CHAPTER III

PHYSICAL AND CHEMICAL FACTORS IN PNEUMOCONIOSIS

SILICA

Silicosis was a definite medical entity, concealed under various names, long before Koch's identification of the tubercle bacillus or Roentgen's discovery of the X-ray. Agricola's observation of the high mortality of the hard-rock miners in the Carpathian district is familiar to all. But strangely enough it was not until

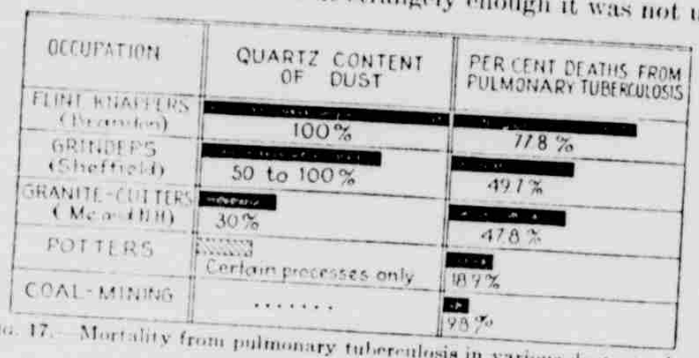


FIG. 17.—Mortality from pulmonary tuberculosis in various dusty trades.

early in this century that the unique hygienic significance of silica began to be realized.

Just who deserves credit for first laying emphasis on silica and particularly upon quartz is not known; however, there is little doubt that Collis' Milroy Lectures brought definitely to a head theories and explanations that had been suggested from time to time by Beattie, Haldane, Hoffman, and others.

In Fig. 17 are shown data adapted from Collis (41) which illustrate clearly the significance of free quartz in respirable dust. The wealth of material collected in the series of surveys started in this country by L. R. Thompson (230) of the U.S. Public Health Service is summarized in Table 9.

Silica occurs most commonly as the mineral quartz, which has a characteristic crystal structure, a specific gravity of 2.66, and a

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hardness of 7; it is weakly birefringent (with indices of 1.54 and 1.55), varies in appearance from transparency to opaqueness, and often is colored brilliantly by various contaminants, as in the amethyst. It is probably the most widely occurring mineral we have and chemically one of the most inert and inactive. Silica is a natural contaminant of a vast number of common minerals and is found in most rocks. Among the commonly occurring forms are ordinary beach sand, chert, flint, sandstone, gritstone, ganister, quartzite, and jasper. Sandstone is always associated with the clays, while many common rocks like granite contain important but varying amounts of quartz. In the above examples, notably chert and flint, some amorphous silica (opal) may be present.

The amorphous or common colloidal variety of silica, opal, usually contains about 10 per cent water, has a hardness of 5.5 to 6.5, and a specific gravity of 1.9 to 2.3. In nature common opal occurs very widely, the varieties such as tripolite and diatomaceous or infusorial earth being used universally for polishes and for thermal insulation.

Until recently no serious effort has been made to appraise the silicotic potency of the various forms of free silica. At present, attention is focused on quartz and little or nothing is known about the physiological effects of the other forms of free silica which have different physical, optical, and chemical properties. A field study by Legge (161) among men handling diatomaceous earth in one of the California deposits indicates, however, that amorphous silica will produce silicosis.

Hardness of Silica and Silicosis. Until about 1915 it was thought that the peculiar physiological action of quartz dust was dependent mainly on its hardness—that the tiny crystals, which at autopsy scratched and dulled the blades of the pathologist's knives, must have been harmful. Men engaged in grinding steel on sandstones were harmed, it was claimed, not only by the sandstone particles but also by bits of sharp hard steel.

These notions were dispelled with finality by Gardner's experiments (84) with silicon carbide, SiC, and fused aluminum oxide, Al_2O_3, both of which are much harder than quartz and second only to the diamond. Gardner showed that the physiological effect of these two artificial abrasives was practically nil as compared with quartz, an observation confirmed by Clark (39)

TABLE 9.—SUMMARY OF THE SIX DUST STUDIES BY THE U.S. PUBLIC HEALTH SERVICE SHOWING THE DUST CONCENTRATION COMPOSITION, AND THE RESULTING HAZARD[1]

	Average dust count in millions of particles per cubic foot of air	Average percentage of free silica (quartz)	Other characteristics of dust	Degree of hazard, under conditions as observed in each study
Granite cutting:				
Hand-pneumatic-tool operators	59	35	Balance mostly combined silica	Great excess of pulmonary tuberculosis after 15 years of more exposure; silicosis in from 2 to 10 years. Silica dust of respirable size; no excess of tuberculosis
Surface-machine operators, etc	30			Negative except for occasional nondisabling silicosis
General air	20			
Less than general air	9			
Anthracite coal:				
Rock drillers	82	31	Siliceous rock	Data insufficient; other studies show severe hazard
Miners and miners' helpers	232	1.5	Carbon and inorganic matter	Dyspnea, sickness from respiratory conditions; excess morbidity from influenza, pneumonia and possibly tuberculosis
Bituminous coal:				
Rock drillers	78	54	Sandstone	Data insufficient; other studies indicate severe hazard
Loaders and machine men	112	1.2	Carbon	Generalized fibrosis chiefly linear in character; excess mortality from influenza and pneumonia
Cement	26	6.8	Primarily lime	Some early pneumoconiosis; excess of disease of upper respiratory tract and of influenza
Cotton-cloth manufacturing	7	7	Crocidolite and silica	Negative
Silverware manufacturing	5	1.7	Metal and other	Negative
Municipal	4	?	Not determined	Negative

[1] After Thompson et al.

on men exposed for a number of years to abrasive dusts. Gardner (85) showed also that the diamond, the hardest substance known, was inert physiologically.

Solubility and Silicosis. It was shown by Gye and Kettle (99, 149), and later widely confirmed that colloidal silica is very toxic, and will produce typical silicotic pathology. This fact was naturally seized upon as giving a happy explanation of the cause of silicosis, namely, that the toxic action of the colloidal silica said to be present in the inspired quartz dust caused fibrosis. That the colloidal silica of Gye and Kettle is not produced by the pulverization or comminution of quartz, chert, flint, sandstone, and the like was ignored. It was argued that, if colloidal silica was definitely toxic, then silicosis was caused by that portion of inhaled quartz dust which behaved like colloidal silica.

The toxicity of quartz particles of colloidal size (0.001 to 0.1 μ) has never been reported. Gardner and Cummings (85) found that quartz of 1 to 3 μ was much more active than quartz of 6 to 12 μ, but neither they nor anyone else have reported upon the silicosis-producing power of colloidal quartz, probably because of the difficulty of preparing the necessary suspensions.

It was reported by Myers (190) that impinger samples of certain dusts gave lower results than sugar-tube samples. The impinger was shipped from the field back to the laboratory so that the aqueous dust suspension was kept more or less in agitation for some days. The sugar tubes, on the other hand, were shipped dry and the dust was wetted only for the time required to dissolve the sugar and filter off the dust.

In studying these discrepancies Myers took dust samples of high-silica rock, chert, from the Joplin, Mo., district, agitated the fine dust in 150 cc. of water in bottles of ordinary glass, of pyrex, and of platinum. After periods varying from 1 to 28 days the dusty suspensions were filtered through a specially prepared Gooch crucible and the amount of silica undissolved was determined from the increase in weight of the crucible.

Myers' figures indicate a solubility of about 27 p.p.m. Commenting upon the results, he states that "the excessive solubility of the silica dust is probably related to its origin. . . . Dust formed from crystallized quartz would probably display much less solubility." It has been alleged repeatedly that Myers' results indicate significantly high solubility of fine quartz dust

in water, whereas he was obviously at some pains to avoid such implication.

Kettle states that Archer (149) "finds the solubility of amorphous silica and ground up quartz in pleural fluid with an initial pH of 8 to be 14 and 4.5 mg. per 100 cc., respectively, after 10 days." This would correspond to 140 and to 45 p.p.m. Kettle states that Archer's results will be published independently but at this writing his data are not available.

Bloomfield, Sayers, and Goldman (23) found 40 p.p.m. of silica dissolved in the urine of miners after heavy exposures to coal dust containing quartz. King and Dolan (151) reported 10 to 60 p.p.m. in the urine of gold miners and about 10 p.p.m. in the blood of normal men, whether exposed to dust or not.

Titus (232) has found the solubility of pure rock quartz, ground to 1 to 15 μ (median 6 μ), to be 0.5 p.p.m. in distilled water. His samples were agitated in bottles varnished inside with a silica-free bakelite and were kept at body temperature for periods up to three months. The supernatant liquid was then ultrafiltered through cellophane at a pressure of 125 atm. and the silica content of the filtrate was determined chemically. Blanks were run on all reagents and on all containers.

Among geologists and chemists quartz is considered an unusually inert and insoluble compound. Sosman (221) remarks that "it is about the last substance on earth that the chemist would have suspected of being poisonous." As a result the so-called "solubility theory" of silicosis is looked upon with justifiable skepticism. Certainly the experimental evidence in favor of such a theory is not impressive.

We are well aware that the chemist's notion of solubility does not always apply to biological phenomena. Perhaps the trifling solubility of quartz is the true explanation of the initiation of the fibrotic nodule in lung tissue. But if this is true, then the toxicity of different forms of free silica should bear some relationship to the solubilites of these same minerals in water. No such relationships have been reported.

Silicates. Inasmuch as it has not been explained why quartz has its peculiar effect upon tissue, there seems no reason to believe that some other chemically inert dust may not act somewhat analogously. Fortunately nature has narrowed the field down to comparatively few possibilities, but industrial developments of

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the future will probably introduce other dust hazards fully as real as that from quartz.

Asbestos. Of the true silicates the mineral commonly called *asbestos* is the only one that has been shown to produce a disabling pneumoconiosis. This condition is different from true nodular silicosis but nonetheless it is a distinct entity. Asbestos is not a true mineral but a general name for any mineral separable into more or less flexible fibers. The commonest variety, the mineral chrysotile, $H_4Mg_3Si_2O_9$, is mined extensively in Canada and is used in making special fabriclike materials, brake linings, special insulation, and the like. It is now believed that at any stage of its processing sufficient exposure to asbestos dust can cause a definite pulmonary disability, asbestosis, with characteristic symptoms and chest X-rays (184).

Chrysotile asbestos is closely related to talc, $H_2Mg_3(SiO_3)_4$, and the two minerals are often found together. The fibrous quality of asbestos seems to be the cause of the peculiar pathology it produces. Chrysotile resembles talc chemically, but the latter is not fibrous and does not produce the same lung pathology.

Sericite. By comparing petrographically fine dust particles in silicotic lungs and in the air breathed by men exposed to these same dusts, Jones (139) showed that sericite was the outstanding common constituent. Sericite is known as a secondary white mica and has the formula $H_2KAl_3(SiO_4)_3$. It is formed mainly by the transformation of potash feldspars; it occurs rarely in the pure state but is widely distributed in nature and is an important constituent of many rocks that give off silicosis-producing dusts.

Jones cited records, since partially refuted, of high silicosis rates among Welsh and South African miners from dusts in which sericite was abundant, and comparatively low silicosis rates among miners in the Kolar gold fields (India) and in Scottish coal mines where the proportion of sericite was low but where the proportion of quartz was high.

It has been claimed by others that the particles Jones calls fibers are actually plates seen on edge. If one troubles to examine a mount of Jones' sericite, it is difficult to understand how such a point of view can prevail; distinct fibers and not plates are seen.

Jones has not claimed that silicosis cannot be produced in the absence of sericite; the evidence that it can occur under such

conditions is, in our opinion, beyond argument. He makes it clear that fibrous sericite is likely to be the binder in rock that is silicosis-producing. It is said not to occur in the free state. It is very hard to obtain quartz-free fibrous sericite, but sericite-free quartz is abundant and was used to produce silicosis in animals some years before Jones' work was published.

In our opinion Jones' most important contribution is not the injection of sericite into the silicosis problem but the clear-cut proof of glaring errors in mineralogy by many who have performed animal-dusting experiments in the past. Elsewhere we comment on the need of mineralogical analyses of the dust actually breathed rather than of the dust in the parent rock—that is, if we wish to know what dust is causing trouble.

As yet there has been no proof that animals dusted with quartz-free fibrous sericite develop typical silicotic nodules like those shown in Fig. 13 (page 26). Of even greater importance is the fact that there has been no indication that sericitic tissue is peculiarly susceptible to tuberculosis—an outstanding characteristic of silicotic tissue.

Sericite, like all mica, has an unusually high birefringence which renders its identification particularly easy—vastly easier than the identification of quartz. For this reason, with which Jones is perfectly familiar, his critics allege that he has given undue importance to sericite.

An argument against Jones' theory was given recently by Cooke (46), who found abundant sericite without silicotic nodules in the lungs of Lancashire miners who had had no important quartz exposure. But in these same mines drillers who had worked extensively in quartz-bearing rock showed silicotic nodules, fine quartz crystals, and sericite. No data on the composition or concentration of the dusts breathed in the two cases are given [see also (76)].

Silicates as a class can by no means be considered harmless. It was pointed out by Sayers (213) that miners' consumption was rather common in the Broken Hill district of Australia where the rock contains considerable sillimanite, Al_2SiO_5, fibrous silicate, and a rather low percentage of quartz, 12.23 per cent. The studies by Badham (12) in this district and earlier in the sandstone quarries (13) of New South Wales give considerable support to Jones' present claims that silicates, particularly fibrous

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varieties, may well be the cause of pulmonary disability. Badham in 1927 coined the word *silicatosis* to cover disability from the inhalation of silicates. Recently McCord (179) has reviewed the data on the effects of silicates.

Other silicates like talc (38), $H_2Mg_3(SiO_3)_4$; shale (38, 149); kaolin (38, 148, 149), $H_4Al_2Si_2O_9$; feldspar (38); cryolite (98), Na_3AlF_6; and pure mica (199) give much less specific pathology than does quartz. A moderate fibrosis may appear after exposure to numerous materials but this fibrosis is usually not disabling.

CARBON DUSTS

As long ago as 1838 Stratton (226) 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.

Cummins and Sladden (51) 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." They consider that a "considerable degree of anthracosis is consistent with working health" and that "coal miners especially exposed to silica dust are liable to develop a silicosis which, complicated by the effects of anthracotic dust accumulation, may lead to disablement and death."

"We believe that in the absence of the silica factor there would be, under modern mining conditions, no serious degree of anthracosis, that in fact anthracosis is essentially a special variety of silicosis depending on the simultaneous or subsequent accumulation of coal dust in the silica-damaged lung."

Collis and Gilchrist (43) and recently Hall and others (102) investigated the health of men with a history of prolonged coal-dust exposure from trimming coal in the holds of ships. Some of the men had experienced long exposures and apparently dust concentrations were often heavy, but, unfortunately, these are not indicated. Impurities, *i.e.*, silica, were absent in any but insignificant amounts. Some fibrosis was found, to be sure, but it was not disabling.

It was suggested by Haldane (100) that carbon dust be blown into the air as an antidote for quartz. Since carbon stimulates phagocytosis, it was argued that quartz and carbon would be less dangerous than quartz alone. In the South African mines dustiness is controlled mainly by wet methods which increase the moisture content of the air. As the mines get deeper, the temperature of rock increases and a high percentage of relative humidity becomes increasingly serious. Haldane suggested that dry methods be used with appropriate exhausts and collectors and that such dust as escapes be physiologically neutralized or diluted by blowing in carbon dust. No serious attempt has been made to test the validity of these claims.

CALCIUM AND MAGNESIUM CARBONATES

Dusts of these compounds commonly result from the handling of limestone and marble, $CaCO_3$; magnesite, $MgCO_3$; and dolomite, $CaCO_3.MgCO_3$. Often the parent rock is comparatively free from quartz.

Workers exposed to these dusts show no unusual incidence of tuberculosis and even mild fibrosis is infrequent. Thus, marble cutters present a very different picture from granite cutters, among whom silicosis is common.

Gardner (86) noted the extraordinary rate at which heavy inhalations of marble dust were eliminated by his experimental animals and believed that the high solubility of marble was the explanation. According to Seidell (217) the solubility of calcite dust below 10 μ is 756 p.p.m. at 35°C.

In the southeastern Missouri lead belt the rock mined is mostly dolomite and silicosis is virtually unknown. Titus (232) found the solubility of dolomite dust from these mines to be 300 p.p.m. in distilled water and over 700 p.p.m. in water through which carbon dioxide was bubbled, both figures being measured

at 36°C. These solubilities are ten to twenty times higher than those of quartz and offer a logical explanation of the harmlessness of the calcium and magnesium carbonates.

The studies by Thompson *et al.* (231) in the cement field showed that a fibrosis could be produced after long exposure, but there was no disability in any way comparable to that he and his associates found in the Barre granite region of Vermont (210).

GYPSUM

This mineral, $CaSO_4.2H_2O$, is very common and is mined and milled in large quantities in various parts of the United States. When it has been partially dehydrated by burning, it again takes up water with avidity so that one might expect it to be especially objectionable when breathed. However, Riddell (203) made a study among gypsum workers and concluded that the dust hazard was not important. The investigations of Miller and Sayers (186) regarding the effect of gypsum dust upon animals also were negative.

IRON DUSTS

Perhaps the most important ore mined today is hematite, Fe_2O_3. In this country and in many others the ore body often contains various forms of quartz, such as chert and jasper, which are notably silicosis producing. None of the oxides of iron, of themselves, however, have been shown to be dangerous, although the lungs of men who have been exposed to the iron dusts are colored characteristically and are called *siderotic*. Such lungs were first described by Zenker (260), then by Goadby (89), and more recently by Stewart and Faulds (224).

Within the last few years there has been a tendency to substitute steel shot for sand in the pressure blasting of castings. The main argument for the change has been the virtual elimination of the silicosis risk in an occupation which formerly was considered hazardous, the assumption being that dust from steel shot is harmless. The workers, of course, are supposed to wear the usual positive pressure air helmets (page 272) whether blasting with shot or sand.

THE ROCK DUSTING OF COAL MINES

As the result of a most fruitful cooperation between British and American investigators studying the prevention of coal-dust

explosions, several standard procedures have been established, one of which is rock dusting. An explosion of bituminous coal dust is possible in normal air only with dust concentrations of the



FIG. 18.—Dusting of bituminous coal mines with powdered limestone to avoid fire and explosion hazard. The finely ground dust is sprayed against the walls and roof as the mine car is pulled along. The U.S. Bureau of Mines recommends the use of pure limestone, dolomite, and gypsum dusts as being physiologically safe. (*Courtesy Mine Safety Appliances Company.*)

order of 10 to 100 grams per cubic meter, which is far above the stable range (see page 252). The propagation of a flame through coal dust takes place, usually, following a small explosion that

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shakes off accumulated dust from rafters, causing momentarily an inflammable concentration. If this rafter dust is mixed with a sufficient quantity of a nonflammable dust, like limestone, an effective barrier to flame propagation results. Of course the obvious cure for the explosion hazard is to prevent dust accumulation or to keep the accumulated dust moist, but sometimes these measures are inapplicable.

Being thoroughly aware of the dangers of breathing dust rich in free quartz, the two governments, followed by others, advocated the use of pure limestone, dolomite, and gypsum for dusting bituminous mines (202). All of these substances were studied by Miller and Sayers (186) with special reference to their use in rock dusting. In Fig. 18 is illustrated a modern rock-dusting machine distributing powdered limestone.

It might be pointed out that a dust explosion in either a mine or a factory is about the worst industrial catastrophe that can occur. Silicosis or any other industrial disease is as nothing to a dust explosion that wipes out an entire plant or mine and most of the employees in a matter of seconds. Consequently, if the management happens to use, in ignorance, a dust that is physiologically dangerous, instead of one that is recommended, this error may, perhaps, be excused.

THE DETERMINATION OF SILICOSIS POTENCY OF DUSTS

In the absence of data on human subjects, an estimate of the likelihood of a disabling fibrosis from breathing a particular dust is determined upon experimental animals. Of course, the great difficulty has always been the avoidance of the five to twenty-five years' exposure so often needed to produce disability in humans. The span of life of small animals is so short that dusting must be very much heavier than is needed to produce silicosis in humans. At best, all such animal dusting experiments are time consuming and expensive so that more rapid methods are desirable.

At the present time the appraisal of dust potencies has been carried out by so many different techniques that results from different laboratories often cannot be compared. It is probable that a technique acceptable for such comparisons will be developed, but the present situation is confusing.

Gardner has developed at the Saranac Laboratories a dusting technique that he has applied with great success to the study of different dusts. He studies also the effects of a special strain of tubercle bacillus before and after prolonged dusting. Direct dusting methods have, of course, been used widely by others.

Kettle has introduced liquid suspensions of dusts intratracheally in animals and subcutaneously, producing in the latter case silicotic pathology in parts of the body other than the lungs. Miller and Sayers (186) injected into the peritoneum of guinea pigs the dust suspended in physiologically inert salt solution and have thus compared calcite, limestone, precipitated calcium carbonate, gypsum, Portland cement, quartz, chert, flint, soapstone, carborundum, rouge, anthracite and bituminous coal, and fly ash. The technique is very simple and significant results are obtained in a matter of a few weeks.

Recently C. K. Drinker *et al.* (62) suggested injecting the dust suspension directly into the lymph stream just above a lymph node. In a very short time indications of the potency of the dust are observable from a portion of the excised node. If phagocytic cells are affected adversely by the dust, then characteristic pathology is observed.

PARTICLE SIZE

Practical Limits of Size in the Air. Particle size of industrial dust is never under control but varies with the method of production and with the nature of the original material from which the dust is generated.

It is impossible commercially to grind any mineral to a degree of fineness and uniformity comparable to that exhibited by metallurgical fumes. There are two reasons for this: first, it takes less force to produce large particles than small; and second, the fine particles act as cushions around the coarse ones, damping the impact and thus preventing further shattering. For this reason in some commercial grinding plants an effort is made to wash out the fines as rapidly as they are formed.

Because of the difficulties associated with commercial fine grinding, Kotzé (154) suggested that ordinary industrial processes are unable to crush appreciable quantities of dust to a size less than 0.5 μ. Bloomfield (20) agrees and in substantiation found, by particle-size measurements of about fifty industrial

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dust samples (collected with Owens' apparatus, page 100), that only 20 per cent of the particles were smaller than 1 μ, with a median size of 1.3 μ. No significant difference in size was observed among the various industries. In contrast to these results, dust in the general atmosphere was found to have a median size of 0.5 μ, with only 3 per cent larger than 1.0 μ. From these data, which agree with the findings of others, including ourselves, it is suggested that industrial-dust particles are larger than 0.5 μ and that the great numbers of particles less than 0.5 μ observed in dust samples are present in normal air as well as in industrial atmospheres and therefore have no hygienic significance. We disagree with these conclusions for several reasons.

1. It is true that dust of submicroscopic size cannot be produced on a practical scale by any present crushing process; the power consumption is too great because of the cushioning effect. But when dust particles are thrown off by the blow of a pneumatic tool, they are scattered immediately and no cushioning or softening of the blow takes place. The effect is like that from blasting.

2. If countless numbers of submicroscopic particles are present in the general atmosphere, particle-size samples collected in factories as well as general-air samples should show their proportionate numbers of such particles. Our investigations indicate that < 0.5 μ particles are not present in vast numbers in normal air since we have never found more than 12 million particles per cubic foot in average city air, with dark-field microscopy.

3. The limit of resolution of the light-field microscope is not much less than 0.5 μ under the most favorable conditions and it seems to us that this method of measurement should not be used to determine the presence or absence of particles smaller than 0.5 μ. Particles of carbon and other organic matter in normal air are likely to be opaque and are therefore visible in smaller sizes than is the case with transparent and semitransparent particles of siliceous material; this opacity tends to exaggerate the difference in size between normal and industrial dusts.

4. Vast numbers of particles below 0.5 μ are generated by industrial processes. For example, Hatch and Pool (117) found that 10^{12} particles less than 0.8 μ are produced each minute by an ordinary pneumatic rock drill.

Higgins *et al.* (127) demonstrated the presence of excessive numbers of mineral particles in a mine heading some 4 hours after work had stopped. Hatch and Pool found ten times as many particles in impinger samples by dark-field microscopy as were noted by ordinary light-field microscopy and showed that these particles were definitely of industrial origin. Thus, a general-air sample taken in a granite shed gave counts of 229×10^6 and 18.9×10^6 per cubic foot by dark-field and light-field illumination, respectively. Therefore, 210×10^6 were too small to be seen by the standard setup. That they were of industrial origin is proved by the fact that the concentration in the general air just outside the plant was only 20×10^6 by dark-field microscopy.

From the above evidence it is our opinion that the lower limit of dust particles produced by operations like rock drilling is well below 0.5 μ, though this lower limit has not been determined. The upper limit is, of course, well within the visible range.

The maximum size likely to be inspired is well within microscopic limits. According to Fig. 2 (page 6), a 10 μ particle settles 0.5 cm. per second and a 20 μ particle settles 2 cm. per second. The practical limit, therefore, cannot be much above 20 μ. This conclusion is supported by the Barre granite study (210), *viz.*, " . . . the difference between total particles and the particles under 10 μ was very slight and was not significant in the dust found in the granite sheds." While the number of particles greater than 10 μ may be insignificant, the bulk of the weight is contributed by such particles. Thus, in several foundry-dust samples we found 73 per cent of the weight contributed by particles over 10 μ, whereas these amounted to only 1 per cent of the total number.

Physiological Limits of Particle Size. The role played by fine particles in the production of lung fibrosis was first emphasized by McCrae (180) in 1912. Seventy per cent of the particles in silicotic lungs were found by him to be less than 1 μ and the largest did not exceed 10.5 μ. Results obtained by others are in substantial agreement. Largely on the basis of this work, Mavrogordato (176) defined phthisis-producing dust as particles of free silica of from 0.5 to 5 μ in diameter. Others put the upper limit at 10 μ and advance several physiological reasons for so doing: large particles are caught in the respiratory tract and

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removed by ciliary action; alveoli are not large enough to admit them; phagocytes will not take up particles over 10 μ in size. The first reason is undoubtedly an important one although it is not probable that such action prevents the entrance of all such particles to the depths of the lungs. Cooke (46) has recently pointed out, with respect to the second, that an alveolus is at least 250 μ in diameter and is therefore large enough to admit particles many times greater than 10 μ. According to C. K. Drinker (60) there is no apparent reason why particles over 10 μ cannot be picked up by phagocytes and transported to the lung tissue.

No physiological reason is required to account for the practical absence of >10 μ particles from silicotic lungs since they are not found in great numbers in the inspired air.

With respect to a lower limit, it has been alleged that particles of the order of 0.25 μ to 0.50 μ are too small to be phagocytosed, that they are too small to be retained in the respiratory passages, and finally that they are not generated by the usual industrial processes. Of these three arguments the last has just been shown to be incorrect.

As to the first, there is no physiological reason why particles below 0.5 μ cannot be phagocytosed. Drinker (65) found phagocytosed dust particles about the size of industrial dust, but his microscopic setup did not admit of accuracy below 0.5 μ. It is well-known that phagocytes ingest true colloids, while some dyes are taken up and coagulated by phagocytes.

Policard (198) claims that small particles are usually lost by the analyst during digestion of the lung tissue. Cooke (46) noted the presence of innumerable small particles, visible only by dark-field microscopy, and states that "there must be, therefore, enormous numbers of ultramicroscopic particles of silica in silicotic lungs."

With respect to the claim that submicroscopic particles are not retained on inhalation, it must be pointed out that the retention figure is purely relative. We found retentions of 40 to 50 per cent (see page 66) with 0.6 μ particles of zinc oxide and even smaller particles of magnesium oxide.

Modern theories of silicosis production lend no support to the idea of fixed limits to the size of particles that initiate fibrosis. Heffernan and Green (124), for example, state that there is no

possible limit to the fineness of the offending dust. It does not follow from this, however, that all silica particles, regardless of size, are equally dangerous. Gardner and Cummings (85) showed recently that a much severer reaction resulted with a given weight of 1 to 3 μ quartz particles than with an equal weight of 6 to 12 μ particles, the latter being comparatively inert. These results are explained in part by the greater solubility rate, although the ultimate amount dissolved is probably nearly constant within the size range of inspired dust. Also, the rate at which particles are taken up by phagocytes and transported in the lymphatics probably increases with decreasing size.

One-half micron particles doubtless will not produce the same total lung damage as equal numbers of 5 μ particles, but the rate of damage is probably faster with the finer particles. With equal concentrations by weight, on the other hand, a greater amount of damage will be produced by the smaller size. Thus it may be said that the rate of progress of fibrosis depends upon the size of the particles, whereas the total amount of damage is determined by the mass concentration of active material.

Neither upper nor lower size limits are known for toxic substances like lead or the metal fumes or the allergic dusts. More violent reactions are obtained from exposure to finely divided zinc oxide than for flocculated and poorly dispersed material (71). Hay fever attacks can be produced at any time of the year, and there is every reason to suppose that broken pieces of pollen are even more potent than fresh whole pollen grains. Solubility and wettability are important factors in determining the reaction to these materials and phagocytosis usually plays an important part as well. In consideration of these facts, we see no reason to suppose that physiological size limits exist for these substances.

DIFFERENTIAL DISINTEGRATION AND SELECTIVE SETTLEMENT

Dust consists of finely comminuted grains or particles composed of the same mineral constituents as the original material from which it was produced, *i.e.*, it contains no new substance. It does not follow, however, that the percentage composition of the air-borne dust is the same as that of the parent substance; there are, on the contrary, two important factors that act to

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change the composition: (1) differential disintegration, and (2) selective settling of the dispersed particles. Under the action of the first, the material may shatter in such a way that one or more constituents tend to break free as large particles while others are released in the form of minute particles. When these are thrown out into the air, the large ones, because of their much higher settling velocity, are rapidly removed from the air, leaving in suspension the finer particles of the dust, with, perhaps, a different composition, to be inspired by the exposed workers. Selective settling is also affected by the shape of the particles and for a given size, flat or platy particles will remain longer in suspension than roundish particles; this may cause a further change in the percentage composition of the suspended dust.

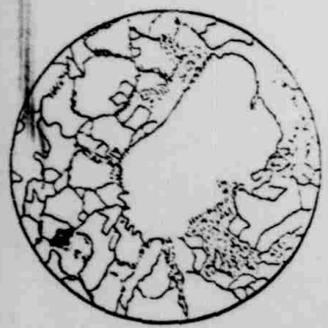


FIG. 19.—A microscopic section of Transvaal "Banket." Clear areas are quartz; acicular aggregates are mostly sericite. (*After Jones; courtesy J. Hyg.*)

The importance of these factors was first emphasized by W. R. Jones (139), who pointed out, for example, that the "banket" in the South African gold mines is made up of large crystals of quartz cemented together with a matrix of fibrous sericite (Fig. 19). When this rock is crushed by the action of a rock drill, the large particles of quartz are set free without much shattering and the sericitic cement is released as fine dust. The large quartz particles settle out of the air rapidly, leaving the sericite in suspension; thus, after 3 hr. settling, Jones found very little quartz in the air; the dust had become almost pure sericite (Fig. 20) (137). The same change was noted by Moir (189) as early as 1915 when he reported, " . . . that many of the particles in mine air, particularly after blasting, are not quartz, but come from the aluminous matrix of the banket: particles of sericite, chlorite and rutile or anatase are comparatively frequent in air after blasting, and when water blasts are in use, seem to resist wetting more than quartz particles do, and consequently remain unlaid." Chemical analysis of air-borne

dust at that time revealed a great increase in its alumina content as compared with the quantity in the original ore. In spite of this early observation, it has been common practice to report the free silica content of the dust in these mines, based on the analysis of the original banket, as 80 per cent or more. In contrast to this, Jones has calculated from chemical analysis

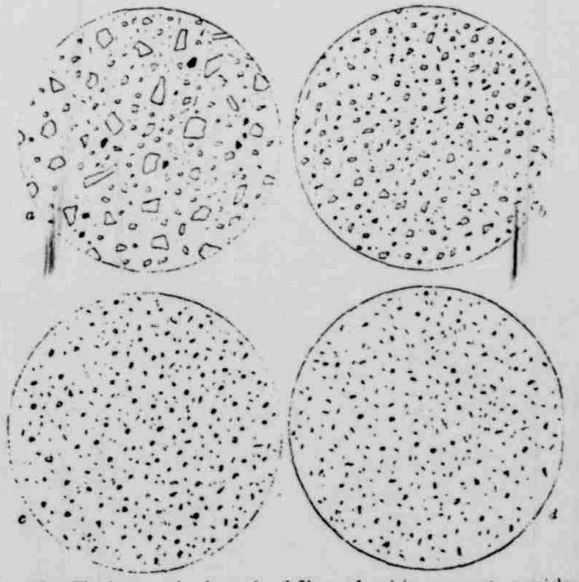


FIG. 20.—The increase in the ratio of fibers of sericite to quartz particles at different periods after blasting in Witwatersrand gold mine. (*a*) About 15 minutes after blasting; (*b*) about 1 hour after blasting; (*c*) about 2½ hours after blasting; (*d*) about 3 hours after blasting. (*After Jones; courtesy J. Inst. Mining Met.*)

of the fine dust itself that its quartz content may be as low as 20 per cent.

To emphasize the significance of those factors Dr. Jones draws the following analogy (80): "When a wall built of quartz boulders is pulled down, the bulk of the dust comes not from the quartz boulders but from the mortar." He says further: "A sericitic sandstone containing 75 per cent or more of free silica can give rise to dust of respirable size which contains less than 25 per cent

of free silica and more than 70 per cent of sericite in minute particles." Work at the University of Birmingham (243) confirms the importance of differential disintegration and selective settling. Analyses of air-borne dusts produced by rock drills showed almost invariably that the free-silica content is appreciably less than for the coarse borings from the same rock. Hurlbut and Beyer (132) showed that the selective settling of certain foundry dusts resulted in the rapid concentrating of sericite in the air-borne dust so that the dust inspired by the foundry workers was rich in sericite in spite of its very low concentration in the original foundry sand.

In the southeast Missouri lead belt, the lead occurs as galena (sp. gr. = 7.4, hardness = 2.6) in dolomite (sp. gr. = 2.8; hardness = 3.7). Because galena is two and a half times as heavy as dolomite, there is a decrease in the lead content of the air-borne dust as compared with the content of the parent rock. Thus we found that the lead content of impinger dust samples from these mines rarely exceeded 0.5 per cent although a composite rock sample averaged over 4 per cent lead. The degree to which these factors act to alter the composition of the suspended dust depends upon the structure of the original material, for this determines the manner in which it crushes. The degree of nonuniformity in the size of particles produced is greater and the tendency for one constituent to be released in larger sizes than others is more marked in the case of a coarse flaky granite or granitic schist, for example, than in a fine-grain compact stone.

Foundry dust presents an interesting case. A good molding sand is made up of about 80 per cent quartz in the shape of coarse particles; the bulk of the remaining material is clay in the form of fine particles which coat the coarse quartz grains. The chemical composition of the finer fraction (say below 10 μ) of material in foundry sand is markedly different from the composition of the coarse fraction. This is clearly shown in Table 10. One notes, for example, that there is over four times as much free silica in the coarse as in the fine fractions, whereas the clay and acid-soluble constituents contribute nearly five times as much to the smaller sizes as to the coarse grains. The organic and other combustible matter is also concentrated in the fraction under 10 μ.

Strictly speaking, relatively little dust is actually produced by the basic foundry processes, such as preparing sand, molding, and shaking out. These operations merely cause the dispersion of the fine material already present in the molding sand without breaking down the coarse particles to any extent.[1] Hence the air-borne dust in a foundry will contain much more clay, etc., of respirable sizes and correspondingly less free silica than the original molding sand.

TABLE 10.—COMPOSITION OF COARSE AND FINE FRACTIONS OF UNUSED FOUNDRY SAND CONTAINING NATURAL BOND

Constituent	Percentage by weight		
	Total sample	>10 μ	<10 μ
Combustible	2.3	0.7	12.7
HCl soluble	5.5	1.6	30.5
H_2SiF_6 soluble (clay)	16.0	12.7	37.5
Residue (quartz)	76.3	85.0	19.2
Total	100.0	100.0	100.0

A microscopic study of the original material from which the dust arises and a knowledge of its geological history will be helpful in estimating the importance of differential disintegration and selective settling in determining the change in composition of the dust from the parent rock. It is clear from the foregoing that one cannot judge the chemical and mineralogical composition of the dust that actually gets into the lungs of the exposed workers by analyzing only the parent substance, nor is it safe practice to analyze for this purpose a deposit of settled dust, such as a "rafter sample," since the settled material, owing to higher settling rate for coarse particles, contains a greatly exaggerated proportion of coarse particles as compared with the number in the air. It is necessary to separate the dust sample into size fractions in order to study the change in composition with size, and the sample itself is best taken directly from the air at the breathing zone (page 153).

[1] Some of the quartz in contact with the molten metal in the mold is broken down by the intense heat and the free-silica content of the fine fraction is increased, but this is counteracted by the dilution given by the powdered coal that is added to molding sand in many iron foundries.

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