.600	0.500

Source: After Lapple and Sheppard (275).

calculated relationships, the straight line indicates the theoretical fall *in vacuo*.

Triangles plotted on the 3-mm curve and circles accompanying the 1-mm curve represent values calculated by the equation for acceleration in the turbulent zone, using in each case, however, the correct terminal velocity. Terminal fall is in the turbulent zone for the 3-mm particle, but for the 1-mm particle the motion does not exceed the intermediate zone. The agreement is satisfactory for the 3-mm particle since the shift from intermediate to turbulent motion occurs at an early point in the fall. Even for the 1-mm particle, the error in the assumption of turbulent motion is not great.

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TABLE 2. CALCULATION OF FREE-FALLING VELOCITY OF 3-MM MINERAL PARTICLE

 $u_i = 1400 \text{ cm/sec}; u_i^2 = 1.96 \times 10^6; \phi = 3.4 \times 10^4; \text{Re} = 2u_i; \frac{3\mu}{4\rho d^2} = 5.7 \times 10^{-4}$

u	Re	C	$C/\phi \times 10^4$	Z^2	$2.3 \log \left(\frac{1}{1-Z^2} \right)$	K	$\frac{K \times 10^4}{5.7C \text{ Re}}$	t	$u \Delta t$	h	$u^2 \times 10^{-4}$
150	300	0.64	0.19	0.019	0.023	0.998	9.1	0.21	16	16	0.022
300	600	0.50	0.15	0.054	0.057	0.992	5.8	0.33	27	43	0.090
500	1000	0.44	0.13	0.130	0.142	0.975	3.9	0.55	88	131	0.250
700	1400	0.44	0.13	0.255	0.255	0.958	2.73	0.78	138	289	0.490
900	1800	0.44	0.13	0.420	0.542	0.917	2.03	1.11	264	533	0.810
1100	2200	0.44	0.13	0.630	0.99	0.863	1.57	1.55	440	973	1.210
1300	2600	0.44	0.13	0.880	2.11	0.752	1.16	2.45	1080	2053	1.690

Dynamic Projection. Dust particles generated by industrial processes are dispersed into air by virtue of the kinetic energy imparted to them initially during formation or release. Neglecting gravitational and other field effects, a particle is projected in a straight line through the air for a distance which depends upon its mass and initial velocity u_0 and upon the air resistance. Thus,

the loss in kinetic energy with distance equals the integrated product of air resistance and distance:

$$-M \int_{u_0}^u u \, du = \int_0^h \mathcal{R} \, du$$

For large particles in the turbulent zone, $\mathcal{R} = 0.44 \times \pi/8\rho u^2 d^2$ and

$$u^2 = u_0^2 e^{-h/h_0}$$

According to this relationship, a 2-mm particle thrown into the air with an initial velocity of 5000 cm/sec would travel 2200 cm, or 70 ft, neglecting gravity, before its speed is reduced to the limit of the turbulent zone (about 1000 cm/sec for a 2-mm quartz particle).

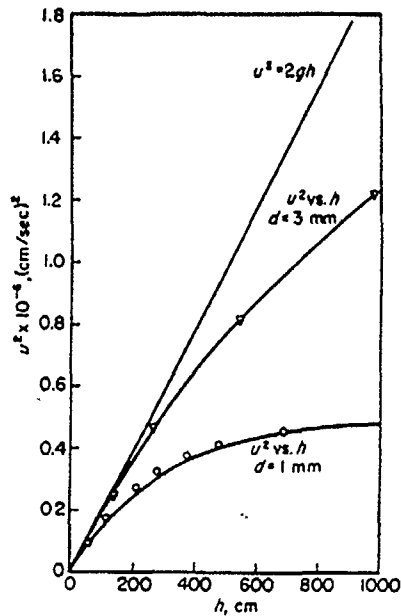


FIG. 5. Particle velocity vs. height of fall, compared with $u_{th} = \sqrt{2gh}$.

In the streamline zone, on the other hand, $\mathcal{R} = 3\pi\mu \, du$ and

$$u = u_0 - \frac{gh}{u_0}$$

A 10- μ particle with an initial velocity of 5000 cm/sec will, by this relationship, come to rest in about 4 cm,* and a 1- μ particle will be projected through still air scarcely any distance at all (0.4 mm) before its kinetic energy is entirely exhausted.

The conclusions from these calculations are of very great significance in the study of dust dispersion in industry and in the

* The distance will be somewhat greater in fact because the beginning motion of the particle will be in the intermediate zone.

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design of dust-control measures (212). They demonstrate the important fact that the spread of microscopic particles beyond their source into the workroom air is not dependent upon the kinetic energy of the particles; such dispersion takes place only by movement of air away from the dust source. The stream of sparks flying away from a grinding wheel is an example of dynamic projection of coarse particles. These are of no hygienic importance, however, because of their size and are of concern in the control of dust hazards only to the extent that microscopic particles are carried along in the air stream set up by the drag of the relatively large fragments. Fundamentally, therefore, dust-suppression measures involve the control of air movement around dust sources and are not directed toward the dust itself. This point is considered more fully in Chaps. 12 and 13.

Stirred Settling. Under still-air settlement, particles of a given size are removed from the air by gravity at a constant rate. With complex vertical mixing of the air such as naturally occurs in open rooms, however, this is not true and the rate of removal decreases with time. We may write, for perfect mixing,

$$\frac{dn}{n} = \frac{u}{h} dt$$

$$n = n_0 e^{-(u/h)t}$$

where n = number concentration of particles in the air at time t

$n = n_0$ at $t = 0$

h = height of settlement chamber

u = settling velocity

Both the rate of settling (number removed per unit time) and the concentration decrease exponentially with time. The relationship may be employed to determine settling velocity and the particle size of the suspension from simultaneous measurements of n and dn/dt .

Brownian Motion. The mass of a microscopic particle is so small that it is driven about in the air by the buffeting action of the gas molecules. Under equilibrium conditions the vectorial sum of molecular blows is zero, and there is no net motion of the particle in any direction. This oscillating behavior is known as *Brownian motion*, which has been described mathematically by Einstein in the following terms:

$$A = \sqrt{\frac{RT}{N} \cdot \frac{t}{3\pi\mu d}}$$

where A = amplitude of motion in a given time t

R = gas constant

N = Avogadro's number

T = absolute temperature

Brownian motion increases in magnitude with decreasing particle size in contrast to the decrease in gravitational settlement. It is evident, then, that for some given size the combined

TABLE 3. COMPARATIVE PARTICLE VELOCITIES DUE TO GRAVITATION AND MOLECULAR IMPACT IN RELATION TO PARTICLE SIZE

Particle diameter, μ	Gravitational settling velocity, cm/sec	Molecular impact velocity, cm/sec
0.002	12×10^{-3}	6.3×10^{-3}
0.01	3×10^{-4}	2.8×10^{-3}
0.02	12×10^{-6}	2.0×10^{-3}
0.10	3×10^{-4}	8.9×10^{-4}
0.2	12×10^{-4}	6.3×10^{-4}
1.00	3×10^{-3}	2.8×10^{-4}
2.00	12×10^{-3}	2.0×10^{-4}

Source: After Gibbs (183).

effect of the two upon particle movement is minimum, the relative instability increasing on one side with increasing gravitational effect and on the other with greater molecular impact. Gibbs (183) gives the comparative values in relation to size for silver particles shown in Table 3.

It will be observed that gravitational and molecular-impact velocities are about the same for particles of 0.2- μ diameter and that molecular velocity is higher for the smaller particles. This point of minimum activity at a particle diameter of about 0.25 μ has great practical importance in the consideration of dust behavior. It represents, for example, the most difficult particle size to remove from the air by filtration or by retention in human lungs. Smaller as well as larger particles are captured more efficiently.

Movement in Centrifugal Field. Particles moving in a rotating gas stream are subjected to the centrifugal force which drives them away from the center of rotation. The centrifugal force is given by

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$$F_c = \frac{\pi}{8} d^2 (\sigma - \rho) r \omega^2$$

where ω is the angular velocity in radians per second and r the radius of curvature of the path. Equating F_c and \mathcal{R} to give the terminal centrifugal settling velocity, we get, for the streamline zone,

$$u_c = \frac{r \omega^2}{18\mu} (\sigma - \rho) d^2$$

Comparing this with the gravitational settling velocity, for the same type of flow, the following relationship is obtained:

$$u_c = \frac{r \omega^2}{g} u_g = \frac{v^2}{rg} u_g$$

where v is the linear velocity of the rotating gas stream. The term v^2/rg is called the *separation factor* (285) since it measures the effectiveness of centrifugal force as compared with gravity for the removal of particles from a gas stream. In cyclone design, for example, it is evident that the radius should be small and the gas velocity high (see Chap. 14). Starting with the equations of motion in a centrifugal field, Davies (103) gives the following relationship for calculating the time required for a microscopic particle to move radially from R_1 to R_2 :

$$\Delta t = \frac{R_2^4 - R_1^4}{4PV_0R_2^3}$$

where R_1 and R_2 = inner and outer radii of the gas stream

V_0 = linear velocity of rotation

P = dimensionless parameter

$$P = \frac{(\sigma - \rho) d^2 V_0}{18\mu R_2} = \frac{u_c V_0}{g R_2}$$

By equating t to the time of descent in a cyclone of normal design, Davies derived the following for the minimum size particle removed by the centrifugal force:

$$d_{\min} = \frac{36\mu R_2}{8(\sigma - \rho)V_0 H / R_2} \left[1 - \left(\frac{R_1}{R_2} \right)^4 \right]^{1/2}$$

where H is the cyclone height.

Impingement. Particles collect on the surface of an obstruction around which dust-laden air flows. This is a form of centrifugal precipitation resulting from the inertial resistance of the particle to change in its direction of travel in conformance with the streamlines of the flowing air. It is evident that the strength

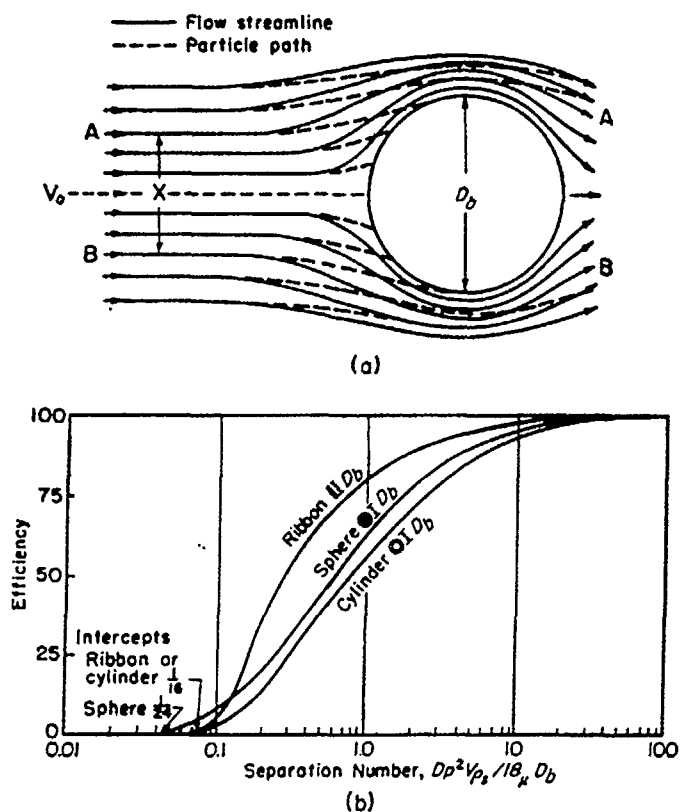


FIG. 6. (a) Mechanism of impaction and (b) efficiency of impingement on ribbon, sphere, and cylinder. (After Lapple, Ref. 335.)

of the precipitating force will vary with the kinetic energy in the particle (mass and velocity), with the air resistance imposed upon the particle, and with the sharpness with which the air flow breaks around the obstruction. Assuming that all particles which come in contact with the surface are retained, then the efficiency of collection is proportional to the ratio x/D_b as shown in Fig. 6. Davies (103) presents the following relationship between efficiency E and the dimensionless ratios:

$$E = f\left(P, \text{Re}, \frac{d}{D_b}\right) = f\left(\frac{u_i V_0}{g D_b}, \frac{V_0 D_b \rho}{\mu}, \frac{d}{D_b}\right)$$

A high air velocity increases both P and Re . For large values of D_b , Re is also increased, but this is more than offset by the lessened values of P and d/D_b . Therefore, the finer the obstruction, for example, the fiber in an air filter, the higher is the efficiency of collection. For obstructions of simple geometric shape, such as a cylinder or sphere, the pattern of streamlines and, hence, the ratio x/D_b can be derived from classical hydrodynamics, but experimental determinations are required for complex shapes. Efficiency curves derived for three simple obstructions in a laminar-flow stream, for microscopic particles, are shown in Fig. 6 (335, 271). Application of these relationships to design and to the analysis of performance in certain types of air-cleaning apparatus is considered in Chaps. 14 and 15. In filtration, the collection of submicroscopic particles depends upon diffusion rather than inertial impingement (see Chap. 15).

A special application of inertial impingement is seen in the design of a number of dust-sampling instruments in which the dust-laden air is discharged through a nozzle at high velocity against a closely positioned collecting plate. The sharp 90-deg bend in the air stream creates a strong centrifugal field, resulting in the deposition of particles in proportion to the dimensionless parameter:

$$P = \frac{\sigma d^2 v}{18 \mu h} = \frac{u v}{g h}$$

where v is the jet velocity and h is one-half nozzle width (301). The design and performance of impinging instruments in relation to basic physical relationships is considered in Chap. 8.

Movement in an Electric Field. Here the force of attraction is the electric gradient acting upon charged particles, and this may be equated to the air resistance to give the precipitation velocity in the streamline zone:

$$F_e = Ene = 3\pi\mu du$$

$$u = \frac{Ene}{3\pi\mu d}$$

where E is the field strength in electrostatic units per centimeter and ne the charge on the particle.

For particles larger than 0.5μ , for which the charging process is rapid, Davies gives the following relationship from Rohmann (351) and Ladenberg (266) between charge and particle size:

$$ne = \frac{E_0}{4} \left(1 - 2 \frac{\epsilon - 1}{\epsilon + 2} \right) d^2$$

where E_0 is the field in the charging space and ϵ the dielectric constant of the particle. For conducting particles this becomes

$$ne = \frac{3E_0 d^2}{4}$$

In the case of smaller particles Davies states that a full theory is lacking, but for small currents and moderate strength

$$ne = 4.25 \times 10^{-4} d$$

From these relationships we have, for large particles,

$$u = \frac{pE^2 d}{12\pi\mu}$$

where

$$p = 1 - 2 \left(\frac{\epsilon - 1}{\epsilon + 2} \right)$$

and for small particles ($< \frac{1}{2} \mu$)

$$u = \frac{9.5 \times 10^{-4} E}{6\pi\mu}$$

These equations give the values of precipitating velocity in relation to particle size shown in Table 4.

TABLE 4. ELECTRIC PRECIPITATING VELOCITY IN RELATION TO PARTICLE SIZE

Conducting particles in a field with $E = 10$ esu (3000 volts/cm)

Particle Radius	Velocity, cm/sec
100	885
10	88.5
1	8.85
0.1	0.88
All sizes (small)	2.8

Source: After Davies.

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Thermal Precipitation. The presence of a clear area around a hot rod in dust-laden air was demonstrated by Aitken (3) who showed that smoke could be removed quantitatively from air passing through a hot-cold tube, the smoke precipitating on the cold surface. The precipitating force, according to Cawood (72), results from the decrease in concentration and velocity of the gas molecules along a temperature gradient. Equating the excess momentum acting on the upstream side of the particle to the air resistance, Cawood obtains the following relationship for thermal precipitating velocity:

$$u = \frac{p\lambda d}{24\pi T} \left(1 + 1.7 \frac{\lambda}{d} \right) \frac{dT}{dx}$$

where p = gas pressure

T = absolute temperature

dT/dx = uniform thermal gradient in hot-cold space

The dependence of u upon the particle diameter in the equation is not correct, according to Cawood, but results from a basic assumption made in the formulation respecting convection currents. For particles of microscopic size ($>\lambda$), Davies (103) gives the following equation:

$$u = \frac{0.036}{T} \frac{dT}{dx}$$

The thermal force is small, and to secure a significant precipitating velocity, dT/dx must be made high. This is accomplished in the dust-sampling thermal precipitator (Chap. 9) by making the distance x very small.

Thermal precipitation accounts in part for the blackening of cold walls above radiators and for the pattern of dust deposit on plastered ceilings. It has not been applied to large-scale air cleaning, although it is employed commercially for the collection of lampblack.

FLOCCULATION

Dusts from materials like quartz and marble differ from fumes (magnesium oxide, for example) in their flocculating characteristics. Freshly formed discrete particles of magnesium oxide are often below 0.1μ in size and therefore exhibit violent Brownian motion in air. This increases their frequency of collision, with the consequent formation of flocculated masses. Whytlaw-Gray

and others (442) showed that the rate of flocculation in still air is predictable and that suspensions of such fumes clear up rapidly owing to the formation of flocs with sufficient mass to settle. Particulate masses of fumes also tend to stick rather tenaciously to vertical walls and other surfaces with which they collide.

The time course of flocculation in a homogeneous smoke, measured by the decrease in the number of separate particles in the suspension, is given by the relationship (442)

$$-\frac{dn}{dt} = kn^2$$

$$\frac{1}{n} - \frac{1}{n_0} = kt$$

where n is the number concentration at time t and k is a constant which is independent of particle size and concentration,¹ having the calculated value of about 3×10^{-10} cc/sec and a somewhat larger value in experimental clouds. Expressing the coagulation rate as the percentage decrease in number concentration per hour (245)

$$-100 \frac{dn}{n} = 1.08 \times 10^{-4} n$$

it is seen that, with dust concentrations ordinarily encountered, the rate of flocculation is negligible; thus, with an extreme dust concentration of $n = 10^4$ per cubic centimeter (300 million per cubic foot), it amounts to only 1 per cent per hour. For typical industrial dusts this concentration would exceed 100 mg/cu m. In contrast, a fume with a particle size of 0.1μ will undergo 50 per cent flocculation in the same time when the weight concentration is no more than 1 mg/cu m. These differences in particle size and concentration of industrial dusts as compared with fumes explain the relative unimportance of flocculation in dust clouds. As a dust cloud clears up, the size of the particles remaining in suspension decreases and the degree of dispersion increases, *i.e.*, the ratio of flocculated to discrete particles becomes less. Con-

¹ In the region below Stokes' law, the Cunningham correction introduces a particle-size effect and the change in particle size of flocs with time causes k to vary also with concentration. In a heterogeneous smoke, the particle-size distribution has additional effect on k . The shape of the particle has negligible influence.

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versely, the percentage of flocs and their size both increase with the age of a metallic fume cloud. This difference between dusts and fumes is nicely demonstrated by Brown's photographs (58) in Fig. 7.

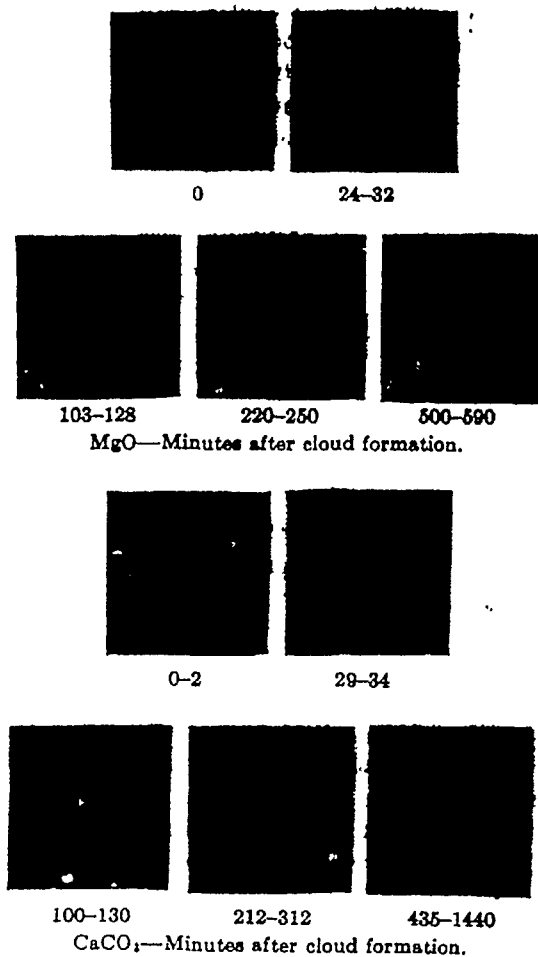


FIG. 7. Variation in particulate size of magnesium oxide and calcium carbonate with age of cloud. (After Brown, courtesy J. Indust. Hyg.)

The foregoing considerations have to do with direct flocculation in air. There is another and quite different source of dust flocculation which has considerable practical importance. This is related to the origin of the dust cloud and the way it is dis-

persed into the air. We may properly distinguish between true dust-generating processes, wherein microscopic particles are formed from larger masses and are immediately distributed into the surrounding air, and the simple dispersion of dust from a bulk of previously ground material. In the first case, the degree of flocculation in the dust cloud will be subject to the foregoing law and thus limited by the concentration. A cloud formed by

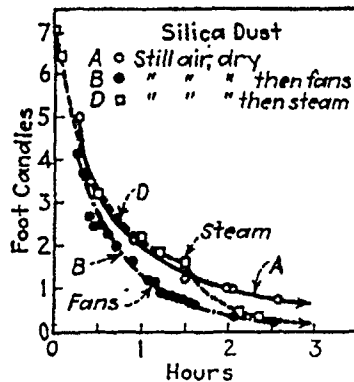


FIG. 8. Effects of turbulent air motion and of steam jets (local humidification) on the stability of silica dust clouds. Dry air refers to normal room air with about 60 per cent relative humidity—not chemically dried air. (Courtesy *J. Indust. Hyg.*)

simple dispersion, on the other hand, may exhibit a marked degree of particle aggregation simply because these aggregates, naturally present in the original bulk material, are not broken up in the dispersing process. The aggregates are tenacious, and a high degree of dispersion from bulk is therefore obtained only with a considerable expenditure of energy. The dust generated by pneumatic chisels in stone-cutting, for example, is relatively highly dispersed, whereas the cloud arising during the handling from storage and packaging of previously ground silica is characterized by considerable flocculation.

Aggregates of fine particles take on the dynamic properties of equivalent large particles. Hence, they are relatively easily removed from the air and, when inhaled, are retained in the upper respiratory tract. A dust cloud formed by simple dispersion from bulk is inherently less dangerous, therefore, than the same concentration produced by a true dust-generating process.

This practical aspect of dust flocculation has received too little attention in the analysis of dust hazards. No quantitative distinction is ordinarily made between the relative degrees of aggregation in dust clouds, despite the fact that very marked differences of considerable physiological importance do exist (218).

The Effect of Air Motion and Humidification upon Flocculation. Turbulent air motion accelerates the formation of flocs owing to

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greater frequency of collision as compared with the rate in still air (417). This applies to suspensions of fumes and mists which flocculate easily, but no great improvement is observed with true dusts. Thus, in Figs. 8 to 10 are shown the comparative effects

of air motion upon the settling rates of dusts, fumes, and smokes. Commenting upon these curves, Drinker, Thomson, and Finn (129) state that "turbulent air motion was found to have no effect on silica dust, a marked effect on freshly generated zinc

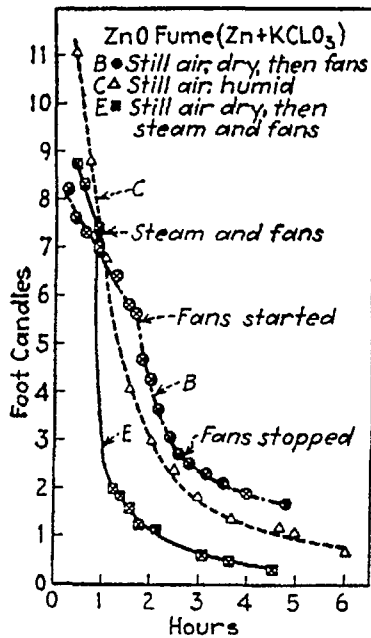


FIG. 9. Stability curves of zinc oxide fume made by exploding zinc powder and potassium chlorate. Note the effects produced by turbulent air motion and by steam jets. Both cause the particles to aggregate into units large enough to fall out of the suspensions. (Courtesy J. Indust. Hyg.)

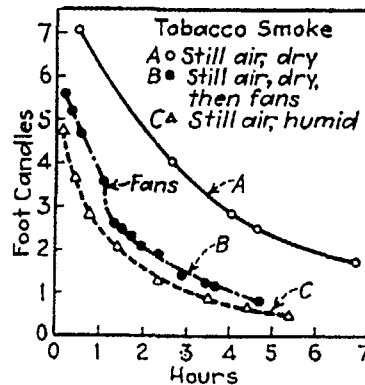


FIG. 10. Stability curves of tobacco smoke. Air motion appears to exert less effect on tobacco smoke than on zinc oxide (see Fig. 9). Curve C represents air saturated with moisture before the smoke was introduced—i.e., general humidification. (Courtesy J. Indust. Hyg.)

oxide, and a considerable effect on tobacco smoke." A fume of lead particles, which do not flocculate vigorously, probably would not be greatly affected by air motion.

Variations in the humidity of the air below saturation have no effect upon the stability of aerosols. It is sometimes alleged that dustiness in a factory is worse on still, humid days than in dry weather because of the greater stability of the dust cloud. We have never seen figures to substantiate this claim; it may have arisen from the fact that dustiness is far more apparent in wet

than in dry weather and also from the fact that the greater air movement on dry days carries away more dust.

Supersaturating the atmosphere with moisture does have a noticeable effect upon suspensions of dusts and fumes owing to the fact that the particles act as nuclei upon which the moisture condenses. The application of live steam in air cleaning is more effective than a water spray. In Figs. 9 and 10 is shown the rapidity with which clouds of zinc oxide and tobacco smoke can be cleared up with steam. In contrast to this, Warren (436) found the efficiency of water blasts for cleaning mine air to be only 62 per cent. During dry drilling, external water blasts do not improve conditions, according to Harrington (206), while Gray (188) states that water blasts and sprays fail to bring down the really fine dust.¹

OPTICAL PROPERTIES

The presence or absence of suspended dust in the air is easily demonstrated by directing a beam of light through a darkened room containing the dusty air. The beam will not be revealed unless there are suspended solid or liquid particles to reflect the light. This test, which was first used by Tyndall in his classic studies of atmospheric pollution, is one of great sensitivity.

The optical behavior of an aerosol varies with the nature of the suspended material, such as its transparency and shape, but it is influenced to a greater degree by the size of particles in the suspension. Distinction may be made in this connection between two classes of particles: those larger than the wavelength of light, which reflect and refract light according to the general optical laws, and a second group containing particles sensibly smaller than the wavelength of light. These particles scatter light in all directions with an intensity that varies with the wavelength of the light; the light is polarized to a considerable extent. The light scattered by large particles is also polarized to some extent in a plane perpendicular to the incident beam.

Particles Larger than the Wavelength of Light. Tolman (414) has shown that the intensity of light reflected by particles larger than 0.6 to 0.7μ is given by the equation

¹ See Chap. 16 for a discussion of spray-type air cleaners.

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$$I = \frac{kc}{d}$$

where I = intensity of reflected light
 c = concentration (weight) of dust per unit volume
 d = particle size

Since

$$c = \frac{\pi}{6} d^3 \sigma n$$

where σ = density of dust particles
 n = number of particles per unit volume of the suspension
 we may write

$$I = k'nd^2$$

where k' includes several physical constants pertaining to the dust. Thus, the strength of the Tyndall beam varies directly

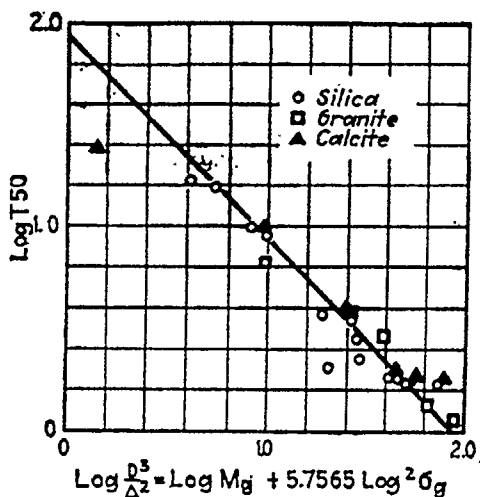


FIG. 11. Relation between tyndallmeter reading and particle size expressed in terms of M_g and σ_g . (Courtesy J. Franklin Inst.)

with the surface area concentration of the particles in the suspension. For equal weight concentrations per unit volume, however, the strength of the beam varies inversely with size (Fig. 11).

Particles Smaller than the Wavelength of Light. In this region the intensity of the beam varies, according to Rayleigh,

with concentration, size, and wavelength of the incident beam in the following manner:

$$I = \frac{knd^6}{\lambda^4} = \frac{k'cd^3}{\lambda^4}$$

where λ = wavelength of light

Again, the intensity varies with the concentration of dust in the suspension. It is also influenced to a considerable degree by the wavelength of light; red rays, for example, are scattered with only one-twelfth the intensity of the rays at the short end of the spectrum. Conversely, the long rays are transmitted through a suspension to a greater degree than the violet rays. Hence, the Tyndall beam developed by minute particles appears blue in color when viewed at right angles and red when examined from the end. This explains the blue color of the sky, which is produced essentially by light scattered by gas molecules and minute particles, and the red at sunset, which comes to us by transmission through the dust atmosphere near the earth's surface.

For equal weight concentrations, the intensity of the scattered light increases rapidly with particle size to a maximum in the region corresponding to the wavelength of the incident beam and then decreases less rapidly with a further increase in size, the exponent of d changing from 3 to -1 . This is nicely shown in terms of the variation in strength of the transmitted beam with particle size (407) in Fig. 12.

A more complete theoretical treatment of the laws of light scattering by small particles was developed by Mie (313). During World War II, this was employed extensively in the optical study of homogeneous aerosols by La Mer and associates (245) who developed methods for determination of particle size and concentration, based upon the selective scattering and transmission of light of different wavelengths and the variation in degree of polarization with particle size. The method is limited, however, to the study of particles of uniform size and has little application to the study of heterogeneous industrial dusts.

Obscuring Power. The intensity of a light beam passing through a dust suspension when viewed on end decreases with an increase in the distance from the light source as well as with an increase in dust concentration. Simon and his coworkers (389)

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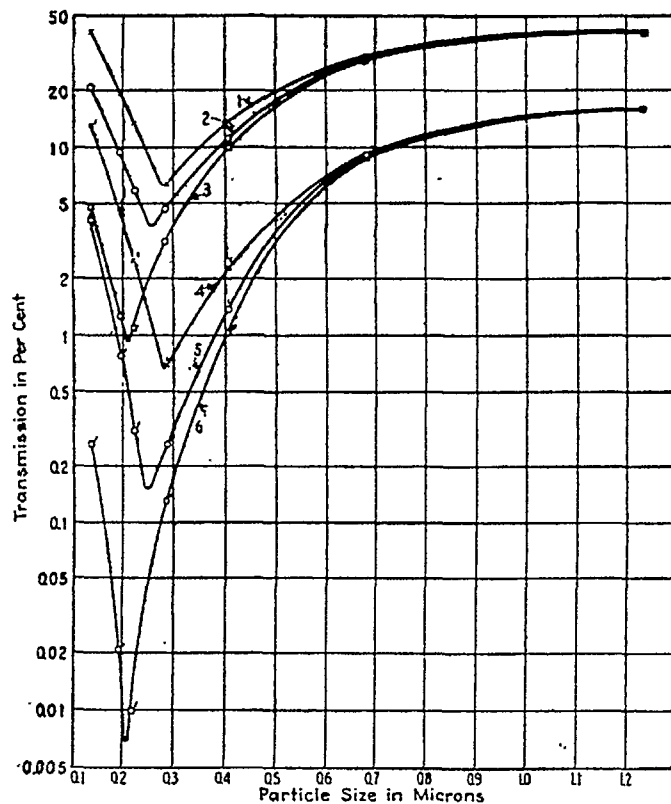


FIG. 12. Variation in light transmission with particle size. (After Stutz, courtesy J. Franklin Inst.)

have shown by theoretical considerations, assuming a suspension of opaque spherical particles of uniform size, that the intensity of light changes according to the logarithmic equation

$$L = L_0 e^{-n(\pi/4)d^2l} = L_0 e^{6ml/4\sigma d}$$

where L and L_0 = intensities of incident and emergent beams, respectively

l = length of path between points where L_0 and L are measured

n = number of particles per unit volume of air

m = weight concentration of dust per unit volume of air

σ = density of material of which the dust is composed

Written in another way, this relationship shows that the *percentage reduction in light* for a given column of the dust-laden air is constant, regardless of the intensity of the incident beam, and that the percentage value varies directly with the number of particles, length of path, and square of particle size.

The correctness of this theoretical equation was demonstrated by Simon (389), who describes a method of measuring the relatively heavy concentration of dust in blast-furnace gas based upon this equation.

It is frequently suggested that this phenomenon could be used as a simple method for determining the concentration of dust in an industrial establishment. The application of the above equation to a practical problem, however, indicates the fallacy of this contention. Assume a concentration of 10 million particles per cubic foot of air (350 particles per cubic centimeter) with a uniform diameter of 2μ , and determine the distance l necessary to reduce the light intensity only 5 per cent, *i.e.*, from 100 to 95. Entering these values in the above equation, we get

$$l = 47 \text{ m}$$

Obviously, this distance is too great for practical use, although to be effective any dust recorder must be sensitive to a degree as close as 10 million particles per cubic foot.

CHAPTER 2

EFFECTS OF DUSTS AND FUMES UPON MAN

Exposure to dusts can produce several distinct types of disability: (1) the pneumoconioses are caused only by dust inhalation; (2) systemic toxic effects are produced as the result of either breathing or swallowing of certain dusts such as lead and manganese; (3) metal-fume fever is caused by inhaling certain metallic oxide fumes; and (4) an allergic reaction, as typified by hay fever, is the direct result of breathing pollen or other organic substances. Dust inhalation is the usual cause of disability; only in the case of a few dusts are there other modes of entrance.

Respiration and Dust Inhalation. The lungs are nonsymmetrical bilateral structures encased in a rather elastic cavity, the chest, and they communicate with the nose and mouth through the trachea, or windpipe. The left lung has two divisions, or lobes, and the right lung has three; the right lung is about 12 per cent larger than the left. (Fig. 13)

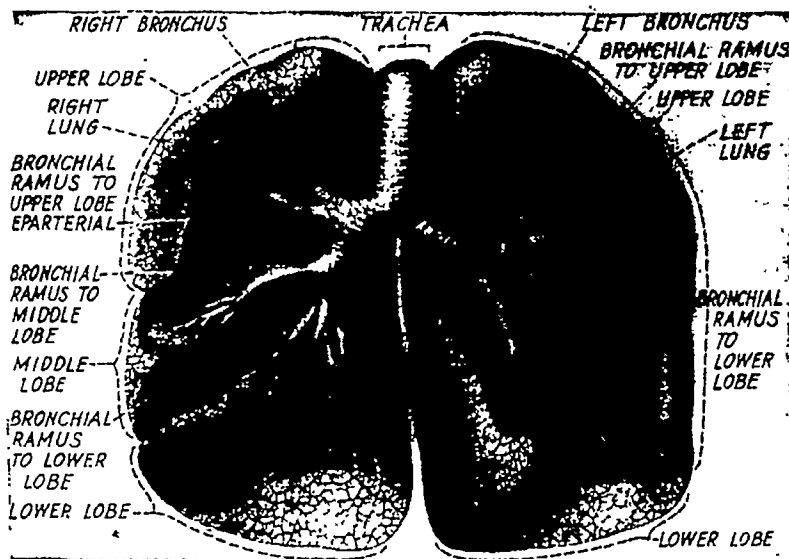


Fig. 13. Lungs, bronchi, and trachea. (After Sobotta and McMurrich.)

In the normal adult, the trachea is about 2 cm in diameter and is fortified with ringlike cartilage with an opening in the posterior part. The trachea is, therefore, strong, fairly rigid in front, and somewhat elastic in back. At the approximate level of the fourth rib, the trachea branches into the bronchi, and these in turn subdivide into bronchioles which lead to the terminal air sacs, or alveoli. It is in the alveoli that gas exchange takes place between the blood and air. Oxygen is taken up by the red blood cells, and carbon dioxide is given off.

TABLE 5. OXYGEN CONSUMPTION AND VOLUME OF BREATHING BY MAN

	Oxygen consumed at 0°C. and 760 mm. pressure, liters per minute	Air breathed at 20°C., liters per minute
Resting in bed.....	0.24	6
Sitting.....	0.30	7
Standing.....	0.36	8
Walking 2 m.p.h.....	0.65	14
Walking 4 m.p.h.....	1.20	26
Slow run.....	2.00	43
Maximum exertion.....	3.00-4.00	65-100

Source: After Henderson and Haggard (231).

The amount of air breathed and the oxygen consumed vary with the task performed and with the individual's size. The figures for an athletic man weighing 150 lb are shown in Table 5.

The untrained man is apt to exceed these figures when performing comparable exercise—thus, in a contaminated atmosphere, the untrained person will work harder and breathe more often than the trained athlete.

The inspiratory and expiratory phases are not exactly alike, but practically we may consider each as taking half the time required for a complete respiratory cycle. Thus with a minute volume of 50 liters, the actual inspiration is at the rate of 100 liters/min, and momentarily rather high velocities occur in the trachea. The velocity in the alveoli proper, however, is practically zero at all times because each alveolus is a dead end. The slight surge back and forth with respiration must be very close

to still-air conditions. Thus there cannot be any driving or high-speed impingement of dust particles into the lung tissue.

Any impediment to breathing is annoying, and if severe it may be alarming. No one, strong or weak, will voluntarily work under conditions that cause respiratory embarrassment. This fact is of the utmost importance in the design of protective equipment, as will be shown in Chap. 17.

The Fate of Inhaled Dusts.

A dust particle the size of a common pollen grain (15 to 25 μ) is likely to be caught in the nasal passages or at the back of the throat. If it should enter the trachea near the center line, there is no reason why it should not pass on down to the bronchi, but it is not likely to reach the alveoli. Collection of such a particle is the result solely of chance impact against the moist walls of the respiratory tubes. Obviously such impact takes place most effectively with particles large enough to have appreciable momentum and rapidly ceases to be effective as the particles approach sizes at which they move as an integral part of the transporting gas. Lining the trachea and extending down to the lower ends of the bronchioles

are myriads of cells with whiplike appendages, cilia, which carry upward any foreign bodies that chance to touch the wet mucus-bathed linings of the respiratory passages. The nasal passages



FIG. 14. Phagocytic cells containing dust, from sputum of man working in a dusty plant. * (Courtesy J. Indust. Hyg.)

likewise are bathed in mucus and lined with cilia. All the mucus moves toward the exits of the nose and mouth and is never stagnant.

Within the alveoli are other cells, phagocytes, which are brought out in vast hordes by the stimulus of foreign bodies, such as dust particles, which they engulf (Fig. 14) (123). The dust-laden cells, which have the power of independent motion,

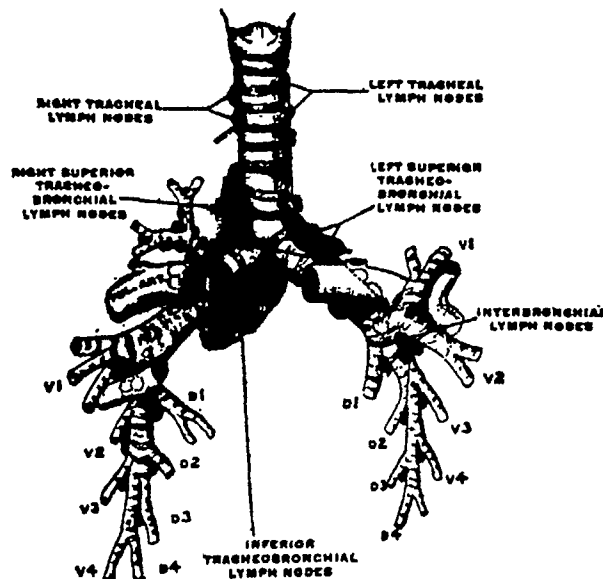


FIG. 15. Position of lymph nodes in relation to the trachea, the bronchi, and the pulmonary artery. (After Gray's Anatomy.)

may pass through the walls of the lung tissue into the lymph and thence into the blood capillaries surrounding the lungs, or they may pass to the finer bronchioles, from which they are removed by ciliary action; thus they eventually reach the mouth and are spit out or swallowed. Within the alveoli there are neither cilia nor mucus.

Most of the dust-laden cells, however, migrate into the lymphatic system, which starts as a meshwork of fine vessels and drains the tissue spaces. These fine vessels come together, forming larger and larger vessels which finally discharge the lymph into the blood stream (Fig. 15). At the various bifurcations of the trachea and the bronchi, the lymph passes through glands or lymph nodes, one of whose functions is the filtration of

foreign bodies. It is at these tracheobronchial lymph nodes that a great deal of dust is deposited by the phagocytic cells, and it is here that fibrosis of healthy lung tissue starts, following quartz-dust inhalation.

Dust particles can pass from the alveoli into the lymph circulation without having been phagocytosed (118). Such particles then can be picked up by phagocytes at any point in the lymph stream or in a lymph node, the latter being particularly suited to such phagocytosis.

Fenn (149) found that all dusts are not phagocytosed with the same readiness; he gave cells an equal chance to ingest various dusts and found that quartz was among those least preferred. Gardner and Cummings (176) noted that the motility or rapidity of migration of cells differed with different dusts, but no prognostic use has been made, so far as we know, of these interesting observations.

PNEUMOCONIOSIS

It has been recognized for centuries that excessive dust inhalation can produce serious pulmonary disease which has been known in the various dusty industries as miners' asthma, miners' phthisis, grinders' rot, etc. Zenker (458) in 1867 proposed the general name *pneumonokoniosis* (a lung containing dust) in place of the special names applied in certain industries. Later this was shortened to pneumoconiosis (240) by no less a body than the International Labour Office, but various spellings continue. The word originally implied that the lung had been seriously damaged by dust—enough to cause disability—but the meaning has been broadened in recent years to include all pulmonary manifestations of dust inhalation, whether the dust is injurious or harmless.

Silicosis and asbestosis are still the most important forms of pneumoconiosis. Names such as *silicatosi*s, *anthracosis*, *anthracosilicosis*, *siderosis*, and *byssinosis* have been given to other forms of pneumoconiosis, and new names are added as studies of the dust problem progress.

Silicosis. For reasons still unexplained silicon dioxide as quartz (free silica) produces the most serious form of lung fibrosis. The American Public Health Association definition of silicosis (11) states that it is a "disease due to breathing air

containing silica (SiO_2) characterized anatomically by generalized fibrotic changes and the development of miliary nodulation in both lungs, and clinically by shortness of breath, decreased chest expansion, lessened capacity for work, absence of fever, increased susceptibility to tuberculosis. . . . " The International Silicosis Conference at Johannesburg in 1930 defined silicosis (241) as a



FIG. 16. Silicosis. Isolated silicotic nodules above; fine nodules below. (After Gardner, courtesy U.S. Public Health Service.)

"pathological condition of the lungs due to the inhalation of free silica dust. It can be produced experimentally in animals. It can be detected by clinical and radiological means, which can be confirmed with the above pathological condition with sufficient accuracy to separate it from other pneumoconioses. It also affords a fair basis for legislative measures."

In general, the damage done in silicosis (and asbestosis) is permanent; an unalterable tissue change takes place in the lungs. Of prime importance is the fact that prolonged exposure to these dusts results in increased susceptibility to tuberculosis, more so from quartz than from asbestos. Gardner showed in the laboratory the great importance of this fact which had long been

EFFECTS OF DUSTS AND FUMES UPON MAN 37

recognized in industry. Deaths from uncomplicated lung fibrosis caused by dust are infrequent, but they have been reported (348).

Free quartz seems to possess a peculiar cytocidal power and can kill phagocytic cells which disintegrate and thereby release their dust load. The surrounding tissue then begins to fibrose and gradually becomes more or less stringy, as is shown in Fig. 16 and 16a; such fibrotic nodules contain dust.



FIG. 16a. Barre granite cutter. Two isolated silicotic nodules. Cellular connective-tissue borders and hyaline fibrous centers. Thickened interlobular septum extending upward to the left of the right nodule. Note dilated lymph vessels in septum. (After Gardner; courtesy U.S. Public Health Service.)

Characteristics of Silicosis. In 1930 silicosis was conventionally reported as being present in one of three stages. In the first, the disease did no measurable harm (and produced no disability). The victim could work as well as ever. But as his condition progressed to the second stage, his respiration was affected, he was bothered by dyspnea, or labored breathing. If his dust exposure continued (and often even if he kept out of dusty air), he was likely to reach a third stage in which dyspnea became severe and to contract pulmonary tuberculosis, generally with fatal results. Whether he developed tuberculosis or not, the health of the person with advanced silicosis was far below normal. We question whether such divisions are valid today, simply because the epidemiological picture of silicosis has changed so.

Silicosis is diagnosable by x-ray only if a good history, with proof of adequate dust exposure, is available. Anyone with normal vision can follow the changes that appear in a series of x-ray plates of the chest taken of a man who has had a severe dust exposure over a number of years and ultimately died of silicosis. Such a series is, today, something of a curiosity. The modern medical student is about as apt to see a case of typhoid fever as he is one of silicosis; so familiarity with the disease is not to be expected.

Silicosis and Duration of Exposure. Silicosis may not become disabling until some years after dust exposure has ceased. Watkins-Pitchford (437) gave examples of Welsh miners who passed the physical examination for enlistment in the British army, fought in the trenches through World War I, then came back to England and died of silicosis. Britton and Head (54) gave more detailed examples of similar latent effects in the United States.¹

This problem of latency may be embarrassing—it is not reassuring to a client to state that some dust-control measure you recommend cannot really be appraised until the men exposed have worked through this vague latent period.

Harrington (207) of the U.S. Bureau of Mines assembled data on the length of exposure required to give definite silicosis; these showed that first-stage silicosis could develop in as short a time as 8 months. Among foundry workers where the risk is low, McConnell and Fehnel (305) in 1934 and Pope and Zacks (338) in 1935 found first-stage silicosis only after long employment. But in severe quartz-dust exposure the condition is very likely to progress and to become complicated by tuberculosis whether the man leaves his dusty occupation or not. Thus the length of exposure that will produce the disease varies with the working conditions and individual susceptibility.

In Great Britain the reports of the Chief Inspector of Factories show the number of deaths from silicosis as well as the ages of the victims. We show Tables 6 and 7 taken from the reports of 1934 and 1947. One could compile the yearly figures and the rates for silicosis, but we believe that the progressive increase in age at death is the important item. We doubt the value of yearly figures or of rates because of this vague latent period of the

¹ We emphasize it further in Fig. 34, p. 107, from South African data.

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disease which makes it impossible to fix causative exposures with any semblance of accuracy.

From all parts of the industrial world the indications clearly point to a lengthening of the time required to produce silicosis.

TABLE 6. FATAL CASES OF SILICOSIS AND ASBESTOSIS INVESTIGATED UP TO END OF 1934 (GREAT BRITAIN)

	Number of deaths	Average age at death	Duration of employment, years		
			Maximum	Minimum	Average
Silicosis.....	261	55.4	60	2.3	34.8
Silicosis with tuberculosis.....	315	52.5	67.0	2.0	32.0
Asbestosis.....	41	41.0	27.0	1.5	12.9
Asbestosis with tuberculosis.....	26	38.0	29.0	0.8	9.9

Source: After Bridge (52).

TABLE 7. FATAL CASES OF SILICOSIS AND ASBESTOSIS INVESTIGATED UP TO END OF 1947 (GREAT BRITAIN)

	Number of deaths	Average age at death	Duration of employment, years		
			Maximum	Minimum	Average
Silicosis.....	1037	58.2	62.0	1.5	34.3
Silicosis with tuberculosis.....	1046	53.6	67.0	0.7	31.3
Asbestosis.....	160	47.5	48.0	0.5	14.9
Asbestosis with tuberculosis.....	72	39.0	29.0	0.8	10.4

Source: After Barnett (25).

The improvement is partly due to the decreased incidence of tuberculosis and not solely to better working conditions. In 1913 the Metropolitan Life Insurance Company established a tuberculosis sanitarium for its own employees, and in 1945 they celebrated its abandonment because they no longer had enough patients to justify maintaining it. This event comes close to being a milestone in public health and shows how spectacularly the tuberculosis rate is being reduced.

Joseph (249), summarizing 25 years' experience (1913 to 1938) in the Rand mines, shows (Fig. 17) the remarkable lengthening in the exposure time needed for development of silicosis in that famous mining community.

We have no data to prove it, but our opinion is strongly that this graph indicates the epidemiological trend of silicosis in the

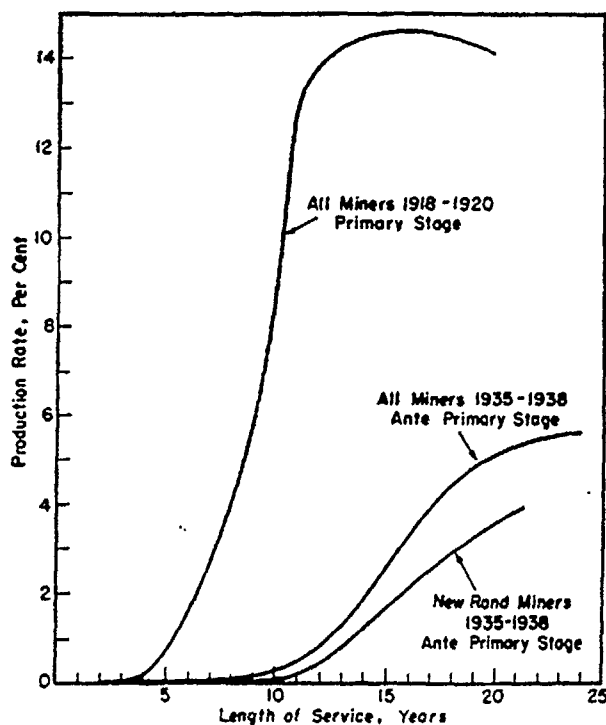


FIG. 17. Length of service vs. rate at which silicosis was produced at dates indicated; Witwatersrand mines. (After Joseph, courtesy *J. Chem., Met. Mining Soc. S. Africa.*)

modern industrial world—a steady and consistent lengthening of the time required to develop the disease. This is tantamount to saying that both the frequency and the severity of silicosis are steadily decreasing.

We are all familiar with Agricola's epidemiological observation (2) that many women in the Carpathian mining district married seven husbands who were carried off to an early death—presumably by silicosis. We cannot question his mortality figures, but we do question his etiology. This remarkable book

on metallurgy was published in 1556. Blasting and pneumatic rock drilling, the main dust producers in mining, are a product of the end of the last century. Dust exposures, as we know them, did not exist in Agricola's time. If tuberculosis had been controlled among the Carpathian miners, we doubt that their mortality would have been unusual.

A significant part of the increase in pneumoconiosis in Britain occurs in their coal miners. It is not a new disease in coal mining, it is found only after years of work in coal dust, it is responsible for peculiar and distinctive chest x-ray markings, it is often disabling and it is compensable.

There is no thought among the British authorities that coal miners' pneumoconiosis is a new disease. Fletcher (159, 238) sums up the present British situation by stating that from 1931 to 1948 there were 22,000 men (90 per cent from South Wales) certified as disabled from coal dust. These men came from about 100,000 underground workers, while only 600 were certified as disabled from 600,000 miners exposed elsewhere in Great Britain.

The importance of the dust hazard, in its effect upon both the death rate for tuberculosis and the death rate for all causes, is shown in Table 8, giving the number of actual and of expected cases (based upon general experience) among workers in the chief dusty trades. These data, which represent the combined experience of 12 life-insurance companies from 1915 to 1926, show excess mortality varying from 114 to 450 per cent of the expected rate for all causes and from 103 to 1833 per cent for tuberculosis. In general, the mining, quarrying, and stone-dressing operators show a higher hazard than the general manufacturing workers.

The Employability of Workmen with Silicosis. We like what Cummins (89) wrote about the disability of the person with silicosis: "It may be said of pneumoconiotic cases in general that what most interests the clinician is the mottling seen in x-ray films; what chiefly attracts the pathologist is the mystery of the silicotic nodule; and what distresses the patient is shortness of breath."

There has been much work directed toward appraising this disability, for there is nothing more distressing than difficulty in breathing. The subject is complicated, and it is overoptimistic, perhaps, to expect a formula whereby percentage disability can be fixed by physiologic tests, with or without x-rays. No one

INDUSTRIAL DUST

TABLE 8. NUMBER OF DEATHS EXPECTED FROM SPECIFIED CAUSES AND NUMBER WHICH ACTUALLY OCCURRED AMONG PERSONS ENGAGED IN CERTAIN OCCUPATIONS EXPOSED TO SILICA DUST (UNITED STATES)

Occupation	Deaths from all causes			Deaths from respiratory tuberculosis		
	Actual	Expected	Percentage actual of expected	Actual	Expected	Percentage actual of expected
Metal-mine operatives (underground):						
Gold and silver mines.....	44	9.77	450	9	1.12	804
Lead and zinc mines.....	22	5.03	437	11	0.60	1833
Copper mines.....	83	22.63	367	24	2.63	913
Iron mines.....	33	12.12	272	4	1.54	260
Quarry operatives.....	37	22.45	165	7	2.66	263
Stone cutters:						
Granite and sandstone.....	29	17.47	166	16	1.64	976
Marble and limestone.....	12	10.55	114	3	1.02	294
Metal industries:						
Grinders.....	46	28.65	161	7	3.33	210
Buffers and polishers.....	89	64.10	139	10	6.80	147
Chippers (not ship).....	38	14.14	269	8	1.30	615
Core makers and sand-molders.....	32	22.65	141	3	2.92	103
Iron and steel foundries:						
Molders, foundmen, and casters.....	202	130.14	155	24	13.38	179
Drillers, flask makers, machine hands, mixers, etc.....	45	31.03	145	7	3.03	231

Source: Ordinary department mortality experience of 12 life insurance companies, 1915-1926 (274).

appreciated these difficulties better than the late L. U. Gardner, whose wealth of experience gives his opinions unusual value. At the request of the Department of Labor and Industry of Minnesota he discussed the subject in their Thirtieth Biennial Report (1945-1946) with special reference to the silicosis problem in their iron mines. What he says applies so generally that we quote parts of his report (171), one of the finest pieces of work in this field:

In the absence of associated tuberculosis of the lungs, silicosis does not ordinarily cause symptoms or disability. Most of the disability in silicotics is a result of associated tuberculosis.

Silicosis is a menace largely because its presence predisposes to fresh tuberculous infection from without, and because, in combination with the tubercle bacillus, inhaled quartz produces massive fibrosis of the lungs.

Contraction of this fibrous scar causes the air spaces in the rest of the lung to over-distend in order to fill the chest cavity. This process of distention is known as compensatory emphysema, and it is emphysema, rather than fibrosis, that gives rise to shortness of breath. Since so many of the older silicotics had associated chronic tuberculosis, shortness of breath came to be recognized as the cardinal symptom of the disease. However, it should be borne in mind that, without tuberculosis, silicosis alone causes little emphysema. Some uncomplicated silicotics may also have emphysema because it is prone to develop in older men, but in them it is not caused by the dust disease.

The problem that faces employers, industrial physicians and compensation officials today is the disposition of cases of silicosis, largely produced by exposure to heavy dust concentrations fifteen or more years ago. At that time there was no general appreciation of a hazard. Today's adjustments to this situation must involve compromises, which it is hoped will become less frequent after the present generation is gone. New employees who have worked only under controlled atmospheric environments should create few problems of this nature. To discharge all men now discovered to have silicosis will not correct the damage that has already been done. Change to surface employment may be temporarily acceptable to a miner but, being a specialist, he is rarely able to command as high wages in another job. Compensation may ameliorate the economic strain, but such payments can only be temporary. The mere knowledge that he has a pulmonary disease of such nature that it necessitates loss of earning capacity may transform a strong and healthy workman into a neurotic invalid. For these reasons, it would seem ill advised to recommend that every case of simple silicosis be discharged as soon as the diagnosis is made.

If the subject is comparatively young, in his twenties or early thirties, there is more reason to advise change of employment than in men over 45. If an iron miner, he may be kept out of development work where there is apt to be some exposure to quartz dust.

In men over 45 who develop silicosis not complicated by tuberculosis, there is even less reason for change of employment. In all probability the disease has taken a lifetime to develop under the high dust concentrations which prevailed before the hazard was locally recognized. Transfer to positions where there is less free silica and much less dust because of modern methods of control may ultimately do less harm than discharge. As long as such men remain with their original employers, they are subject to periodic examination, which will detect superimposed tuberculosis in early stages when it is amenable to treatment. Discharged from their jobs, they lose the benefits of such control, for the silicotic nodulation in their chests is a cause for rejection in any plant using x-rays as part of its physical examination program. A few such rejections may turn an able workman into a discontented neurotic.

The young silicotic workman who develops tuberculosis should be sent to a sanatorium as promptly as possible. Only there has he any chance to cure his infection, and there he is not a menace to the public at large.

Old silicotics with massive conglomerate disease in which latent tuberculosis generally plays a part are apt to be partially disabled by shortness of breath. Sanatorium treatment does them no good; in fact, to put them to bed merely increases their dyspnea.

In this country, the most acceptable compromise has been continued employment at jobs compatible with the subject's condition. Many of them are able to do regular work as miners; some can be usefully employed as pump men or at other jobs that do not involve severe physical exertion. The major difficulty is to find enough jobs of this nature to keep such old employees on the payroll.

Experience has demonstrated that most of them do reasonably well for prolonged periods. Followed in annual examination films over periods as long as ten or twelve years, their disease gradually increases in extent and their shortness of breath becomes more marked. Sputum examinations should be made from time to time to make certain that their infection has not become active and that they consequently are not a public health menace. Negative results may be expected until such time as the x-ray reveals more rapid changes in their disease. When this finally happens, hospitalization for the protection of others is indicated.

This recommendation may seem heartless but, for the most of these cases, it is perhaps the kindest treatment that can be offered. Until medical science finds some means of combating the infection, the expect-

ant treatment is as good as anything that can be offered for these tragic results of past ignorance.

Asbestosis. The pathologic changes produced by asbestos are not like those of silicosis. The asbestos fibers group about the neck of an alveolus and stimulate the formation of a diffuse fibrosis. There is no definite migration or transportation of the dust particles to the lymph nodes and no formation of the fibrous nodules shown in Fig. 16a. As the fibrosis increases, the reduction in lung area causes serious dyspnea. Lanza (273) suggested that the enlarged hearts noted frequently in his cases of second-stage asbestosis may be the result of the increased work of the heart resulting from this condition; it takes more work to pump blood through the asbestotic than through the normal lung.

Gardner stated (175, 170): "On grinding these fibrous minerals to a very fine state of subdivision they do not become more irritating but practically lose all power to provoke tissue reaction . . ." Vorwald *et al.* (433) continued the animal work initiated by Gardner and concluded: "The duration of exposure required to develop the pulmonary reaction to inhaled asbestos dust is inversely proportional to the concentration of long fibers in the atmosphere; as the concentration is increased, the reaction develops in shorter time."

In silicosis it seems to be a general rule that, after a certain point, the victim's condition grows worse even if his exposure to dust has ceased. But Wood and Gloyne (455) stated that they have seen patients with asbestosis "whose condition appears to have remained stationary since stopping work in the factory," but they advised definitely that the individual with asbestosis be removed from his dusty job. Merewether (311) and Lanza were less certain on this point.

Asbestosis Bodies. In the lungs of patients who have died after prolonged exposure to asbestos dust and in the sputum of men with considerable asbestos-dust exposure are found what first were called *curious bodies* and later *asbestosis bodies* (Fig. 18) (140). While somewhat similar bodies can occur in the lungs of coal workers and even of normal persons, it is admitted that asbestosis bodies in sputum are characteristic of asbestosis. Stewart (402) gives considerable diagnostic weight to their presence as do Sparks (397) and Gloyne and Merewether (184).

Asbestosis and Lung Cancer. The British require autopsies of persons who have allegedly died as a result of industrial exposures such as cause asbestosis or silicosis. The 1947 report of the Chief Inspector of Factories (25) states that, of 235 cases of asbestosis autopsied between 1924 to 1946, 31 or 13.2 per cent were complicated by carcinoma of the lungs or pleura. This figure should



FIG. 18. Asbestosis bodies in sputum. (After Ellman, Ref. 140; courtesy J. Indust. Hyg.)

be compared with that of their cases of silicosis of whom 6884 were autopsied over the same period and in which 1.32 per cent showed cancer of the lungs. This latter is about the rate reported in the 1946 census in the United States (13 per cent of all deaths were from cancer and 1 per cent from cancer of the respiratory tract).

We do not imply that our American pathologists and our hospitals are less careful than the British in collecting data from autopsies. For example, Vorwald and Karr (434) at the Saranac Laboratories reviewed such data from their own experience and concluded that "inhaled dusts," except those containing recognized carcinogenic substances, "cannot in general be considered

One of the most important duties of the Bureau of Mines is to advise our mining industry in matters of safety. The prevention of fires and explosions in mines falls to their lot (see Chap. 6). By 1930 the dusting of bituminous mines, to prevent explosions, had become an accepted practice and the Bureau was charged with recommending dusts that could be used safely and would not cause silicosis. The dusts had to be cheap, which means that the minimum of handling and of processing could be allowed.

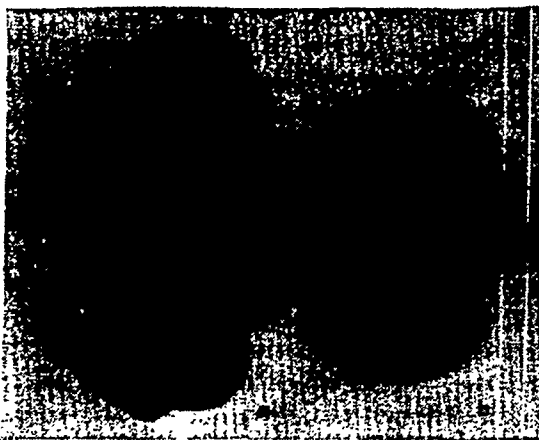


FIG. 19. (a) Liver of rabbit 1 year after injection of 500 mg of 1 to 3 μ quartz. (Course of 20 injections in 1 month, each dose contained 5 cc of 1 per cent suspension in physiological salt solution.) Massive silicotic cirrhosis and fibrosis. (b) Same, with addition of 0.33 per cent gelatinous colloidal alumina. (After Gardner, courtesy *J. Indust. Hyg. & Toxicol.*)

In order to carry out this assignment Miller and Sayers (315) adopted Mavrogordato's (299) intraperitoneal method of testing the toxic effect of dust on guinea pigs. As a routine they found that it was best to run all tests with controls of quartz and anthracite coal dust and to kill their animals at intervals of 14, 45, and 90 days, although their first experiments were run for as long as a year.

They found that it was practicable to divide the commercially available dusts into three general classes: (1) those causing an absorptive reaction: calcite, limestone, precipitated calcium carbonate, cement, gypsum, and dolomite; (2) those causing a proliferative reaction (the silicosis producers): quartz or sand, diatomite, tripoli, and various combinations of natural dusts high

in quartz; (3) those causing an inert reaction: alundum (Al_2O_3) and silicon carbide (SiC), anthracite and bituminous coal, bentonite and kaolin, fuller's earth, feldspar, mica, talc, soapstone, shale, traprock, pyrophyllite, sericite, volcanic and precipitator ash (from power plants), hematite (as jeweler's rouge), and asbestos.

As the result of this work the Bureau approved the use of the dusts in the first class—those causing “an absorptive reaction.” It is interesting to note, after some 20 years, that their ranking of dusts as potential silicosis producers has not been changed by any of the more elaborate methods since devised or by epidemiologic studies.

Up to about 1950 the harmfulness of the potential silicosis producers was more or less rated in proportion to the free quartz of fine particle size. Sayers' three classes were sound at the time he suggested them. Now we would probably accept the first two, namely, the absorptive and the proliferative classes, but the third still is being explored. It is no longer enough to say that mineral dust is safe to use simply because it is low in quartz.

Aluminum Therapy. Denny and Robson (111) at the McIntyre Mine in Schumacher, Ontario, noted in 1936 that “the presence of small amounts of metallic aluminium almost completely prevented siliceous material from passing into solution.” Later they and Irwin (111) showed a relationship between reduction of solubility of free silica by aluminum powder and a decrease in the occurrence of silicotic lesions. They then “tried to prevent silicosis in quartz-dusted animals by giving them daily inhalation of powdered aluminium” and “were completely successful.” The quotations are from King (251) who gives the best appraisal of this interesting episode that we have seen.

Denny and Robson's animal experiments were checked and confirmed by Gardner (179), Fig. 19, at Saranac Lake, by King (251) in London, and by Policard (337) in France. Gardner had often referred to “protector dusts” and suggested that hydrated alumina would work better than metallic aluminum powder. Also it is easier to disperse in air, presents no explosion problem, and does not require fresh grinding as it is stable.

It was natural to test the efficacy of aluminum on patients with silicosis, especially men with respiratory embarrassment but without tuberculosis. In 1944 Crombie *et al.* (85) reported

improvement of about half of a group of 34 patients with silicosis who were treated by being given freshly ground aluminum dust to inhale. Denny and Robson patented the treatment and assigned it to the McIntyre Foundation which then granted licenses to properly qualified physicians. If the treatment was to be used at a factory or mine, the Foundation required proof that modern dust control and medical control were enforced.

In 1948 Berry (39) at Denver reported a careful study of 35 patients with silicosis, without tuberculosis, but with definite respiratory embarrassment. Twenty-six breathed aluminum hydroxide at concentrations of 300 million particles per cubic foot by impinger counts and nine breathed filtered air, none of them knowing which men were the controls. Concentrations were obtained by a carefully adjusted modification of the dusting equipment used at the U.S. Bureau of Mines for testing respirators (see Chap. 17). Berry concluded that "in the aluminum treated group, no objective changes were observed which could be convincingly attributed to the metallic therapy," and that is about where the matter stands today (10).

Colloidal Silica. In 1937 Bruce (65) of Stockholm described cases of silicosis among men making silicon alloys. The actual numbers involved were very small, and he could not decide whether exposures resulted from dust generated in handling the quartz used as raw material or from the silica fumes which resulted from the spontaneous burning of vaporized silicon. The fume escaped from "the furnace in the form of an immense, dense, spreading, white jet of smoke." The particles were examined by Sundius, state geologist, who found them to be mostly finely divided powder of silica with some quartz grains. Under the microscope they showed abundant flocs with discrete particles, presumably in the pigment range of size. We do not question Sundius' report, but we are confident that present-day methods of pigment microscopy, using the electron microscope, would place the particle size of this fume in the colloidal range.

In 1947 Shaver and Riddell (373) in Canada reported cases of severe pulmonary disability, new to industry, which "disclosed a peculiar type of lung shadowing, together with a pneumothorax which had developed spontaneously." Shaver's first patient was seen in February, 1942.

The men affected were working around electric furnaces making

a synthetic abrasive comparable to the natural mineral corundum, Al_2O_3 . In the trade it is called both alundum and aloxite. The raw materials were bauxite, $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$; coke; and iron. Silica was not added, as such, but was present in the bauxite in trifling amounts.

The furnaces had a steel shell, and cooling water was sprayed around the upper edge. Within the melt, temperatures were about 2035°C . When fusion had been completed, the furnace was cooled, the wall removed, and the pig weighing about 8 tons broken up; the pieces were then sorted and crushed for shipment. The process was fairly old as such things go, and no trouble had been experienced up to 1942. Even in retrospect we doubt if Shaver's cases should have been predicted. In any event they were not.

In writing up this incident, Jephcott *et al.* (244) reported: "A faster rate of production was obtained in some plants during the war," and "This change caused a marked increase in the amount of fume given off." Jephcott found the fume to be a mixture of which the significant constituents were 35 to 64 per cent alumina and 16 to 54 per cent silica.

In Germany, Gärtner (181) reported severe reactions, with some tuberculosis, among *Korunsmelzerns*, caused by overloading the industrial capacity of their plants. We pointed out that the raw material in Shaver's cases had a low silica content but that the fume evolved contained high percentages of alumina and silica. Gärtner (181) suggests that the German troubles were essentially the same as those reported by Shaver and Riddell and that mullite, $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$, identified in both Canadian and German furnace fumes, caused the disabilities.

It is unlikely that the etiology of this unique disease, known as Shaver's disease, will be worked out in a systematic fashion. As soon as it was suspected that the capacities of the Canadian plants were overtaxed, steps were taken to remedy conditions and the exposure of the workmen was controlled. Animal work since then has not brought out anything conclusive, so we are informed, and no more human exposures are apt to occur.

OTHER PNEUMOCONIOSES

Silicates. Exposures to silicate dusts were common in industry long before modern methods of rock drilling, crushing, milling,

and conveying had been developed. Excepting only asbestos, the silicates together with limestone, gypsum, and coal had not this unpleasant legacy of involvement with tuberculosis at the time modern bulk handling of raw materials was becoming commonplace. It is our belief that our very modernization made some processes, formerly handling silicates safely, somewhat risky. By 1950 this situation was generally recognized and now is being brought under control.

In 1927 Badham (19) in Australia coined the word *silicatosis* to cover the pulmonary disabilities resulting from breathing the various silicate dusts (113). In 1933 McCord (307) reviewed the subject which was considered at each of the first four Saranac symposiums. The recent summary by Koelsch (251) shows clearly that the problem is recognized all over the industrial world.

We now have good laboratory or field studies of exposures to talc (115, 376, 372), mica and pegmatite (116), pyrophyllite (136), various clays (256), fuller's earth (310, 69), pumice (394), sillimanite (182, 250), mullite (251), olivine (257), and others. The list is sure to be enlarged. We doubt that any responsible person, in this age, would condone heavy dust exposures, especially chronic exposures, to any silicates on the doubtful premise that they have not been shown to produce the nodules of classical silicosis and have not the bad name of involvement with tuberculosis.

Mineral and Glass Wool. Mineral wool is made by blowing molten slag from the spouts of furnaces adapted from small foundry cupolas. Glass can be made into fibers similarly. Later developments of Fiberglas are beautifully mechanized and bear little resemblance to the early process. Both mineral wool and glass wool are artificial silicates the composition of which is controlled by the ingredients of the melt. Fiberglas is now sold in spooled thread as yarn from which fabrics can be made by adaptations of standard textile processes.

Either type of fiber can be made up in batts of convenient size to handle, or it can be collected as fluffy wool and blown in between the walls of houses for insulation. Fiberglas, for some time, has been an important insulating material both thermal and electrical. Men handling it for the first time complain of skin irritation from the tiny spicules, especially around their

collars and cuffs. They have asked whether it would not be irritating to the lungs if breathed. Animal studies (146, 174) and periodic examinations of workers (121) indicate that there is no danger at all of pulmonary damage from either mineral wool or Fiberglas.

Carbon Dusts. As long ago as 1837 Stratton (405) wrote:

On examining the bodies of elderly persons we find the lungs always of a dark color. Sometimes the color is much deeper in various parts of the lungs which then are as black as charcoal; at other times the whole lungs are uniformly of a dark color. The first appearance is considered healthy, the second receives the name of melanosis, and the third is what has been called the black lung of coal miners and may more shortly be defined as anthracosis.

In 1928 Collis and Gilchrist (81) had reported upon the health of coal trimmers, men who loaded coal into barges at Cardiff and had no mining experience. Collis noted no significant disability because, as he thought, there was not enough silica in the coal.

In their monograph on the lungs of coal and other miners in Australia, Badham and Taylor (20) in 1938 wrote: "We find ourselves by no means in agreement with the opinion that coal-miners' lung is only the product of free silica.—That coal-dust and not the country rock is to blame is shown not only by the analysis of affected lungs and coal seams, but by the fact that we have seen individuals affected with pulmonary fibrosis who did not work underground but only on the screens."

Cummins and Sladden (90) in 1930 examined many coal miners' lungs, pathologically, histologically, and chemically and then correlated these studies with case histories. Commenting on Haldane and Mavrogordato's opinion on the relative harmlessness of carbon (because it is more easily removed from the lungs than is quartz), they state that both coal dust and silica in large amounts may be present in the lungs of coal miners but that "coal is only retained in large amounts when there is a really high silica content, and there seems no doubt that in general the absorption of silica favours a retention of coal dust when this is freely available as in coal-mining or coal-trimming conditions."

The whole question of pulmonary disease among British miners and coal handlers was reopened in 1937 by the Medical Research Council's Committee on Industrial Pulmonary Diseases.

A full account of the resulting progress with excellent bibliography is given by Fletcher and Gough (159). Widespread pulmonary disease was found, more in anthracite than in bituminous coal handling. Recently Ray *et al.* (343, 344) reported convincingly that either pure coal or graphite, with only 2 per cent quartz contamination, could initiate typical silicotic fibrosis. In comparing the pathogenicity of different coals Fletcher and Gough say that it "does not appear to be directly related to their free silica content, but may depend upon some property associated with the 'rank' (i.e. volatile matter) of the coal." Their anthracites with 5 per cent volatile matter were more potent than the bituminous coal with 30 per cent volatile matter.

In the United States in 1949 there were 76,000 anthracite and 409,000 bituminous miners (162). There have been no studies on the health of the whole industry, but there have been good studies of representative samples. In 1935 Sayers *et al.* (365) published a report of their field study with physical examinations, dust determinations, and petrographic analyses of conditions under which 2711 miners worked. They reported an incidence of 22.7 per cent anthracosilicosis. In 1941 Flinn *et al.* (160) made a similar study among bituminous miners in Utah and reported the occurrence of 3.2 per cent anthracosilicosis among 545 miners. It is more than doubtful that one could correctly extrapolate this last figure to cover our soft-coal miners in other parts of the country, but the consensus indicates that a figure of less than 2 per cent anthracosilicosis is about right, as of 1951.

The coal mines of Britain are probably more vital to the national economy than is the case in the United States. In both countries the industry has had some rude economic and social jolts in which the workers' health is by no means the main issue (238). Whether one calls coal miners' pulmonary disability pneumoconiosis or anthracosilicosis seems to us unimportant compared with the proved facts—with dust control and a modern medical program the industry is not an unhealthy one.

Beryllium. The pulmonary manifestations of beryllium poisoning, or berylliosis, occupy a large space in the industrial toxicological literature of the present era. This metal is used metallurgically in small amounts as an alloy with copper, aluminum, and magnesium and in steels. It has had considerable usage in phosphors (as a complex silicate of zinc) for fluorescent

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lamps, but so much trouble resulted from poisoning that this application has been discontinued.¹ The most important use today is as the pure metal in atomic-energy installations.

The medical aspects of pulmonary beryllium poisoning place it logically with the pneumoconioses. Symptoms can be caused, apparently, by inhaling fractions of a milligram per cubic meter. This ranks its theoretical toxicity with the lethal war gases, but such is by no means borne out generally in practice. Estimates of toxicity either on men or on animals vary greatly, and one must conclude, as suggested by Sterner and Eisenbud (401), that some other process (as yet unidentified) enters the picture to account for the great differences in reactions which have been noted and the puzzling epidemiology.

Beryllium poisoning in its various forms, acute and chronic, has been described in detail by Hamilton and Hardy (203). Acute poisoning is generally less of a problem than the chronic type, which takes months or even years to become apparent. The respiratory distress of the severe chronic cases is extreme, the chest x-rays are characteristic, and the prognosis generally is poor.

Once the disease was recognized, much of the risk was eliminated by process control and careful medical supervision, but cases are still (1954) cropping up. Sterner and Eisenbud (401) state that more than 100 cases of pulmonary granulomatosis (the chronic type of poisoning) and more than 200 of acute pneumonitis have occurred during the past several years among individuals exposed to beryllium and its compounds.

Eisenbud *et al.* (138) reported 11 possible cases of beryllium poisoning among persons living in the neighborhood of a beryllium-producing plant. Concentrations which might have been breathed were estimated at 0.01 to 0.1 microgram/cu m. While Eisenbud points out that there is no justification for applying these data for estimating hazards of exposed workers, a manufacturer whose plant handles and processes beryllium in any amount should be aware of these figures. The degree of process control which they imply is most exacting. •

¹ By agreement among U.S. lamp manufacturers, production of Be phosphors was discontinued June 30, 1949.

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