PLAINTIFF'S EXHIBIT

MET-441

microns in diameter, administered in 20 doses over a period of sixty days.* Particles introduced by this method are retained in the capillary systems of various organs long enough to be phagocytosed. Most of those of the standard size adopted for this test pass through the vessels of the lung and come to rest in the sinuses of the spleen and the sinusoids of the liver. A few lodge in the capillaries of the bone marrow but practically none remain in the renal vessels. The mobile phagocytes then transport them into the connective tissues where they either remain in masses or enter the lymphatics and are carried to regional lymphoid tissues. Wherever a sufficient number of particles is thus collected one expects to discover evidence of the reaction characteristic of the material. If uncombined silica has been injected a progressive fibrosis occurs which becomes visible to the naked eye within three months and continues to progress throughout the life of the animal. (Figure 2, *a, b, c, d, e, f.*) All silicates and all non-siliceous particles that have thus far been tested have provoked such slight amounts of chronic inflammation within

* A sufficient quantity of particles between 1 and 5 microns in diameter is prepared by elutriation in water or other suitable fluid. They are washed and sterilized by dry heat. A weighed amount of the particles is placed in a sterile watch glass and at one side a few drops of physiologic salt solution are added. By careful trituration with a rubber "policeman" the dust is gradually worked into a uniform suspension, adding more drops of the saline solution as necessary. It may require several hours to work up the full gram of particles but when finished one has a thin watery paste with no clumps and all of the particles wetted. For routine purposes enough salt solution is added to bring the final suspension up to 1 per cent strength. Suspensions of relatively insoluble dust are again sterilized in an autoclave. Tests with pure quartz have demonstrated that such treatment does not increase its irritating properties. More soluble dusts have to be sterilized dry and suspended immediately before injection. Injection of 5 cc each are made every three days into the ear veins of full grown rabbits until the full dose of 1 gram has been introduced. To protect the ear veins from local injury by the dust, a few cc of salt solution are washed through them from a fresh syringe before withdrawing the needle. As a routine procedure 4 rabbits are injected with each type of dust; 1 is killed on completion of the last injection and the others six, twelve and twenty-four months thereafter.

periods of one and two years that microscopic sections must be used to detect it. (Figure 3, *a*, *b*, *c*, *d*, *e*.)

Many other injection methods are being used with considerable success in spite of their objectionable features. For example, the intraperitoneal technique of Sayers and Miller[2] (1934) will give gross evidence of reaction to free silica within a few weeks or months. The procedure is simple and requires no special apparatus. One or two cc of a 10 per cent saline suspension of dust particles that will pass a 350 mesh screen are injected directly into the abdominal cavity of a guinea pig. Particles slowly soluble in water provoke a transitory reaction which later disappears, leaving no trace of the dust or the cellular changes. Full doses of more soluble substances like sodium silicate and dolomite are apt to kill the animal immediately because of their strong alkalinity ; but smaller quantities may be tolerated. Insoluble dusts produce a minimal amount of inflammation which does not increase with the elapse of time and the injected particles remain in the tissues for an indefinite period. Free silica either alone or in association with other materials causes progressive proliferation resulting in the formation of fibrous nodules several centimeters in diameter after six to eight months. The silicates produce nothing like the reaction to free silica ; some of the hydrous forms are capable of causing necrosis or death of the tissues but such reaction is of microscopic proportions and it has not been followed by significant amounts of fibrosis.

On the basis of their experience with this test Miller and Sayers classified the activity of dusts as proliferative, absorptive or inert. The only cause of proliferative reaction which they or other investigators have discovered is free silica. The slowly soluble compounds of calcium are generally classified as absorptive. The inert minerals include most of the silicates and a wide range of insoluble non-siliceous substances. It has

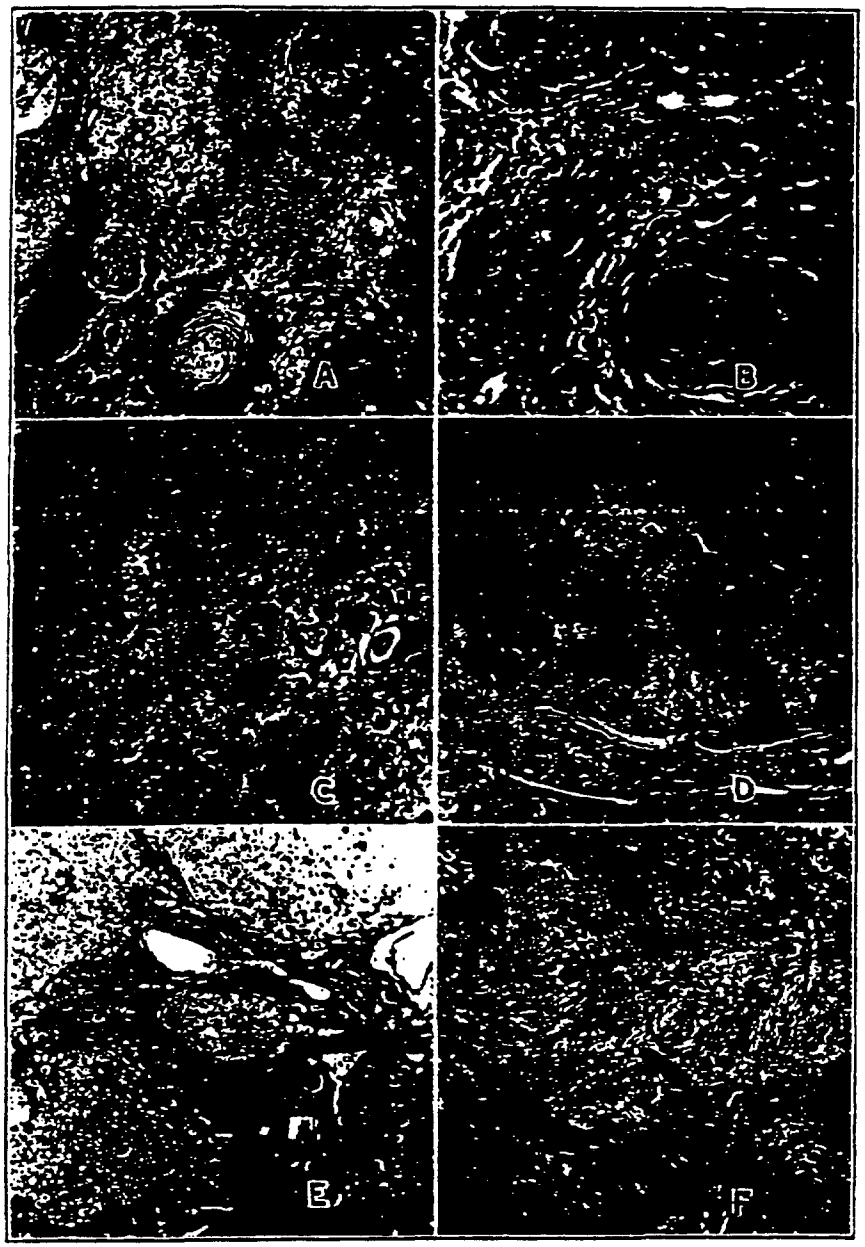


FIGURE 2. See caption on page 265.

been assumed that non-proliferative reactions in all animals killed within a period of one year after intraperitoneal injection indicates that a mineral is incapable of causing significant responses by living tissues. Perhaps this assumption is unwarranted : longer contacts might result in an interaction between foreign particles and the body fluids that would provide a stimulus to cell proliferation. But even if time is the essential factor, which has hitherto been too greatly curtailed, one would expect some evidence of a progressive change within a period of twelve months. Such has not been the case in an investigation of some 30 different minerals, other than free silica, investigated in the writer's laboratory. The tissue changes have remained stationary or actually retrogressed.

Another method of testing is that of intratracheal injection of particles suspended in physiologic salt solution. It was used extensively by Kettle[3] (1930) and by Lemon[4] (1933). The injection of fluid into the air spaces causes a transitory, inflammatory edema of the lungs which may be followed by more chronic changes in the presence of irritating silica. Because of the difficulty in differentiating between

FIGURE 2

Intravenous injections of pure free silica. *a*. Normal quartz, one year after completing injections. Replacement of most of parenchyma by diffuse and nodular fibrosis. *b*. Normal quartz, 22 months after completing injections. Higher magnification of nodular and diffuse fibrosis with necrosis still in progress along cluster of parenchyma cells at upper border. *c*. Tridymite, 80 days after completing injections. Destruction of most of parenchyma cells and replacement by diffuse fibrosis. *d*. Tripoli, one year after completing injections. Extensive nodular fibrosis : large area of diffuse fibrosis at lower border. *e*. Opal, one year after completing injections. Residual fibrosis and collections of large phagocytes in portal connective tissue. Reaction subsiding rather than progressing. *f*. Diatomite, two years after completing injections. Widespread nodular fibrosis replacing much of parenchyma.

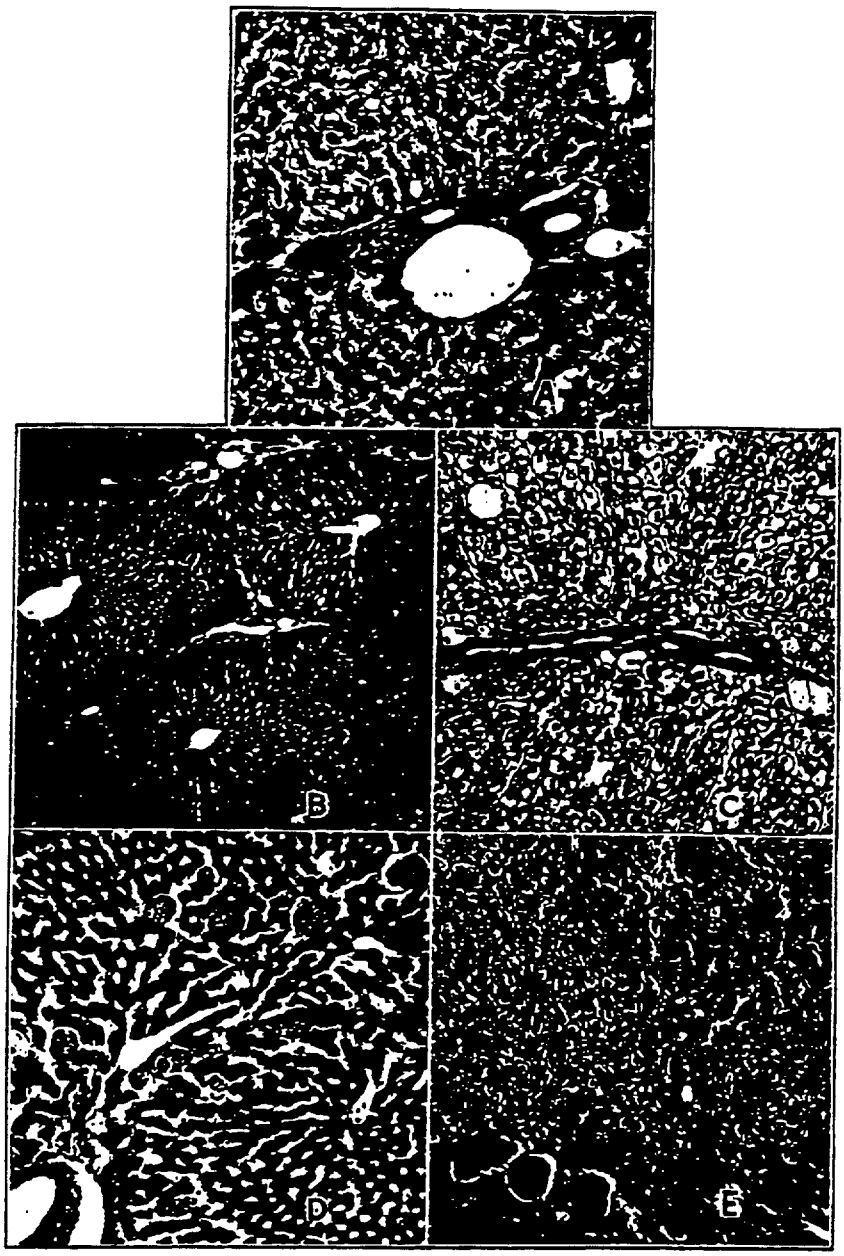


FIGURE 3. See caption on page 267.

the non-specific effects and the specific ones produced by the particles themselves, the lungs are not as good a place to study the results of such injections as the lymph nodes which receive their drainage. Particles accumulate in the tracheobronchial nodes by physiologic mechanisms and there produce specific reactions commensurate with their physicochemical composition.

As already indicated, results can be obtained by direct injection of suspended particles into the subcutaneous tissue, the testis, the eye and other organs, but in all cases the nonspecific reaction is confusing. A series of intratesticular injections now under observation demonstrates more evidence of cellular reaction to many of the silicates than to nonsiliceous substances. Since this observation is at variance with the findings in intravenous and intraperitoneal tests with the same substances it is difficult to evaluate the results.

Intracutaneous injection was tried and for a time it appeared that this might prove a valuable diagnostic procedure. Injection of 0.1 cc of a 0.2 per cent suspension of silica particles under 3 microns in diameter *into* the skin of a guinea pig will cause a local inflammation in a few hours. Between eighteen and forty-eight hours thereafter a central

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FIGURE 3

Rabbit livers after intravenous injection. *a*. Aluminum oxide, 18 months after completing injections. Particles collected in large phagocytes situated in portal connective tissues. No fibrosis. *b*. Garnet, 6 months after injections. Phagocytes filled with particles scattered widely through sinusoids and in portal areas. No fibrosis. *c*. Feldspar, one year after injections. Large phagocytes filled with particles in portal areas and in sinusoids. No fibrosis. *d*. Fibrous sericite, 8 months after injection. Giant phagocytes still scattered through sinusoids. No fibrosis. *e*. Talc particles, 2 years after injection. Giant phagocytes collecting in and about a portal area; some lymphocytic infiltration. Focus of proliferation about phagocytes in parenchyma with early necrosis and slight polynuclear infiltration. No fibrosis.

zone of ulceration develops so that the area resembles a strongly positive tuberculin reaction. Comparable injection of non-siliceous particles causes only a transitory swelling and redness which quickly subsides leaving a central spot of pigment if the particles are colored. Unfortunately some of the silicate dusts also produce rapid inflammation and it has not always been possible to differentiate them from reactions to free silica.

A wide choice of *animal species* is open to the experimentor and he can select one adapted to his purpose by reason of anatomic peculiarities. White rats of strains that are resistant to pulmonary infection make excellent subjects for dust inhalation experiments as their lungs develop nodular fibrosis during a six to eight month exposure to pure silica. These lesions more nearly resemble the silicotic nodules of human beings than any yet observed in other animals. (Figure 1 *a, b*) But the white rat is naturally resistant to tuberculous infection and little is known of the cause of its immunity. Guinea pigs, on the other hand, develop a modified type of silicotic nodulation at a somewhat slower rate; the reaction is specific for silica but it bears less resemblance to the human lesions. (See Figure 5-*c*) However, guinea pigs are susceptible to tuberculosis and so much is known about their response to this infection that they are invaluable agents. Rabbits of certain breeds react readily to inhaled silica and develop nodular fibrosis. Such nodules tend to undergo necrosis with subsequent calcification, a change encountered in certain human beings who are apparently free from infection. The rabbit's large, superficial ear veins makes it the animal of choice for intravenous injections. (Figures 2 *a* to 2 *f*) This species is extremely susceptible to tubercle bacilli of bovine type but less so to those of human origin. In rabbits alterations of native susceptibility induced by coexistent silicosis have been well demonstrated

by infection with human type tubercle bacilli. Cats react well to inhaled silica ; their relatively small hearts and large lung fields make them admirable subjects in which to follow the course of a pneumoconiosis in roentgenograms. Dogs react rather slowly to silica injected by vein, but advanced though somewhat localized visceral changes in the liver have now been produced. Domestic fowl develop nodular fibrosis of both the lungs and the appended air sacs when exposed to the inhalation of silica. (Figure 5 *a*) The specificity of such reaction in chickens has not been tested by parallel exposures to other dusts but there is no reason to doubt that this species is unique. Even gold fish and tadpoles develop a characteristic necrosis followed by fibrous proliferation when suspensions of silica are injected into their tissues. White mice react in a similar manner to injected silica but they apparently have very effective upper respiratory protective mechanisms for after a year's exposure by inhalation only a few phagocytes filled with silica are observed in their lungs.

General Tissue Responses to Various Kinds of Mineral Particles

Non-siliceous Particles. Tests of this nature in different animal species are demonstrating that all relatively insoluble non-siliceous particles, except those generally recognized as poisonous, tend to produce the same cellular changes. The particles are ingested by mononuclear phagocytes which transport many of them into the connective tissues. There they remain or through the agency of the lymphatic vessels they are carried to the nearest lymphoid tissue. The same phagocyte seems to be capable of taking in an extremely large number of particles of the size under consideration. Its cytoplasm enlarges to accommodate the burden and in many instances its nucleus divides to form a small giant cell. In the latter case the newly formed nuclei tend to arrange them-

selves in a single row beneath the surface membrane. Overloaded cells are apparently paralyzed for they generally remain at the site where they develop. The smaller cells which happen to have ingested fewer particles exhibit their customary amoeboid activity and they are chiefly responsible for the accumulation of particles in the stroma and lymph nodes. In the case of non-siliceous substances they may pile up enough particles to produce gross pigmentation but this is associated with the most insignificant changes in the fixed tissues. There may be small accumulations of lymphoid cells and perhaps a proliferation of a few fibroblasts. Once formed such reaction does not progress or at least no progression has been observed over a two year period. While the histologist might be justified in describing this picture as a cellular fibrosis it is far too slight to be detected by gross inspection or palpation.

The manifestations of such reaction in the livers of rabbits injected intravenously consist of isolated mononuclear and giant phagocytes scattered through the sinusoids and collected in small masses in the connective tissue about the bile ducts. (Figure 3, *a, b, c, d, e.*) A few lymphocytes may infiltrate the latter area. The picture is essentially the same whether observed immediately after completing the injections or two years later. The spleens of such animals usually show more phagocytes and larger giant cells, most of which remain in the sinuses and cause little or no reaction in the fixed tissues.

The result is the same whether the foreign body is hard and insoluble (e.g. diamond, aluminum oxide, silicon, the carbide of silicon, rutile) or softer (e.g. coal, iron oxide) or slowly soluble (e.g. gypsum, marble, calcite, limestone). With the latter substances the cells tend to disappear as the particles dissolve. Still more readily soluble materials like dolomite are toxic because of the rapid change in hydrogen

ion concentration which they produce, but such effects are of no interest in this connection.

The silicates constitute a group of minerals whose biologic activity needs thorough investigation for they have frequently been suspected of causing pulmonary fibrosis in industry. If the generally accepted solubility hypothesis is valid many of them should be capable of such action for they are dissolved or otherwise affected by water. The recent literature contains several papers by petrologists who warn of the potential hazards from silicates. These authors have argued that since the asbestos silicates can cause pulmonary fibrosis, other forms that are also affected by water should produce similar reaction. They assert that asbestosis, and by inference "silicatosis" in general is merely a silicosis produced by the silica left after the body fluids have leeched the bases out of the silicate molecule. The validity of their speculations awaits demonstration.

The roentgenograms of persons exposed by occupation to the dusts of silicates like feldspar, mica and talc offer the most obvious and at the same time the most puzzling evidence of the existence of corresponding silicatoses. Many of these films reveal localized massive shadows which should probably be interpreted as a result of infection but there are some in which a fine, uniformly distributed reticulation characterizes the picture. Whether such shadows are actually due to reaction to the particular silicate with which the individuals last worked, should be determined by careful study of post-mortem material. Chemical and petrographic analyses must be made to determine whether there may not be appreciable quantities of free silica as well as silicates in the tissues. Histologic study of sections must demonstrate the character and distribution of the lesions, both those due to dust and those arising from associated infection. The possibility that certain kinds of dust particles in excessive quan-

tities may of themselves cast shadows on the film must be explored further. This idea was once entertained and discarded but Enzer[5] (1937) has now demonstrated that the apparent nodulation of electric arc welders is probably due to aggregates of very fine mineral particles in the lungs with no associated fibrosis. His observation necessitates further investigation of the subject to determine whether other dusts may not have similar effects. Proof of such properties would account for many of the shadows seen in the roentgenograms of silicate workers and would be more in keeping with the experimental observations to be reported in the following section.

To test the capacity of every known silicate to produce reaction in animals would involve a tremendous amount of labor and would serve no useful purpose for many of these minerals are of no industrial importance. The group of 24 silicates on page 273 has been chosen to include varieties used in industry and ones representative of important mineralogic classes. (Figures 3 *a*–3 *e*)

The specimens for this study were supplied by Professor Esper S. Larsen of the Department of Geology at Harvard University. Either he or Dr. Alton Gabriel of the U.S. Bureau of Mines analysed them petrographically and their chemical composition was determined at the author's laboratory. The rocks were pulverized in an iron mortar and then ground in steel ball mills until all of the particles were 3 microns or less in diameter. Wherever possible the grinding was done dry but in some instances it was necessary to add water or petroleum ether. To make certain that the composition of the different minerals had not been altered during this treatment the particles were again analysed in various ways. Petrographic examination so frequently failed with material of this size that this procedure was abandoned but chemical analysis was always done. A few minerals which

Anhydrous Silicates

Class	*Group*	*Variety*
Polysilicates ($R_2Si_2O_5$)	Feldspar	• Soda microline
Metasilicates ($RSiO_3$)	Pyroxene	Rhodonite
	Amphibole	• Anthophyllite (fibrous)
	"	† Tremolite
	"	† Soda tremolite
	"	† Amphibole
	"	† Crocidolite (blue asbestos)
	"	Beryl
Orthosilicates (R_4SiO_4)	Garnet	Almandite?
	Topaz	Sillimanite

Hydrous Silicates

Water of Crystallization	Zeolite Division	• Analcite (artificial)
Essential Water	Mica Division	Muscovite
	" "	Biotite
	" "	• Sericite (fibrous)
	" "	• Sericite (platey)
	" "	† Amosite (fibrous)
	Serpentine and Talc Division	† Serpentine
	" "	† Chrysotile (fibrous)
	" "	† Talc
	" "	• Glauconite
Water Variable	Kaolin Division	Dickite
		Halloysite
		Montmorillonite

Titano-Silicate

Anhydrous	Titanite

• Action observed for a year or more.
† " " " four months.

were appreciably altered were excluded from the study on this account. One substance, chrysotile asbestos, was also checked by roentgen-ray diffraction because of a peculiar change which suggested that its composition might have changed. When suspended in water, the ground fibres developed a marked tendency to agglutinate into compact ball-

like masses. Dr. William F. Bale of the University of Rochester very kindly compared the roentgen-ray diffraction patterns of untreated and treated asbestos and reported that there had been no change. It was therefore concluded that the treatment with water had not altered the molecular structure. This test was not used for the other minerals.

Suspensions of all of these silicates in physiologic salt solution were injected intravenously into rabbits and intraperitoneally into guinea pigs in the doses already mentioned. The study has not been completed but as noted in the above table the effects of 8 of the minerals have been followed for a year or more and 8 others, for at least four months. Most of the remaining ones have been injected but only a few animals of each series have been killed.

Within the period of observation no rabbit successfully injected with any of these silicates has shown evidence of connective tissue proliferation. Intraperitoneal tests on guinea pigs which concentrate much larger quantities of particles in localized areas have confirmed these observations. Two of the silicates have thus far proved difficult to inject intravenously. Glauconite particles agglutinate rapidly in aqueous suspensions and tend to cause thrombi in the rabbits' ear veins. None of the animals could be given more than 0.4 gm of this substance for after 9 injections all of the larger ear veins had been thrombosed. Chrysotile asbestos killed 8 rabbits either immediately or within twenty four hours, again probably because of its tendency to agglutinate in water. Although no thrombi could be found in the cerebral or other vessels it is believed that its action was mechanical rather than chemical because serpentine, which has the same chemical composition was tolerated readily. Furthermore, intraperitoneal injection of chrysotile caused no untoward effects. Incidentally the latter has failed to cause either fibrosis or the formation of asbestosis bodies in guinea pigs. Miller and

Sayers (1934)[2] had the same experience on injecting chrysotile intraperitoneally and were forced to classify asbestos as an 'inert' mineral. It is still possible that fibrosis may develop later for none appeared until the sixteenth month in guinea pigs inhaling this substance. However, this outcome is not anticipated in view of the excessive doses administered by the injections under discussion.

While evidence of fibrosis has invariably been lacking it cannot be maintained that all of the silicates have been absolutely inert. A rabbit has just been killed two years after intravenous injection of feldspar. The particles have localized to produce pigmentation of sufficient intensity to be visible grossly as a network of fine, yellow lines about each lobule. Microscopically the picture is essentially the same as the one at twelve months, shown in (Figure 3–c). The only change has been a further concentration of phagocytes in the portal areas. Another rabbit has died of an acute broncho-pneumonia approximately two years after a similar injection of talc particles. In this case the cellular reaction is much more advanced than that at the last sampling period. About the portal collections of phagocytes there is a well marked infiltration with lymphocytes. The collections of mononuclear cells in the sinusoids show active proliferation and in many of them there is necrosis with an infiltration of polynuclear leucocytes (See Figure 3–e). The possibility that some of the reaction in the liver is secondary to the acute infection in the lungs cannot be excluded.

Another unusual finding has occurred in animals injected with fibrous sericite. The sample selected by the petrographers as the most likely counterpart of the variety that Jones[6] (1933) described as the cause of silicosis has had an effect upon the phagocytes which is unique among silicates. Like free silica in the spleen, it has produced epithelioid changes in the monocytes and caused the formation of

giant cells of the Langhan's rather than the simple foreign body type. No other silicate has acted in this manner; the flat scaly sericite and the feldspar produced cells that were indistinguishable from those called out by inert non-siliceous minerals. The exact significance of this cellular change is not understood but there is nothing to indicate yet that it is a preliminary step in the formation of fibrosis as Drinker, Field and Drinker[7] (1934) suggested. The last rabbit injected with *fibrous* sericite died of a chronic abscess of the right lung after twenty-one months. The capsule of the dome of the liver immediately beneath the abscess was thick and fibrous but in the other portions of this organ and in the spleen and lymph nodes the reaction was essentially the same as that in the preceeding members of the series. If this silicate were capable of causing fibrosis such reaction would be expected in the presence of chronic infection.

One other effect has been observed which might be of some significance. Anthophyllite, both types of sericite, amosite, chrysotile and glauconite have caused a limited amount of necrosis when injected intraperitoneally into guinea pigs. Such reaction has always involved only small numbers of cells in the centres of masses of phagocytes but it has occurred in all animals injected with these substances. It has persisted without change for at least a year and has never been replaced by calcification. In no instance has there been any suggestion of fibrosis at its margin. It is interesting to note that three of these substances have a fibrous structure and that all but anthophyllite belong to the hydrous group of silicates. Such changes may be entirely non-specific but the fact that they occurred in every animal in each series and under conditions where non-specific pressure effects are minimal makes it necessary to mention them.

Intratesticular injections of garnet, chrysotile asbestos, talc and feldspar have caused inflammatory reaction whose sever-

ity has increased in the order named but for reasons stated above the significance of such findings is doubtful. Possibly the more marked responses to talc and feldspar may be indicative of specific irritating properties but if this is the case the effects are only produced by excessive local concentrations.

So much space would not have been given to reporting incomplete observations had not Professors Briscoe [9] and Brammall [8] (1937) recently postulated that those silicates which are affected by water should be capable of producing pulmonary fibrosis. Since their observations on the behavior of silicate rocks in nature and their test tube experiments have attracted considerable attention it has seemed worth while to present as much biologic evidence on the subject as is now available. Thus far their predictions have not been verified by the injection tests. While it is still possible that sericite and some of the other silicates may cause fibrosis after longer periods of contact with the tissues this outcome is not yet predictable. As will be shown presently, free silica injected under the same conditions produces its effects within a few months. According to hypothesis, the silicates that are more soluble should cause reaction in a shorter period of time. It might be claimed that the whole experimental program is invalidated by the failure to produce fibrosis with asbestos, but as already indicated *fibrous* foreign bodies present unique problems in the lungs which do not exist in other organs. However, final conclusions are reserved until after completion of the study.

Various forms of *free silica* have been subjected to the same methods of testing. This phase of the study is more nearly completed, although certain important types have still to be investigated. The following varieties have been under observation for at least a year after injection into both rabbits and guinea pigs :

Crystalline Silica	*Cryptocrystalline Silica*	*Amorphous Silica*
Normal Quartz	Chalcedony	Colloidal Silicic Acid
Tridymite (25% cristobalite)	Tripoli (Seneca, Mo.)	Silica Gel (16% H_2O)
Cristobalite		Opal (4.1% H_2O)
Vitreous Silica		Diatomite (7.6% H_2O)

The three conversion forms of quartz, tridymite, cristobalite and vitreous silica were prepared synthetically by Dr. L. H. Milligan of the Norton Company. It should be noted that the tridymite is not pure but contains about 25 per cent of cristobalite. The amorphous silica in the gel phase is a commercial product of high purity containing 0.033 per cent of Fe_2O_3 and 0.00005 per cent MnO as contaminants. It was made from sodium silicate. By petrographic analysis the unground diatomite was found to contain about 10 per cent of quartz but practically all of it was removed by elutriation of the ground material in water. All of the other substances were pure materials.

All of the crystalline and cryptocrystalline varieties of free silica have provoked a progressive fibrosis in both rabbits and guinea pigs. Intravenous injection into rabbits causes a silicotic cirrhosis of the liver and spleen with replacement of more and more functional tissue by hyaline fibrosis. Coincident regeneration of liver cells is sufficiently active to maintain hepatic function and life. One year after completing the injection of 1 gram of 1 to 3 micron particles whole lobes of the liver are reduced to exceedingly hard, white leathery scar, while regeneration has produced irregular lobules of new glandular tissue at the periphery. The spleen becomes large, pale, smooth and exceedingly hard. Microscopic sections may reveal no trace of normal structure. Both in this organ and in the liver there is a diffuse fibrosis in which are embedded characteristic silicotic nodules of laminated hya-

line fibres. Many of the latter have necrotic or calcified centers. The only normal elements left in the areas of diffuse reaction in the liver are bile ducts and blood vessels. (Figures 2 *a* & 2 *b*)

The evolution of this process has been described in a previous publication. (Gardner and Cummings 1933) [1] Here it suffices to relate that the silica particles coming to rest in the smaller blood spaces of the liver and spleen are engulfed by mononuclear phagocytes. Many of these primary phagocytes are killed and ruptured. Mavrogordato's 'ghost cells' are rare in organs other than the lung and only in that of the white rat has the author found them at all common. As they break down, the phagocytes release their particles and new cells quickly wander into the area to take up the material thus liberated. Repetition of this process results in an excess of cells. Now the number of particles per cell is no longer so great that the phagocytes are killed; they are merely stimulated. As manifestations of such stimulation one sees alterations in the morphology and the physiologic activity of the phagocytes. In the spleen they undergo the same 'epithelioid' changes that occur in tubercle formation and produce giant cells of the Langhan's type. These modifications have never been observed with any other mineral except fibrous sericite. As a further evidence of irritation the stimulated cells move with unusual rapidity. They collect in compact nodules in the organ first involved and they migrate quite rapidly into the nearest lymph node. Such action concentrates irritating silica in contact with the connective tissues. These elements are in their turn affected and undergo primary necrosis followed by proliferation. In the liver, the parenchymatous cells are killed with an invasion of polynuclear leucocytes. The destroyed areas are quickly replaced by proliferating connective tissue. A diffuse obliterating fibrosis results from the silica which remains scattered; nodular fi-

brosis develops about collections of silica brought to the portal areas by stimulated phagocytes.

The picture that has been described has been produced repeatedly by injecting 1 gram of silica particles, 1 to 3 microns in diameter. A further investigation of the effect of dosage has demonstrated several points of interest. As little as 0.1 gram will cause nearly as much reaction but in twice the time. Even 0.05 gram produces microscopic reactions but gross evidences of disease are only barely apparent after two years. When the dose is reduced to 0.01 gram the liver develops no lesion but the hepatic lymph node, which receives the drainage of this organ is completely destroyed and replaced by silicotic fibrosis. The lymphatics are capable of completely eliminating such small amounts of irritant so that the viscus escapes. The spleen, on the other hand, has no extravisceral lymphoid tissue. Most of the particles which lodge in its sinuses remain there and as a consequence even the minimal dose provokes a certain amount of nodular fibrosis.

Intravenous injection of too great a quantity of particulate silica is toxic and causes a reaction simulating that from colloidal silicic acid. Rabbits will not tolerate more than 0.05 gram of silica in 1 per cent suspension at a single time. If one attempts to introduce 0.1 gram the animals die very promptly with acute symptoms of intoxication. They shiver, gasp, run about in an excited manner and fall dead within a few minutes. Autopsy reveals an intense engorgement of the splanchnic vessels and perhaps petechial hemorrhages into the serous membranes. In guinea pigs a single dose of 0.02 gram injected into the heart generally has the same effect. The age of the suspension does not influence its activity; fresh preparations are just as potent as ones which have been kept in the refrigerator for several months. Comparable suspensions of non-siliceous particles have no such effect. It is therefore

inferred that in sterilizing the suspensions enough solution has occurred to liberate silica molecules, part of which assume a colloidal form.

The size of the silica particle has a marked influence upon the rate of reaction. All of the results thus far discussed have been produced by injecting particles 1 to 3 microns in diameter. Larger ones cause less active responses by the tissues: smaller ones are more irritating. Large splinters of quartz embedded in the subcutaneous tissue excite no more cellular response than pieces of carborundum of the same size. Particles of quartz 10 to 12 microns in diameter can be injected into rabbits' ear veins but owing to their size most of them are caught in the capillaries of the lung instead of passing through these vessels to the liver and spleen. However, they react just as well in the lung. They produce, not a progressive fibrosis, but merely a foreign body tubercle, which changes very little in two years' time. Intravenous injection of particles of silica less than 1 micron in diameter causes rapid death from acute degeneration of the liver cells. This has been proved for normal quartz, tridymite, cristobalite and vitreous silica. The animals have generally died before a half a gram or even less could be injected.

Recently a commercial vitreous silica composed of particles too small to be resolved under the highest magnifications, was submitted for a test of its toxicity. By indirect methods the particle size had been estimated at 0.0002 microns. It was of course anticipated that this material would prove extremely toxic when injected intravenously for a suspension in water should approximate the colloidal silicic acid used by Gye and Purdy. 1 per cent suspensions by weight were freshly prepared before each injection. The rabbits tolerated the material without symptoms; all of them remained well and were killed at intervals during a year. Only the last animal showed gross evidence of disease which con-

sisted of small localized areas of fibrosis in the liver. Microscopically there were slight traces of silicotic reaction in all other members of the series. Apparently the particles were so extremely small that most of them passed through the various capillary beds and were excreted in the urine. Colorimetric analyses of the latter in two animals yield high values. 27.17 and 32.95 mg. per 100 cc. Only a very few particles remained in the organs to produce disease after a year's time.

Guinea pigs injected intraperitoneally with 10 per cent suspensions of the same forms of free silica particles develop hard white nodules, 2 to 3 cm. in diameter in the omentum and other subperitoneal tissues. The centres of these lesions are at first soft and necrotic but after a year many have calcified. The retro-sternal and hepatic lymph nodes are enlarged and show varying grades of silicotic reaction. The mesenteric nodes ordinarily escape.

Aside from the experience with this unusual material just described the experiments have demonstrated conclusively that the intensity of tissue reaction to silica is inversely proportional to the size of the particles. The amount of surface exposed to the action of the fluids and cells is the obvious explanation. A gram of particles less than 1 micron in diameter presents infinitely more surface than the same weight of 10 to 12 micron particles.

While all of the forms of crystalline and cryptocrystalline silica mentioned above produce reactions of this type there are appreciable variations in the rate and severity with which they act. The tridymite has been outstanding. (Figure 2–*c*) It is extremely irritating and has killed most of the animals prematurely. In two different series of rabbits the maximum period of survival was eighty days and many animals died before the injections were completed. All showed an acute hepatitis with an associated replacement fibrosis, dif-

fuse rather than nodular in type. The guinea pigs tested with this substance have also suffered an excessive mortality although repeated attempts finally produced one animal which survived to be killed after eight months. At autopsy its peritoneal cavity showed extremely large fibrous nodules with calcified centers. Cristobalite was not as irritating but caused a more rapid reaction than quartz; the fibrosis was always diffuse rather than nodular in type. Next in order are probably the cryptocrystalline varieties, chalcedony and tripoli. (Figure 2–*d*) although in some of the tests they caused no more reaction than quartz. Vitreous silica is about as potent as normal quartz. In the order of the intensity of reaction produced, these different silicas might be arranged as follows: tridymite, cristobalite, chalcedony and tripoli, normal quartz and vitreous silica.

The *amorphous silicas* have yielded surprising results. Diatomite (Figure 2–*f*) caused as much and as rapidly progressive, nodular fibrosis as chalcedony. While this substance may have been contaminated with a minute amount of quartz, it seems hardly likely that this was the cause of the reaction for other mixtures containing much more quartz have not had a similar effect. Amorphous silica (See Figure 2–*e*) as opal excited much less reaction: the nodular lesions remained cellular in type and only a limited amount of diffuse fibrosis developed. Two years after completing the injections there was definitely less reaction than after one year. Amorphous silica prepared artificially by powdering the gel precipitated from colloidal silica was no more potent than fibrous sericite. It produced epithelioid changes in the monocytes and giant cells of the Langhan's type but no fibrosis developed in one year's time. The action of colloidal silicic acid in the dispersed phase was thoroughly investigated by Gye and Purdy.[10] (1922, 1924) These authors described in detail the toxic effects upon the liver, spleen and kidney of

rabbits. An illustration in their paper shows stimulated endothelial cells and the formation of giant cells. With repeated doses of small amounts of colloidal silica they produced a diffuse fibrosis of the liver and spleen.

The results obtained with these different forms of amorphous silica are perplexing and difficult to explain on any basis yet proposed. Perhaps no attempt should be made to explain them until more observations have been made. A study is contemplated with a series of silicic acid gels which contain varying amounts of combined water. Possibly this may yield information of value but it seems hardly probable for the active silicic acid in dispersed colloidal form contains the same amount of water as the inactive substance in the gel phase. Perhaps the capacity to take up more water may be of more significance. If the very marked response obtained with diatomite can be accepted at face value any explanation based upon water content falls. Mr. E. W. Thompson [11] (1937) in commenting upon this finding has suggested that the unexpected activity might be due to the tremendous surface created by the presence of countless, minute holes perforating the shells of the diatomes of which this mineral is composed. But if this were true it would seem as if at least some reaction should have occurred from the silica gel.

The possibility of *"aging" of silica* with consequent loss of irritating properties has received some credence recently. Professor Brammall adopted Heffernan's [12] suggestion (1935) that freshly fractured particles may be more active because of unsatisfied oxygen atoms which are free to combine with bases in the body fluids. This theory assumes that blasting or grinding actually disrupts the silica molecules, an effect which as yet awaits proof. In the aging process it is assumed that the oxygen atoms on the surface of the fractured silica combine with water or with bases and are thus rendered incapable of reacting with the tissues. On the basis of this hy-

pothesis Denny, Robson and Irwin [13] (1937) exposed rabbits to silica actually fractured in the dusting chamber by grinding quartz pebbles in quartz-lined mills. Their animals developed cellular silicotic nodules of the lungs after an exposure of only six months. The writer has never tried this type of experiment. With the commercially ground silica used in his laboratory a minimum of eighteen months has been required to produce the same results. The rate of development of the lesions was essentially the same whether the exposures were continued for the full period or whether the animals were exposed for six months and then set aside in a normal atmosphere for a period of one year. But one cannot be too certain that these apparent differences are altogether due to the character of the silica dust. The daily exposure of sixteen hours was twice that used by the author in his own inhalation experiments with rabbits. Furthermore it is not too certain that the concentration of atmospheric dust employed by Denny, Robson and Irwin may not have been partially responsible for the rapidity of reaction. While they report konimeter counts of 4000 to 8000 particles per cubic foot of air, it is not altogether justifiable to conclude that these figures are equivalent to 112,000,000 and 224,000,000 particles per cubic foot of air, the results obtained by mathematical conversion. Experience is indicating that each type of dust counting instrument has its own standard and that the results obtained with one of them are not convertible into counts or weights secured by other methods. This would seem to be particularly true where high concentrations are involved. It is felt that judgment on the effect of freshly fractured silica should be reserved until animals can be exposed under comparable conditions to the same dust before and after it has been allowed to age.

While it is granted that freshly fractured silica may be more potent than that which has aged for some time the

writer is positive that the aging process is not a progressive one. For his dust inhalation experiments he has been in the habit of purchasing both chalcedony and normal quartz in lots of two tons from commercial sources. These materials are received in 200 pound paper sacks and stored in a reasonably dry building but subject to marked variations in atmospheric humidity. The last supply purchased in 1932 has been used for many different experiments started from time to time during the subsequent years. As far as can be determined silicosis has developed just as rapidly in animals which began to inhale these two dusts in 1936 as it did in others exposed four years previously. Likewise sterile suspensions of silica particles in physiological salt solution, which are kept in the refrigerator for many months have neither increased nor decreased in capacity to excite reaction in the tissues. These observations indicate that if a loss of potency occurs it is not complete and that silica remains active even when suspended in dilute aqueous sodium chloride solution.

Mixtures of Free Silica and Other Minerals

The reaction to mixtures of free silica and silicate or non-siliceous particles is not governed solely by the amount of the first substance. Often the adulterating components are not mere inert diluents which reduce the amount of free silica available to react upon the tissues. Some of them seem to accelerate and others definitely retard its action. Briscoe [9] (1937) and his co-workers have shown that the addition of a variety of substances to suspensions of silica in the test tube alters its solubility. They have inferred that the rate of reaction in the body would be correspondingly altered. Denny, Robson and Irwin,[13] (1937) after making similar observations, used metallic aluminum to prevent the development of silicosis in rabbits. MacDonald, Piggot and Gilder [14] (1930) and later others have reported cases of rapidly de-

veloping silicosis from the inhalation of mixtures of alkalies and silica in the manufacture of soap powders. McCord, Flemming, Ainslee and Johnston [15] (1936) have published experiments on guinea pigs injected intraperitoneally with mixtures of silica and alkalis which seem to show an accelerated silicotic reaction. No phase of the problem has been investigated sufficiently to permit generalizations but the following experiences are illustrative of inhibitory action. Others will be cited later when the effects of inhaled dust are discussed.

Before describing the reactions to injections of mixed dusts it should be mentioned that unusual care must be exercised in their preparation to prevent alteration in composition. This is likely to happen for the hard quartz components will obviously resist grinding longer than softer substances like iron or certain silicates. As a consequence the number of fine free silica particles will be comparatively small unless the grinding is continued for prolonged periods. Elutriation in water also alters the composition of the mixed dusts owing to variations in settling rates of different components. The only satisfactory method of treating mixtures is to grind them until none of the particles exceed the desired maximum size. Chemical and petrographic analyses of the material before and after grinding are essential to make certain that there has been no alteration in the different minerals or their percentage composition in the mixtures.

Four different mixtures have been injected into rabbits and guinea pigs and the reactions have been followed for a sufficient period to allow an evaluation of their potentialities; 5 others are under observation. Crude *fluorite ore* containing 57.16 per cent of CaF_2, 31.06 per cent $CaCO_3$ and 10.46 per cent SiO_2 caused a delayed and a typical form of silicotic reaction when tested by the guinea pig and rabbit methods already described. Guinea pigs injected intraperitoneally

showed nothing suggestive of silicotic fibrosis in a period of three hundred days. No specific silica reactions appeared in the rabbits until the seventh month when the giant cells in the spleen began to assume characteristics of the Langhan's type. In the one year animal there were microscopic foci of diffuse fibrosis in the portal septa and an early silicotic fibrosis with calcification in the hepatic lymph nodes. The last rabbit of the series was killed at the fifteenth month. The fibrosis in the liver had advanced to a stage where it was visible to the naked eye. Microscopic sections revealed a more extensive diffuse fibrosis without nodule formation and without the hyaline swelling of collagen seen in typical silicosis. There was no appreciable necrosis of adjacent liver cells. The hepatic lymph nodes were almost completely replaced by hyaline silicotic foci, many of which had necrotic or calcified centers. A control series of rabbits treated with almost pure fluorite particles (CaF_2 98.7 per cent, SiO_2 0.08 per cent) developed no significant changes in the same period of time.

This experiment demonstrated that the injection of 0.146 gm. of quartz in combination with 0.88 gm. of calcium fluoride and calcium carbonate would cause fibrosis but that the development of this reaction was delayed and assumed a typical form only in lymph nodes draining the liver where lymphatic activity had concentrated an unusual number of silica particles. As already noted (p. 280) one half this amount of silica (0.05 gm.) not associated with other substances is sufficient to produce much more fibrosis in only a year's time. One can only conclude that the calcium fluoride or the calcium carbonate or both had slowed and modified the effect of the quartz. The particles were in the tissues for they could be seen inside of giant cells. The latter were situated in the same locations that they always assume. But the silica did not affect the cells for a long time. Incidentally

both of the adulterants are substances which have been suggested as accelerators of the action of silica. Nicol [16] (1933) and later McNally [17] (1935) postulated that fluorides were responsible for solution of silica in the body. Calcium carbonate is one of the alkalis which McCord [15] (1936) found would accelerate the reaction to silica. The observations just reported are at variance with their findings.

Granite from Barre, Vermont is a natural mixture containing about 33 per cent quartz and 66 per cent of the silicates mica and feldspar. It has always been slow to cause silicosis in human beings, exposures of fifteen to twenty or more years being frequently reported. Inhalation by guinea pigs and rabbits has never produced nodular fibrosis within the usual period of a year or two regardless of the concentration employed. (Figures 4 *a* & 4 *b*) To learn more about its action 4 groups of rabbits were injected intravenously with varying doses of granite particles. The first group received 3.33 grams containing 1 gram of quartz, the second 1.67 grams or 0.5 grams of quartz, the third 1 gram containing 0.3 grams of quartz and the last 0.5 gram or 0.15 gram of quartz. All members of the first group, injected with a full gram of quartz, were killed during a period of twenty two and a half months. None of them developed gross evidence of fibrosis although there was enough pigmentation in the portal connective tissue to demarcate the lobules. In an animal killed at the end of twelve months the spleen contained giant cells of the Langhan's type and the liver exhibited occasional minute foci of monocytic proliferation in addition to localized collections of large dust-filled giant cells. (Figure 4 *d*) For the most part, however, the picture resembled that produced by the inert silicates. In the last animal of the series, killed after twenty two and a half months, the microscopic foci of proliferation were appreciably larger, the parenchyma cells adjacent to them were beginning to degenerate and polynuclear



FIGURE 4. See caption on page 291.

leucocytes had invaded them and the centre of the monocytic nodules. (Figure 4*e*) Even at this time the evidences of activity were localized and in most places the reaction had remained static. Unfortunately there were no survivors in this group so that it was not possible to determine the time necessary to produce progressive disease.

Two members of the second group injected with a dose of granite containing 0.5 gram of quartz were not autopsied until the twenty seventh month when one of them died with gross evidence of coccidiosis. Microscopic examination of this animal's liver revealed an advanced cirrhosis with hyaline fibrous nodules and necrosis of the surrounding liver cells. In its spleen, however, the reaction was still in the giant cell stage with no evidence of fibrosis. The companion animal, with no infection, presented a picture of moderate cellular activity comparable to that produced by twice the dose after twelve months contact with the tissues.

The members of the other two groups injected with doses

FIGURE 4

Inhalation of various dusts. *a*. Chalcedony, 9 months exposure plus 4 months in a normal atmosphere. Domestic Fowl. Nodules of young fibrous tissue along walls of air tubes. *b*. Asbestos, 28 months. Guinea pig. Fibrosis surrounding terminal bronchioles and alveolar ducts as a collar. *c*. Pure chalcedony, 21 months. Guinea pig. Nodular fibrosis and perilymphatic linear fibrosis in areolar coat of an artery. *d*. Mixtures of equal parts of quartz and gypsum, 25 months plus 2 months in a normal atmosphere. Guinea pig. Large dust-filled plaques inside of thick-walled air spaces. The nodule in the centre along the lower border is cellular and not fibrous. Even such nodules are rare. *e*. Hematite (6 per cent SiO_2), 29 months. Guinea pig. Massive collection of phagocytes filled with dust particles. No fibrosis in adjacent alveolar walls. *f*. Ferruginous chert (50 per cent SiO_2), 22 months exposure plus 24 months in normal atmosphere. Guinea pig. Higher magnification of a lesion resembling that caused by hematite (figure 4e). Slight thickening of alveolar walls adjacent to dust-filled plaques inside air spaces.

of granite containing 0.3 and 0.15 grams of granite respectively were all killed during a period of eighteen months. All but one revealed an inert type of reaction. The exceptional animal, injected with the larger dose and surviving for eighteen months had developed microscopic evidences of fibrosis in the portal areas.

Intraperitoneal injection of granite dust into guinea pigs has failed to produce any evidence of fibrosis within one year's time.

This experiment points to a very definite inhibition of the action of quartz in the presence of the silicates mica and feldspar. It shows that a full gram of quartz in such combination causes only an early type of silicotic reaction in twenty two and a half months, an effect which has been observed with the same amount of quartz alone within twelve days after completing the injections. That *time* rather than than the number of quartz particles is the more important factor is indicated by the findings in the group injected with the dose containing 0.5 gram of quartz. Here twenty seven months contact with the tissues caused as much or more fibrosis. While in one such animal there was a complicating parasitic infestation which should theoretically accelerate reaction, in another the result is clearly defined. The significance of the time factor is substantiated by the absence of fibrosis one year after the injection of a large dose of granite into the peritoneal cavity of guinea pigs.

Ferruginous chert from the Lake Superior iron mining district has been the subject of intensive study in connection with clinical and engineering investigations in this industry. In many of the mines the rock runs about 50 percent of silica of the chalcedony type.

Intravenous injection of the standard dose of 1 gram of such chert produced a modified form of silicosis which developed less rapidly than the reaction to an equivalent

amount of pure silica. The fibrosis was confined to the portal areas and after a year's time it appeared as if an equilibrium had been reached as necrosis of liver cells was no longer visible. (Figure 4 *f*) In a series of rabbits injected with 2 grams of chert containing approximately 1 gram of silica an advanced stage of sidero-silicosis had developed within eight months; at eighteen months the lesions were more extensive and still progressing. The involvement was never as generalized as in animals injected with pure silica, but the affected areas were quite completely replaced by fibrous tissue. Intraperitoneal injections into guinea pigs caused large silicotic nodules in a year. Apparently hematite in aqueous suspension with silica does not retard the action of the latter to the same degree as the silicates feldspar and mica in granite.

Dust collected from an air filter located in one of the *Johannesburg gold mines* has been studied because of the general interest in the disease in this industry. The sample submitted was composed of small particles but they varied so much in shape and size that they were reground with water in a porcelain mill until none larger than 4 microns in diameter was left. Examined under polarized light an excessive number of brilliantly refractile acicular particles was seen. Dr. Gabriel furnished the following estimate of the petrographic composition: "Essentially quartz and fibrous sericite with platy muscovite, a trace of feldspar and some opaque material (ilumenite?) as accessory minerals."

A partial chemical analysis showed 55 per cent of free silica and 1.48 per cent of combined silica.

Intravenous injection of a suspension of the 4 micron particles of this dust produced silicotic fibrosis but at a slower rate than either pure silica or chert. After six months the tissues were only beginning to exhibit cellular activity. After sixteen months however there was gross evidence of

fibrosis of moderate severity in the rabbit's spleen and liver. Intraperitoneal injections into guinea pigs caused a reaction of the silicotic type which had not yet become fibrous in eight months. The findings with this material are of interest in view of the high content of sericite in the mixture which should, according to the Jones theory, accelerate the reaction to quartz. If anything this sample of South African mine dust has caused a slower reaction than might be anticipated.

Other mixtures of silica with coal, carbon and iron in varying proportions are under investigation but their action has been followed for only six months, a period too short to expect any silicosis to develop. Their presence in a suspension of fine silica particles prevents the development of acute symptoms on intravenous injection. The action of gypsum with silica dust will be discussed in the following section.

Inhalation of Various Dusts

The action of inhaled dusts is described in a separate section because of its direct practical bearing on the problem of pneumoconiosis. There are many methods of subjecting animals to dust inhalation but the types of apparatus need not be described here. The main objective is the maintenance of a rather constant atmospheric concentration of dust in an enclosed space, large enough to accommodate a very considerable number of animals and sufficiently well ventilated so that the humidity does not become excessive. Since inhalation experiments must be continued for at least twelve to eighteen months it is essential to use only healthy animals and to take every precaution against the development of epizoötic pneumonia and other infections. The maintenance of proper temperature and humidity and the avoidance of overwhelming dust concentrations are therefore important.

Some method of determining and recording the concentration of dust in the atmosphere is essential for comparative

studies. The writer has employed the Greenburg-Smith impinger technique [18] (1932) since this is the standard procedure in the United States. In addition to making counts at the recommended magnification of 100 with light field illumination, comparative counts are also made under dark field illumination at the same magnification. The latter is quite essential to visualize the excess of small particles less than 1 micron in diameter, which have been employed. (Particles much larger than 3 microns are not used because they are unlikely to produce much result in the limited period of such experiments.) Counts are made at the breathing zone of the animals and large amounts of air-borne dust are collected over periods of hours for chemical analysis. Both are necessary to determine the amount and the composition of the dust actually inhaled. As will be shown, samples taken in various parts of the dusting chamber may have quite a different composition. The counts have been repeated every month or two but the chemical analysis were not rechecked unless the number of particles varied greatly. According to custom the counts are recorded in number of particles per cubic foot. While it is possible to convert this figure to numbers of particles per cubic centimeter, the usual standard in the British Empire, it is doubtful whether the conversion means a great deal. In dealing with the high concentrations used in the experiments to be discussed the different instruments ordinarily employed do not measure absolute quantities. As mentioned above, there is urgent need that some international standard be adopted so that the conditions defining exposures in different countries can be more accurately compared.

The experimental results on which this discussion is based were produced by exposing animals in groups of 100 to 150 to high concentrations of various dusts, composed of particles less than 3 microns in diameter, for periods of one to two or

more years. The average light field dust counts have varied in different experiments from 100,000,000 to 800,000,000 or more per cubic foot, the corresponding dark field counts being 3 to 5 times as high. These concentrations have been maintained for eight hours a day, six days a week. The animals have remained in the same rooms for the other sixteen hours of each day and since considerable dust collects on their bedding it is constantly being stirred as they move about. Dark field counts taken at night, after the motor agitating the dust is turned off, usually reveal from 30,000,000 to 80,000,000 fine particles in the air inside their cages. It is therefore obvious that the exposures have been severe; for eight hours daily the dust concentrations have been very heavy but no greater than the worst encountered in industry. In addition there have always been significant amounts of dust in the air throughout the life of the animals.

The results of these inhalation experiments performed upon guinea pigs, white rats, rabbits, cats, fowl and a few individuals of other species have thrown considerable light upon the evolution of various forms of pneumoconiosis. These can best be illustrated by considering the reactions to 4 different types of dust: (1) non-siliceous dust; (2) free silica; (3) mixtures of free silica and other substances; and (4) the fibrous silicate, asbestos. Other silicates have not been tested in this manner owing to the fact that they have caused so little reaction by injection.

By no means all of the particles that are inhaled reach the lungs; some probably possess properties such as wetability and a tendency to clump which favor retention in the upper respiratory tract. Since this feature has not been investigated it will be dismissed with the statement that perhaps 50 per cent of the inhaled particles are caught on the sticky mucous membranes lining the tortuous passages of the nose, throat, trachea and bronchi. Ciliary action and

the cough and other reflexes carry them to points from which they can be expectorated. It is logically assumed that mouth breathers inhale more particles into the lungs than persons who breathe through the nose. Lehmann [19] (1936) demonstrated that the nasal filter was less efficient in subjects with silicosis than in ones without this disease. Unpublished experiments by A. J. Vorwald,[20] working in the writer's laboratory, would seem to prove the reverse although the interpretation of his results is difficult. He produced a partial nasal stenosis in guinea pigs by cauterizing the nostrils with silver nitrate. Most of the animals could not accommodate themselves to breathing by mouth. They swallowed air and died with greatly distended stomachs. A few were more tractable and after a period of training they were exposed to high concentrations of hematite dust for about a year. When killed both visual examination and chemical analysis showed much less iron in their lungs than in the controls breathing normally. The meaning of this experiment is not clear; but it is mentioned to indicate the difficulties involved in attacking this aspect of the problem.

Non-siliceous dusts. The general treatment of inhaled particulate dust which enters the lungs is perhaps best illustrated by the reaction to non-siliceous materials; for silica is so irritating that it confuses the picture and fibrous asbestos is treated in an absolutely unique manner. Particles of coal, (Gardner [21] 1933), iron, gypsum, marble (Gardner and Dworski [22] 1922), carborundum (Gardner [23] 1923) etc., that succeed in reaching the terminal bronchioles tend to drift into the subpleural air spaces. There they encounter mononuclear phagocytes which migrate from the interior of the septa and move about on their surfaces. Opinions differ as to the nature of these cells; many believe that they are epithelial in origin with special function because of their position; others, including the author, believe that they are

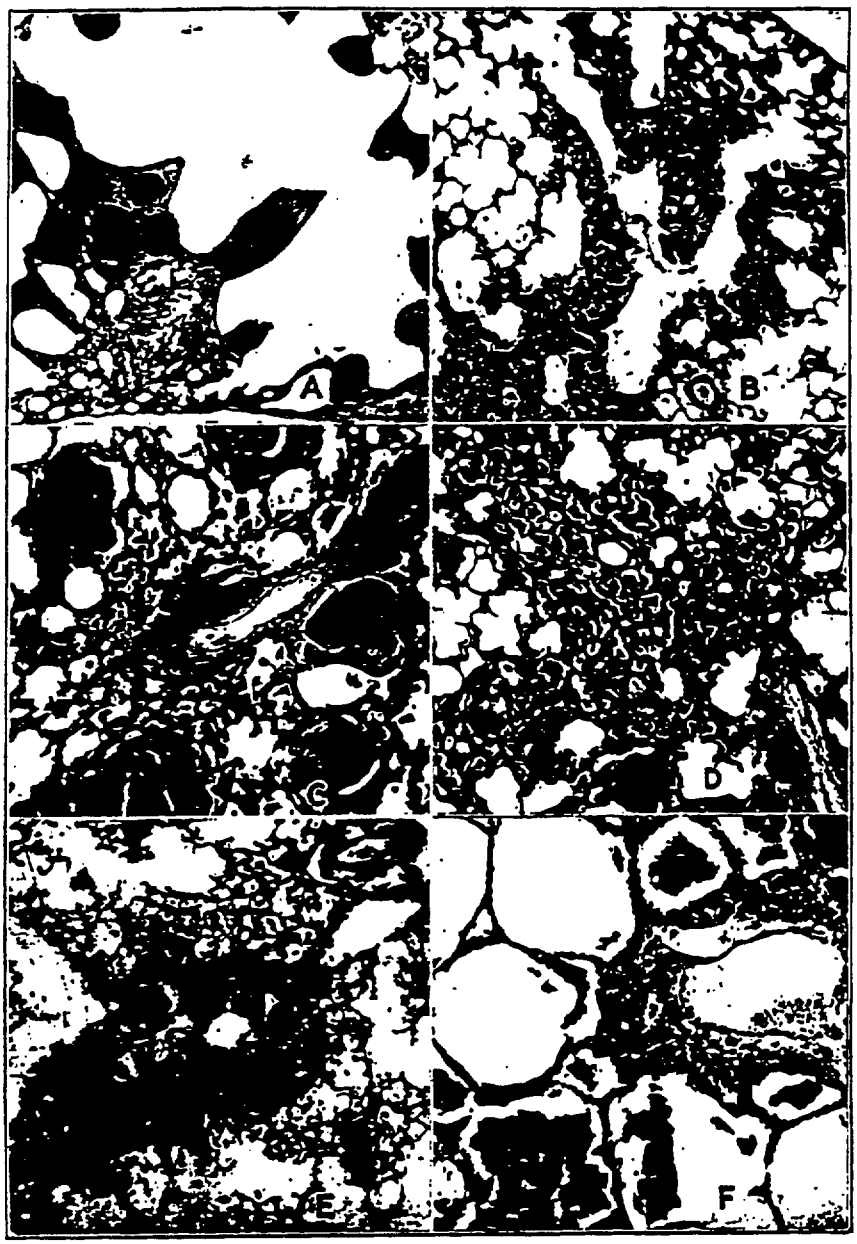


FIGURE 5. See caption on page 299.

ordinary histocytes or connective tissue phagocytes that happen to have formed in the connective tissue separating air spaces. There is also a theory that they are monocytes which have migrated out of the blood stream. Whatever their origin they are freely moving monocytic cells which surround and engulf minute foreign bodies with which they come in contact. They remain inside the air space for some time continuing to pick up any particle in their path. When excessive concentrations of dust have been inhaled the phagocytes become over-distended and apparently paralyzed for they remain inside the alveoli for many months. (Figure 5*f*) When only an occasional dust particle must be removed the cells pick them up and wander about until they happen to reach the vicinity of a deposit of lymphoid tissue. This may be at the point where an interlobular septum joins the pleura and the deep and superficial lymphatic systems communicate; it may be on the bronchial system at the distal end of

FIGURE 5

Reactions to granite and chert dusts. *a.* Inhalation in guinea pig after 2 years exposure and 6 months in normal atmosphere. Small focal collections of dust-filled phagocytes scattered throughout parenchyma. *b.* Detail of one of the areas shown in figure 5a. Collections of dust-filled phagocytes in a group of air spaces. Perilymphatic reaction in walls of small artery. *c.* Inhalation in guinea pig with chronic pneumonia. Exposed for 13 months and then allowed to live for 22 months in a normal atmosphere. *d.* Liver of rabbit one year after intravenous injection of 3.3 gm. granite particles (1 gm. SiO_2). Collection of dust-filled phagocytes in portal connective tissue. One of the very rare areas of cellular proliferation beside such a collection. *e.* Liver of rabbit two years after intravenous injection of the same dose of granite particles. Necrosis has begun in the larger proliferative foci and there is proliferation in and about the small clumps of phagocytes. *f.* Liver of rabbit one year after injection of 1 gm. of chert (50 per cent SiO_2). Heavy fibrosis in portal area with an atypical nonhyalinized nodule. Two small focal areas of early necrosis in adjacent parenchyma.

the alveolar ducts or at the bifurcation of arteries or veins. In any of these locations a small number of lymphoid cells surrounds a lymphatic vessel. The phagocyte leaves the air space and enters the lymphoid tissue. There it may either remain or pass through into the lumen of the lymphatic. In the latter event the current then carries it toward the hilum with the tracheobronchial nodes as its ultimate destination. The cell may not reach this goal but may be held up in any of the lymph nodules along the way. Probably not all particles enter the lymphatics through the agency of phagocytes; a certain number may pass directly into these vessels. Small amounts of dust in practically normal lungs are most apt to reach the nodes at the root; as the quantity becomes larger there is a tendency for accumulations to appear in the more peripheral lymphoid tissues. When excessive numbers of particles are inhaled over prolonged periods of time this orderly sequence of events does not follow. Many of the phagocytes do not succeed in entering the lymphatics through the localized deposits of lymphoid tissue. They accumulate in interstitial tissue in all parts of the lung. The heaviest deposits occur in the areolar coats of blood vessels, in the interlobular septa and in the pleura; there are smaller amounts in the walls of the bronchi. Since these are the locations where larger lymphatic trunks also occur the distribution is perilymphatic in type. (Figures 4 *b* and 5 *f*) Whether dust-laden phagocytes pass into or out of the lymph vessels in these locations has never been demonstrated.

The dust particles thus accumulated by phagocytic cells exert the same effect upon the tissue of the lungs that they do in other organs. The injection experiments demonstrated that non-siliceous matter produces only very slight amounts of chronic inflammation. The same is true in the lungs but since the number of particles collected in any focus is even smaller the reaction is apt to be less severe. Gross inspection

shows linear and focal areas of pigmentation in the pleura, linear deposits along the trunks with focal collections in the associated lymphoid tissues and pigmentation of the tracheobronchial lymph node.

The amount of cellular reaction is insufficient to be recognized by palpation. In microscopic sections there may be some proliferation of connective tissue but it involves so few cells that one is hardly justified in characterizing the reaction as *fibrosis*. The changes produced in animals with pure non-siliceous substances are less severe than those encountered in human beings. The latter are generally due to much longer exposure and in most instances there is a certain amount of contaminating silica to accentuate the reaction.

Free silica. Animals exposed to pure silica in the form of quartz or chalcedony develop lesions comparable to those seen in human silicosis. (Gardner[24] 1932) The inhaled particles are dealt with in the same manner as the non-siliceous ones just described but the irritating silica produces changes which disturb the mechanisms for physiologic disposal. The primary phagocytes are killed and degenerate, attracting polynuclear leucocytes. An excessive number of new mononuclear phagocytes form in the alveolar walls and then migrate into the air spaces producing the condition which Irvine, Strachan and Simson[25] described as "bronchiolitis." (1930) Under the influence of silica these cells undergo epithelioid transformation and giant cells of the Langhan's type develop. Stimulation also increases the rate of amoeboid activity so that the phagocytes move toward the lymphatic system with unusual rapidity. The concentration of silica in and about the lymphoid nodules stimulates the local connective tissues. The latter proliferate to form cellular nodules that replace the lymphoid elements. As the lesions increase in size they encroach upon the adjacent lymphatic vessels and ultimately compress their lumina. Such

reaction takes place simultaneously in the intrapulmonary lymphoid tissues and in the tracheobronchial nodes. It is particularly well demonstrated in rabbits and albino rats, species which normally have well developed lymphoid tissues inside the lungs. This sequence of events with the resultant impairment of the drainage system of the lungs constitutes the first stage in the development of silicosis.

After it is well established particles that are inhaled subsequently are perhaps eliminated less readily. At least it appears that they now tend to accumulate at various points in the walls of the air spaces. Here a repetition of the process produces a second generation of nodules which in this instance develop from irritation of the local connective tissues. With this stage true silicosis, which is characterized by "discrete nodules uniformly distributed throughout the parenchyma of the lung" may be said to begin. (Figures 1 *a* & 5 *c*) With concentrations of from 200,000,000 to 400,000,000 particles per cubic foot, mature lesions appear in animals in eleven or twelve months; with only 100.000.000, twenty-five to twenty-six months are required. Hard, pearly white nodules, 1 mm. or less in diameter, project above the pleural surface and are scattered over its cut surface. The tracheobronchial nodes are greatly enlarged, very hard and exhibit a pearly lustre on section. The hepatic lymph node is also involved although at a somewhat later period. It is believed that this node does not receive its drainage directly from the lung but from the liver. With heavy exposures many inhaled particles enter the blood stream which carries them to the liver and spleen. In the latter they are retained and produce nodules; in the liver they remain only temporarily until the lymphatic system carries them out to the hepatic lymph node. Reaction in this node develops simultaneously with that in the spleen. Later, when the node is completely fibrosed the silica accumulates in the liver and visceral nod-

ules develop. Other nodes in the animals are rarely affected. Hepatic lymph node involvement is common in human silicosis: abdominal visceral nodules occur but they are rare.

With concentrations of silica in excess of 500,000,000 particles per cubic foot the defense mechanisms of the lung seem to fail. Nodules develop simultaneously in the lymphatic system and in the walls of the air spaces. In the latter there is also a diffuse, fine fibrosis and so many free phagocytes are killed that the picture has been described as a dust pneumonia. Such reactions have been encountered in human beings exposed to excessive concentrations of almost pure silica. The writer observed them in a few sandblasters who had worked without adequate protection and in a number of men who had been employed in a notorious tunnelling operation in the United States. (Gardner 1933)[26] A similar picture was found in men digging a tunnel for a sewer in Johannesburg. (Irvine, 1935)[27]

It is of no moment to describe the minor variations of this reaction which appear in different species except to state that they exist and that their counterparts have been observed in different human subjects. Such for example are the excessive tendency to necrosis followed by calcification which is the rule in rabbits, the more discrete and dense hyaline fibrosis of albino rats which is the usual form in human cases, and the less circumscribed foci of guinea pigs. The silicosis of fowls (Figure 5 *a*) is interesting because it probably develops without primary lesions in a well organized pulmonary lymphatic system. It has been claimed that the lungs of birds lack such a system and although this statement has not been verified by detailed anatomic study, the inhalation experiments have failed to disclose evidence of it. Even with moderate concentrations of dust, primary nodules seem to develop here and there in any portion of the

pulmonary stroma. Nothing comparable to tracheobronchial lymph node disease develops.

There is one feature which should be emphasized, namely, that the typical nodulation has been reproduced in all these various species without evidence of coexistant infection. Many writers still maintain that such complication is essential but these experiments constitute proof to the contrary. The silicotic lesions often simulate tubercles but repeated intracutaneous tuberculin tests on several large series of guinea pigs has definitely eliminated this possibility. Other infections, notably chronic pneumonia and pulmonary abscess are frequent complications but the diffuse obliterating character of the reaction can be recognized and differentiated from pure silicosis.

The cause of death in animals with silicosis is not always obvious. Superimposed pulmonary infection is unquestionably the most common one. Animals with the confluent, fine diffuse fibrosis from excessive exposures or those with extensive fibrosis from organizing pneumonia develop chronic passive congestion and die with dilated right hearts. Rats with discrete nodulation have never shown cardio-vascular effects. Renal lesions have never been observed in any species. There has been nothing to suggest a general poisoning of all the tissues such as Collis and Yule (1933)[34] postulated. Reactions develop only in organs whose anatomy is such that they retain appreciable collections of silica particles.

Inhalation of Mixtures of Free Silica with Other Substances

The inhalation of dusts composed of both free silica and other minerals has not always produced the same effects in the lungs of experimental animals that the same mixtures appear to have caused in human beings. Not a few experimentors have reported the reproduction of lesions *resembling*

those of human silicosis but their illustrations belie their descriptions. In view of the unqualified success with pure silica these results are perplexing and demand an explanation. To dismiss them on the grounds of the inadequacy of the experimental method might well mean a lost opportunity to discover important principles which govern the development of pneumoconiosis.

It is conceivable that the experiments have failed because they have not actually reproduced the conditions of industrial exposure which have been defined by occasional sampling of the atmospheric dust. Whether analysis of the rock being worked and counts of the number and size of the atmospheric dust particles are adequate to define the extent of the silica hazard may be questioned. The composition of the dust in many industrial environments undoubtedly varies from hour to hour; at times it may contain much higher proportions of free silica than others. In mining and in large plants like foundries the concentration of silica in the atmosphere depends upon the nature of particular operations. Many employees shift frequently from jobs involving exposures to high concentrations of almost pure silica to others where the silica is highly diluted with various substances. Obviously the exact duplication of such conditions for experimental animals would be difficult and an explanation for the failures of experiments on this basis is highly theoretical.

Experimenters have not always appreciated the complexities of their problem. Not infrequently someone reports that he has worked with a dust produced by grinding the rock that was being worked in the industry under investigation. As already noted, this involves pitfalls, for to obtain a dust whose components are present in the same proportions in which they existed in the original rock it is necessary to reduce all of that rock to particles of the desired size. If it is only partially ground the harder silica is resistant and may easily

be eliminated in subsequent separations. The dust itself should be analysed as a check. Even then there is sometimes a suspicion that the relationship of components is altered. In the process of grinding it has even been suggested that the particles of silica become mechanically coated with the softer materials, but actual proof of such an effect is lacking.

Inhalation experiments, unlike those by injection, do not guarantee contact between the tissues and all of the component particles of a given dust. The rôle of the different factors which govern inhalation is of unusual importance in dealing with mixed dusts but they have hitherto received too little attention. Particles that are large and heavy, as is apt to be the case with quartz in improperly ground mixtures, settle more rapidly than smaller and lighter ones. Different kinds of mineral particles suspended in the atmosphere do not necessarily remain separated ; in fact they tend to agglutinate if they carry opposite electrostatic charges or possess hygroscopic properties. The aggregates are heavy and remain suspended in the air for limited periods ; they are also more readily caught by the protective mechanisms of the upper respiratory tract. Selective exclusion of some component of a mixed dust could readily result from a greater degree of wetability and consequent adhesion to the mucous surfaces of the upper respiratory tract.

Some of the experimental 'failures' are probably the result of undue curtailment of the factor of *time*. There is a tendency to think that by increasing the reciprocal factor of dosage the time may be shortened to conform with the limited span of life in ordinary experimental animals. To what extent this is true awaits demonstration. The injection tests, already discussed, indicate that certain substances like the iron oxide in chert, the silicates in granite and the calcium carbonate and calcium fluoride in crude fluorspar may inhibit the action of many times the effective dose of free silica. The duration of

such inhibition has not been established but the development of slight reactions in animals surviving for long periods suggests that it is overcome in time and that at least a modified silicotic fibrosis ultimately develops.

Finally the experimenter may have defeated his purpose by insisting that results always be demonstrated in the lungs that are normal. This viewpoint is rational but one should not neglect to observe the effects of different dusts in the presence of infection for a great many human subjects have such complications. While it has been demonstrated beyond question that free silica can cause typical silicotic fibrosis in normal tissues, it has not been proved conclusively that apparently inert mixtures of silica and other substances may not produce progressive reaction in the presence of infection. It will be shown presently that the inhalation of the natural mixtures granite and ferruginous chert has not produced nodular fibrosis in normal animals but that in ones with tuberculosis the reaction approaches the nodular type (Figure 4 *c*). These results may be due to a release of the inhibitory action of the non-siliceous elements in the respective dusts or they may merely reflect the greater activity from a high local concentration of silica caught in the inflammatory reaction to the infection.

The purpose of this section is to demonstrate that the number, size and composition of the non-siliceous components of a mixed dust often determines the behavior of the particles of free silica. Consequently it is necessary to describe in detail the conditions of the inhalation experiments to be cited as proof.

Hematite contaminated with 6 per cent quartz. Guinea pigs, white rats and rabbits have been compelled to inhale excessive concentrations of this dust for periods of three and a half years. They developed a pigmentation of the lungs and lymph nodes but none of them have shown anything even suggestive

of a silicotic reaction. A group of surviving guinea pigs were removed to a normal atmosphere and allowed to live for another eight months. Then they were killed but autopsy revealed no progression of their pneumoconiosis.

The average total concentration of dust at the breathing level inside the cages was 580,000,000 particles per cubic foot of air by light field count and by dark field, 6,250,000,000. Chemical analysis of the air-floated particles at the same point revealed 7 per cent of silica which by computation is equivalent to approximately 40,600,000 quartz particles (463,750,000 by dark field). Size frequency counts demonstrated that 95 percent of the total air-floating particles were less than 2 microns in diameter; none exceeded 3 microns. Such concentrations were maintained for seven to eight hours a day, six days a week over the period specified. The animals were not removed from the dusting room at night but remained in the same cages. Counts taken during this period revealed between 3,000,000 and 7,000,000 particles per cubic foot by light field and 56,000,000 to 205,000,000 by dark field count. The total represents a very considerable exposure to silica over a period of three and a half years and yet the reaction in the lungs was that to a non-siliceous dust.

It consisted grossly of linear and focal deposits of brick-red dust in the pleura, along the blood vessels and in the pulmonary and mediastinal lymphoid tissues. Microscopic examination showed compact collections of phagocytes filled with iron particles located inside of groups of air spaces or crowded into the areolar coats of arteries and the stroma of lymphoid tissues. (Figure 5 *e*) Connective tissue proliferation was negligible except in the tracheobronchial lymph nodes where a limited amount of such reaction had developed about very large collections of dust-filled phagocytes.

Chemical analysis of the lungs of animals killed at the end of the experiment, eight months after the cessation of the

dust exposure, demonstrated high ash values ; the average for 4 animals was 22.88 per cent of the dried lung tissue. Iron constituted 76.15 per cent of this ash ; the silica content was low, being only 4.89 per cent. After much shorter exposures to pure silica one finds 40 to 80 per cent of silica in the ash. Obviously so little silica had accumulated in the lungs of these guinea pigs exposed to hematite contaminated with 6 per cent of quartz that no silicotic reaction developed.

Ferruginous chert containing about 50 per cent of silica. Petrographically the dust employed consisted of a mixture of hematite, ferruginous chert, normal quartz and a small quantity of rutile. Chemical analysis revealed 46.8 per cent of free silica. The first experiment made with this dust failed to produce silicotic nodulation after exposures of eight hours a day over a period of one year and two months even though the total dust concentrations were excessive (light field counts over 1 billion and dark field counts in excess of 4 billion). Only a non-specific pneumoconiosis developed. Surviving animals allowed to live two and one half years in a normal atmosphere showed no progression of the reaction to dust. The histologic picture was essentially the same as that in animals exposed to hematite. Chemical analysis of their lungs at the end of the exposure yielded an average ash value of 10.25 per cent of which 5.8 per cent was silica. After two and a half years the silica content of the lung ash had decreased to 3.18 per cent. This was attributed to elimination of silica from the lungs by way of the lymphatics as the histological sections showed considerably more reaction in the lymph nodes at the end of the period. Unfortunately no chemical check was made by analysing the nodes.

The failure to reproduce the anticipated modified form, sidero-silicosis, after such long exposures to such excessive concentrations of dust demanded an explanation. It had been perhaps reasonably assumed that the animals were breathing

air containing at least 500,000,000 particles of silica per cubic foot by light field count and in other tests as low a concentration as 100,000,000 particles per cubic foot of pure quartz had repeatedly caused nodular fibrosis in about twenty-five months. A careful investigation of the conditions disclosed that while most of the particles in the dust received from the mine were less than 10 microns in diameter, only about 50 per cent of them were less than 3 microns. Most of the silica particles were in the range between 3 and 10 microns. The behavior of this mixture in the dusting chamber proved surprising. There was a very marked reduction in the percentage of silica particles between the hopper where the dust cloud was created and the air inside the animals' cages, never more than 6 feet away. The original material contained 46.8 per cent of silica; that which settled on the rafters showed 38.4 per cent while inside the cages the air-floating dust contained only 10.47 per cent.

The actual quantity of available silica of a size likely to produce much reaction was only 3.5 per cent greater than that in the hematite experiment cited above. In spite of the total concentration in excess of 1 billion particles per cubic foot there must have been only a little over 10,000,000 silica particles per cubic foot (40,000,000 by dark field count) in the animals' cages.

In view of this experience another experiment was started with more of the same chert ground so that all of the particles were less than 3 microns in diameter. This proved expensive and time-consuming but 1500 pounds of such dust were finally obtained. The total dust count by light field averaged 552,000,000 and by dark field, 1,983,000,000 particles per cubic foot of air. Inside the animals' cages 41.0 per cent of the particles were silica, giving an estimated concentration of available silica particles of 220,000,000 by light field and by dark field 793,000,000 per cubic foot of air. There had still

been a reduction of silica content between the hopper and the cages but with this very fine dust such reduction amounted to only 22.9 per cent instead of 36.3 per cent as in the previous experiment.

As before, guinea pigs, rabbits and white rats were exposed to this dust and killed at intervals to observe the progress of their disease. The experiment is not yet completed but after two years of treatment no sidero-silicosis has developed. The lungs of the different species are heavily pigmented and the walls of air spaces containing masses of dust-filled phagocytes show slight chronic inflammatory reaction. (Figure 5*f*) There is no fibrosis either in the lungs or the associated lymph nodes. The lesions in the more sensitive white rats are essentially the same except for focal collections of phagocytes in the lymphoid tissues.

Chemical analyses of the lungs of 4 guinea pigs exposed for two years showed only 15.5 per cent of ash of which 1.6 per cent was silica. Obviously the dust has not entered the lungs in any great quantity in spite of the excessive concentration in the atmosphere. The silica content of the ash is surprising in view of the atmospheric concentration of 220,000,000 particles per cubic foot, 98 per cent of which were under 2 microns in diameter. The conclusion seems inescapable that clumping or some other phenomenon either in the atmosphere or in the upper respiratory tract has retarded the inhalation of both iron and silica.

To make certain that the silica in this mixture was capable of producing fibrosis it was tested by intravenous injection into rabbits. Four of these animals were treated with 2 gm. of chert, which would contain the standard dose of silica; four more received 1 gm. All members of both series developed a modified nodular fibrosis (Figure 4*f*) although the reaction to the smaller amount did not progress as rapidly as that to pure silica. These findings were also confirmed by intra-

peritoneal guinea pig tests. Thus there seems to be no question but that the silica in the chert was in an active form.

To learn whether the iron would influence the action of silica that was already in the body another inhalation experiment was performed in which animals were exposed on alternate weeks, first to the hematite dust already mentioned and then to pure quartz. The former was carried on in the same room and at the same time as the other hematite experiment where dust concentrations in excess of 500,000,000 particles per cubic foot of air were maintained. The quartz concentrations were also high, averaging approximately 800,000,000 per cubic foot of air by light field count. The exposures were continued for twenty-two months and a group of survivors was kept for another six months in a normal atmosphere.

After an exposure of one year the connective tissues about masses of dust-filled phagocytes in the lymphoid tissues and the pulmonary stroma had begun to proliferate. Such reaction continued to progress throughout the remainder of the exposure and during the period after removal from the dust house. It occurred in focal areas scattered throughout all parts of the lungs. The borders of these foci were not sharply defined; there was no central necrosis and no hyalinization of collagen which characterizes the mature reaction to pure silica in the guinea pig. In the tracheobronchial lymph nodes, however, more typical silicotic nodules made their appearance after only six months of exposure; in all of the animals killed subsequently the lymph node lesions were larger and more numerous. The pulmonary foci resembled the early stages of the modified form of silicosis known as sidero-silicosis which one generally finds in hematite miners. Had the exposures been prolonged further it is assumed that at least some of the pulmonary nodules would have developed characteristic central zones of laminated hyaline fibrosis.

These different experiments with mixtures of hematite and

varying quantities of free silica point very definitely to a modifying action of the non-siliceous component of the dust. The greatest effect seems to have taken place in the atmosphere where, because of clumping or perhaps other means, much of the silica falls out of the atmosphere before it is wafted to the breathing zone of the animals a few feet away. Perhaps more of the silica, caught in the clumps of iron particles is retained in the tortuous passages of the nose. Comparatively little enters the lungs as demonstrated by the chemical analyses of these tissues. Much longer exposures should ultimately produce reaction but of the modified type (sidero-silicosis) observed when alternate exposures to pure silica and to hematite were employed.

If iron dust is such a definite protector against silica it is natural to enquire why the miners who are exposed to the same form of dust should ever develop sidero-silicosis. Much of the miner's exposure might be compared to that of the guinea pigs which were compelled to breathe pure silica and almost pure hematite on alternate weeks. The occupational histories which one obtains of so many years work in rock and so many in ore are only the roughest index of the actual character of the dust which a man breathes from day to day and hour to hour. On the other hand, *time* may be the more significant factor. Could these animals have been exposed for periods of ten or fifteen years enough silica would have undoubtedly entered their lungs to cause fibrosis. The principles demonstrated by these experiments may explain the failure of approximately ¾ of most hard rock miners to develop silicosis even though they have apparently been exposed to the same amounts of dust as the other quarter of the men who do develop the disease. These results also suggest the advisability of staggering employment in rock and ore to avoid prolonged exposure to dust of high silica content.

Artificial mixtures of calcined gypsum and pure silica. At-

tention was called to a similar protective action by gypsum dust in a clinical study of a group of workmen. A few of these men had been engaged in grinding calcined gypsum with buhrstones and two of them had been chipping the stones in the same room for periods of five and ten years respectively. This is a notoriously hazardous operation. Dust counts taken as they worked were high and the concentration of silica was such that one predicted a hazard. Examination of the men, however, showed no evidence of silicosis.

Another group of workmen in the same industry make 'sanded plaster' by mixing sand with calcined gypsum. In their department the dust counts were very high and chemical analysis revealed too much silica in the atmosphere. The size of the silica particles was unfortunately not determined. While they were small enough to have remained suspended in the air they had been produced from a washed sand and should theoretically have been fairly large, probably greater than 3 microns in diameter. Six men were found working in this department who had been employed from five to twelve years. One of them had worked exclusively on a machine packing sanded plaster for a period of ten years. A roentgenogram of his chest showed no abnormalities whatsoever; the films of the other five were either negative or revealed moderate degrees of exaggeration of the linear markings. In spite of the absence of evidence of nodular silicosis the conditions of employment were deemed dangerous and it was assumed that the period of employment had not been long enough to produce changes demonstrable by roentgenogram. To test this supposition the gypsum company was asked to have examinations on all men engaged in making sanded plaster in its various plants throughout the state. The company cooperated and brought together 17 men who had been employed at this work for periods varying from ten to thirty-three years. All of them were given complete physical examinations, including roent-

genograms but none showed even a suggestion of silicosis. One had a normal film and the others exhibited the usual degrees of linear exaggeration to be expected in persons of their age. The intensity of this reaction did not increase with the duration of exposure so that it might or might not have been produced by the dust that the men had inhaled.

Here was clinical evidence of protective action against silica provoked by another non-siliceous material. Examination of the dust in the mills demonstrated that it was composed of good sized clumps which settled out of the atmosphere rapidly. It was not possible to determine the relative proportions of silica and gypsum in any one clump nor the spacial relationships between the two kinds of particles. But it was proven that clumps existed and as it is known that silica particles carry a negative charge while gypsum has a positive one, it was assumed that the electrostatic effect was responsible for the clumping.

From the clinical standpoint it seemed that the protection from gypsum was presumably much more complete than that conferred by iron for no case of even a modified form of silicosis was discovered in the gypsum industry. To test the protective action of this substance further another series of animal experiments was made.

A group of guinea pigs, injected intraperitoneally with a buffered suspension of finely ground calcined gypsum particles developed no fibrosis although there was some necrosis in the centres of the largest masses of dust. In animals killed during the ensuing year these necrotic foci had become calcified. This experiment indicated that no fibrosis and practically no other reaction could be expected from inhaled gypsum.

Nevertheless 100 guinea pigs were exposed for two years in a dusting room to concentrations of gypsum dust averaging 448,000,000 particles per cubic foot by light field and ap-

proximately twice this amount by dark field count. The particles were fine, 96.3 per cent being less than 3 microns in diameter. No significant reaction developed. Most of the dust apparently dissolved for only occasional phagocytes were found scattered through the air spaces of the lungs. In the tracheobronchial lymph nodes a moderate amount of chronic inflammatory change developed about clumps of phagocytes containing less soluble particles. The latter reaction progressed somewhat in successive animals but it never attained a degree worthy of the name fibrosis.

Having demonstrated that calcined gypsum itself causes no effects of importance, the action of gypsum in combination with quartz was then investigated. In the first experiment, equal volumes of pure quartz * and pure gypsum dusts were placed in the agitating hopper in one of the experimental dusting rooms. The rotating paddle in this apparatus soon mixed the two dusts very thoroughly. A chemical analysis showed 49.7 per cent of SiO_2 and 45.8 per cent $CaSO_4$. The average concentration of the dust generated with this mixture was 460,000,000 particles per cubic foot of air by light field count and 900,000,000 by dark field. A size frequency count revealed that 97.8 per cent of the air-floated particles were less than 3 microns in diameter. Theoretically this dust cloud should therefore have contained 223,500,000 particles of silica less than 3 microns in diameter.

Analyses revealed that, as in the case of mixtures of iron and silica there had been a very marked reduction of the amount of silica in the air which reached the interior of the animals' cages. Chemical analysis of dust collected with an

* The quartz employed for the purpose consisted of 100 per cent normal quartz as determined by chemical and petrographic analysis. Most of the particles were less than 10 microns in diameter. It was the same material used in the experiments previously discussed and its capacity to cause fibrosis at the time it was used was checked by two other experiments that were being carried on simultaneously.

impinger at this point showed an average silica content of only 29.6 per cent, a reduction of over 21 per cent from that of the material in the hopper. Dust settled on top of a cage 6 feet above the floor showed a higher percentage of silica than that in the hopper, the figures being 53.7 and 49.7 per cent respectively. As a further check, counts of the number of particles in the original alcoholic suspensions of air-borne cage dust were compared with those on another portion of the same suspension which had been treated with acid to dissolve the gypsum. This method revealed only 42,750,000 acid insoluble particles per cubic foot by light field and 127,750,000 by dark field count. Thus there can be no question but that much silica had been removed from the atmosphere by the time it reached the interior of the cages. By actual count the number of particles was over five times less than the estimated value. The discrepancy between the computed and the actual number of particles is probably due to the small weight of very fine silica particles.

To demonstrate the extent to which aggregates had formed in the atmosphere a dry slide was placed inside of an empty cage for a period of 15 minutes and a size-frequency count of the clumps settling on it was made. Their number in various sizes was as follows:

Size	*Number*
0 – 5 microns	52 clumps
5 –10 "	18 "
10–20 "	17 "
20–30 "	7 "
30–40 "	5 "
40–50 "	1 "

The maximum size is not very large but when similar preparations were made outside of the cages, where the dust

settled directly on the slides, the clumps were so large and numerous that they could neither be counted nor measured. But all of the figures reported are materially greater than the maximum of 3 microns for the individual particles.

Guinea pigs kept in the atmosphere just described for periods of twenty-five months and survivors removed to normal atmospheres for a subsequent period of six months failed to develop typical silicotic nodulation of the lungs. Until the exposures had been continued for a period of seventeen months their lungs exhibited no localized reaction whatsoever; the response consisted only of phagocytes scattered widely through the air spaces. But then the cells began to collect in masses within the terminal bronchioles and to migrate into the lymphoid tissues in increasing numbers. Proliferative reaction in the pulmonary framework ensued but not in the form of nodules; there was merely a thickening of the alveolar septa adjacent to clumps of intra-alveolar phagocytes. (Figure 5 *d*) Similar pulmonary changes were found during the next eight months. In the tracheobronchial lymph nodes hyaline silicotic nodules were discovered after twenty-three months of exposure and continued to occur in most but not all of the animals killed subsequently. In members of the series killed after removal from the dusting room the pulmonary reaction increased in intensity; a modified cellular type of nodule developed but usually it did not undergo necrosis nor exhibit characteristic hyalinization. Its borders were always ill-defined. In only 2 guinea pigs killed during the first month after cessation of the exposure were any hyaline foci discovered and these were few in number; in the cases examined later such nodules were absent.

Through an unfortunate oversight no chemical analyses were made of the lungs of these animals but the anatomic evidence points to a marked reduction in the amount of silica inhaled. It took twenty-three months for enough to be con-

centrated in the tracheobronchial lymph nodes to cause mature reaction, four times as long as is required with pure silica. Within the lungs enough never accumulated to produce nodulation except in two animals which seemed to respond more readily than their fellows. The lesions in the exceptional cases were sufficiently well marked to raise the question as to whether longer exposures would not ultimately produce nodular fibrosis in a majority of the animals.

To answer this question another inhalation experiment was started but it has not yet been completed. Less silica was employed in the second mixture in the hope that the observations might be extended over a longer period of time. 1 volume of quartz and 3 volumes of gypsum were placed in the hopper of the dusting device. Chemical analysis after mixing revealed 31.4 per cent of SiO_2 and 62.4 per cent of $CaSO_4$. The silica content of this dust showed a similar reduction from the hopper to the breathing zone. In the latter position an analysis of an impinger sample revealed only 17.1 per cent of silica, a decrease of 14.3 per cent. The average total concentration of dust in the atmosphere inside the animals' cages was 553,750,000 particles per cubic foot of air by light field count; under dark field the figure was 1,577,000,000. By computation the number of quartz particles at the breathing zone should be 94,000,000 per cubic foot or on the basis of the dark field count, 367,667,000.

Guinea pigs and white rats have now been exposed to this mixture of silica and gypsum for twenty months and the results are essentially the same as those of the previous experiment. Silicotic reaction has not appeared in the lungs. Chemical analysis has demonstrated less than 5 per cent of ash and correspondingly low figures for silica (approximately 15 per cent of the ash). For relatively pure dusts like silica and hematite the amount of ash is three to five times as great. These findings indicate that not much dust of any type is

entering the lungs and that the silica in particular is less than would be anticipated in view of the atmospheric concentrations described.

To ascertain whether gypsum dust already present in the lungs will alter the reaction to silica inhaled independently, one group of guinea pigs were exposed on alternate weeks to pure gypsum and pure silica. A second group that had inhaled gypsum for two years was placed in an atmosphere of pure quartz on a schedule similar to those previously described. In neither experiment did the gypsum have any apparent effect upon the development of silicosis.

The experiments with gypsum dust seem to demonstrate the principle of protection, which is probably responsible for the lack of evidences of silicosis in the men exposed in localized parts of the plants. Although the industrial atmospheres contained quantities of silica which were considered hazardous, not enough of this substance appears to have entered their lungs to cause reaction demonstrable in a roentgenogram. Had the buhrstone grinders not been inhaling gypsum along with silica dust it is hardly likely that they could have escaped.

Granite. A final example of the same principle is probably offered by an experience with granite dust from Barre, Vt. The dust employed contained 35 per cent of free silica as quartz. Inhalation experiments [28] (1920) were made many years ago, before the necessity of evaluating all of the factors had become apparent. The dust for the test, obtained from the collector of an exhaust system in a cutting shed, was composed of a mixture of fine and coarse particles. Average dust counts by light field illumination at the breathing level of the animals revealed 957,000,000 particles less than 10 microns in diameter, and of these 465,000,000 were less than 1.5 micron in diameter. At the time 50 guinea pigs were exposed in boxes 6 x 3 x 2 feet in diameter for eight hours a

day from which they were removed at night. The longest period of exposure was two years ; a few animals were allowed to live as long as six months after cessation of the dust exposure.

The maximum reaction to this amount of granite dust was definitely greater than that to hematite but still it did not even simulate the nodular response to pure silica. (Figures 4 *a* and 4 *b*) It consisted of dust-filled phagocytes collected in focal areas within groups of air spaces or in the areolar tissues along the lymphatic trunks. The connective tissues had been somewhat stimulated for the external coats of the arteries and the larger septa were thickened though by a cellular, rather than a fibrous type of reaction. In the lymphoid tissues the granite exerted more effect. In a few of the longest surviving animals the tracheobronchial nodes contained isolated nodules whose centres were beginning to degenerate. In the lungs nodules never developed except in the presence of infection. Even then the focal lesions were not typical of silicosis. They consisted of masses of cellular connective tissue from whose margins strands of a similar nature radiated into the surrounding stroma. (Figure 4 *c*) There was no central area of necrosis, no hyalinization of collagen and no tendency of concentric lamination. Such foci were not tubercles for they developed in non-tuberculous as well as tuberculous lungs, but neither were they typical silicotic nodules. It was assumed that characteristic central hyaline zones might ultimately appear but this did not occur within the two and a half year period of observation.

These experiments were completed long before facilities for accurately defining the number and size of the free and combined silica particles in the atmosphere were available but the records indicate that the dust employed was not deficient in fine quartz. Chemical analysis of the lungs were not made but re-examination of sections in polarized light

today discloses myriads of doubly refractile particles that look like quartz. The more recent injection experiments with the same kind of granite indicates an explanation for another apparent failure: the action of the quartz was retarded by the other components of the dust. In normal animals the phagocytes were not stimulated so that they failed to concentrate the quartz in focal areas; in tuberculous animals the infection caused an appreciable tendency to localization. But even when this had occurred, the silicates prevented the free silica from exerting its usual action upon connective tissue cells. There was some stimulation but it would undoubtedly have taken many more years of contact before typical silicotic foci developed.

These observations are in accord with clinical experience among the granite cutters at Barre. In non-infected individuals nodular fibrosis only develops after exposures of twelve to twenty years, even though the dust concentrations have been excessive. In roentgenograms of these men Russell, Britten, Thompson and Bloomfield [29] (1929) reported that linear reactions were much more common than nodular ones. Such shadows would be cast by the sheaths of perilymphatic cellular connective tissues about the blood vessels. Only this type of change was present in several post-mortem specimens which these investigators submitted to the writer for pathological study. The modifying action of infection was well demonstrated in another pair of lungs subsequently received from the same community. There had been a self-limited tuberculous infection which was localized to a portion of one lower lobe. About this lesion were a number of small typical silicotic nodules. In the other portions of the lungs the reaction was not nodular but linear and perilymphatic in distribution.

Granite dust would therefore seem to be a material containing inhibitors which are capable of preventing quartz

from acting on the tissues for a considerable period of years. The effect of these substances is apparently exerted within the tissues in a manner not yet understood. Infection tends to neutralize the inhibition so that the quartz can act more rapidly. Ultimately the protective action is overcome and a more or less modified silicosis develops. It would be profitable to determine quantitatively the amount of feldspar or mica or other unnamed substance which is necessary to neutralize the action of a unit quantity of quartz.

From the experimental and clinical observations that have been cited it no longer seems reasonable to assume that the silica hazard is only proportional to the amount of free silica in an atmospheric dust. The other substances present in combination with the silica modify its action. Some of them, like iron and gypsum, prevent its inhalation; others, like the components of granite seem to prevent it from affecting the tissues. The mode of action of metallic aluminum has not yet been determined although the preliminary reports suggest that it may fall in the latter category. Much more must be done to evaluate the quantitative relationships which govern the action of inhibitor substances on silica but that they exist and exert a very definite influence is the burden of this argument.

Asbestos

The only form of asbestos tested by inhalation in animals has been chrysotile but there is every reason to believe that the other fibrous silicates would produce similar effects for in human beings the reactions to all members of this group are apparently indistinguishable. When guinea pigs, albino rats and rabbits were exposed simultaneously to chrysotile dust of an average concentration of 43,000,000 particles per cubic foot of air only the guinea pigs developed significant reactions. (Gardner and Cummings 1931) [30] Apparently the

upper respiratory protective mechanisms of the rabbits and rats were adequate to exclude fibrous foreign bodies. After about seventy days exposure, asbestosis bodies had developed about fibres of chrysotile within the air spaces of the guinea pigs lungs. These asbestosis bodies closely simulated those found in human beings but were considerably smaller. They presented the same golden-yellow color, the club-shaped terminal swellings and the transverse segmentation of the iron-containing deposit upon the mineral fibres. They were located very largely in the alveoli opening along the sides of the respiratory bronchioles. Many of them were free ; some were surrounded by giant cells of the foreign body type. As the inhalation continued more of them formed in the same location where they either remained or penetrated the wall of the bronchiole. None could be found in the intra-pulmonary or tracheobronchial lymphoid tissues. Only the non-fibrous particulate elements of the dust were transported to the lymphatic system.

With further exposure the walls of these air spaces, penetrated by the fibrous foreign bodies, gradually became thicker due to an infiltration with mononuclear leucocytes. After fifteen months a moderate amount of fibrous tissue had formed, which surrounded the bronchiole like a sleeve. At the time it was believed that contraction of this fibrous sleeve would close the tube and produce an atelectasis of the peripheral air spaces. Study of the further stages of the disease has failed to confirm this prophecy. Instead, the reaction seems to extend peripherally along the bronchiole apparently because the foreign bodies are deposited further along its course. This, in turn, seems to be due to the smoothing of the inner surface and perhaps the loss of elasticity of the walls of the tube. As more fibres are inhaled they apparently pass through the smooth, inelastic bronchiole and are deposited in the alveolar ducts given off at its terminal end. These tubes in

their turn respond to the local irritation and their walls become fibrous. In time the still more distal atria are similarly involved. Although appreciable reaction in the alveolar sacs and alveoli has not been observed within two years and nine months of exposure, it now seems more probable that these structures are eventually involved by the process of peripheral extension.

In another group of guinea pigs it was demonstrated that the reaction to inhaled asbestos dust is not a progressive one. The animals were exposed to the same concentrations of chrysotile as used in the first test for a period of eight months and twenty days. They were then removed to a normal atmosphere and members of the group were killed at intervals during a subsequent period of three years. At the end of the exposure, chronic inflammatory reaction had developed in the walls of the respiratory bronchioles. During the next three months this process gradually progressed to form a slight amount of fibrous tissue. Thereafter the reaction was, if anything, retrogressive in character. At the end of the three year period there were very thin sleeves of fibrosis about the bronchioles but no extension into more peripheral air spaces had occurred.

In 1937 a third experiment with chrysotile was begun. This time the asbestos fibres were ground in a steel ball mill until practically none more than 3 microns in length were left. It was anticipated that, if the irritation were of a chemical nature, the reaction should proceed more rapidly. Average concentrations of 175,000,000 particles per cubic foot (light field count) are being maintained in the dusting room. Thus far *the response to 4 times the concentration of a much finer dust has been less pronounced than that obtained in the first experiment.* Instead of being held on the irregular surfaces of the respiratory bronchioles, the particles have passed immediately into the terminal air spaces. The very short fragments

of asbestos are surrounded by a typical golden-yellow coating and have the appearance of minute asbestosis bodies. Practically all of them are found within the bodies of mononuclear phagocytes. Only a few can be detected in the interstitial tissue. Most of these seem to be intracellular. Some have been transported to lymphoid tissues. Evidence of chronic inflammatory reaction in the terminal bronchioles and other parts of the pulmonary stroma are practically absent. Compared with animals exposed for similar periods to the longer fibres of chrysotile in the first experiment, the picture is very different and more nearly resembles that produced by inert dusts.

These experimental observations seem to be indicating that asbestos fibres cause fibrosis in the lungs because they act as mechanical irritants in an organ whose function involves considerable movement. The long fibres cannot effectively be removed by phagocytes and the lymphatic system; they penetrate the walls of the bronchioles and with each respiratory effort they continue to injure adjacent cells. The development of a protective coating about them must materially reduce the friction but as long as the inhalation continues new uncoated fibres are constantly accumulating to keep up the irritation. This is inferred from the lack of progression after the exposure has ceased. If the irritation were chemical in nature one would expect that it would develop more rapidly with finer than with large fibres, that it should be produced by injection into organs other than the lungs, as is the case with free silica, and that serpentine, whose composition is identical with that of chrysotile, should also cause fibrosis. But none of these effects have been observed. Final proof of the mechanical action of asbestos upon the lung is still lacking; it remains to demonstrate that the inhalation of pure, very long fibres of chrysotile will produce results even more quickly than the dust used in the first experiment, which contained only a limited amount of such

material. However, the findings in the various experiments already finished all point to mechanical irritation. Since summarizing these observations a paper by Sundius and Bygdén [31] (1937) has come to hand. As a result of elaborate chemical and petrographic analyses of asbestos dust and asbestosis bodies these writers have reached the same conclusion.

The experimental exposures have thus far failed to reproduce the widespread fibrous lesions which have been observed in a few of the human cases of asbestosis. Where the latter are uniformly distributed throughout the lungs but retain their characteristic fine, interstitial arrangement they may be considered as the result of prolonged and intensive exposure. But where a human case reveals localized areas of massive fibrosis, it seems most probable that infection has complicated the picture. The majority of tuberculous infections in guinea pigs with asbestosis tend to spread for a time but subsequently heal with the formation of considerable areas of fibrosis. Likewise, accidental non-tuberculous infections of the lungs may heal and organize to produce fibrosis. The similarity between these foci of healed tuberculous and non-tuberculous infections in experimental animals and certain massive areas of fibrosis in the human cases strongly suggests a common origin. Furthermore, in guinea pigs the interjection of the factor of infection causes the fibrosis to become progressive and it is felt that the same may be true of human cases. This may explain the belief, entertained by certain authorities, that asbestosis is itself a progressive disease.

Infection and Pneumoconiosis

One of the important contributions to the study of pneumonoconiosis in recent years is the demonstration that silicosis specifically predisposes to tuberculosis and that the combined action of silica dust and the tubercle bacilli produces a chronic progressive disease which is responsible for

most of the cases with marked disability. The group of investigators in the Miners' Phthisis Medical Bureau at Johannesburg[32] (1930) clearly differentiated the respective rôles of the factors of infection and dust. Collis[33] (1915) in his Milroy Lecture of 1915 showed that pneumoconioses other than silicosis were not associated with an excess incidence of tuberculosis although they might predispose to pneumonia. Recent work in this country and in Great Britain[34] is now indicating that the latter is probably true only of the bronchopneumonias; the incidence of lobar pneumonia seems to be little higher in persons with pneumoconioses than in others.

In considering this phase of the subject, a definite distinction should be made between slight or healed infections which play only an etiologic rôle and clinically active infections which modify the course and symptomatology of silicosis. The former may merely damage a localized area in the lungs so that abnormal quantities of dust are retained. Even though the infection is completely healed, the formation of scar tissue or the less perceptible alterations of the local lymphatic circulation modify the deposition of dust and the resultant form of the pneumoconiosis. On the other hand, the inhaled dust may alter native susceptibility to bacteria and the course of resultant infections in the lungs.

Non-tuberculous pneumonias develop spontaneously in animals inhaling dust with annoying frequency but so little is known about the mechanism responsible for these epizootic conditions that it is hard to evaluate the rôle of the dust. It seems highly probable that other environmental factors in the dusting rooms play considerable part in the spread of infections. At least their frequency is not very much greater where irritating free silica is involved than in the case of inert materials, like gypsum or marble. The pneumonias are probably more chronic and more frequently organized when

they complicate silicosis than other pneumoconioses but this result is by no means invariable. On the other hand such infections may modify the response to the inhaled dust. A purulent bronchitis opposes such a barrier to inhaled dust particles that very few of them enter the terminal air spaces. Preexisting foci of chronic pneumonia entrap unusual quantities of dust and the resultant concentration of particles sometimes causes much more reaction than occurs in normal portions of the lung. Silica accumulating in an inflammation starting to organize accelerates the process and produces diffuse obliterating fibrosis. Acute pneumonias superimposed upon well established pneumonoconiosis may be unusually fatal.

For the study of tuberculosis several controllable technical procedures are available. The writer has found that in silicotic animals primary inhalation infection with a particular attenuated strain of tubercle bacillus gives results comparable to those observed in human beings. He has therefore adopted this method as a standard procedure for testing the influence of other dusts on tuberculosis. His work has been criticized because it attempts to compare the results of a *primary* infection in animals with the chronic disease arising from *reinfection* in the human subject. The validity of this objection is fully appreciated and the original program of investigation contemplated artificial reinfections in animals previously sensitized. However, repeated attempts demonstrated that the vaccinating infection would generally become progressive in any animal exposed to silica regardless of the site of administration. Since endogenous reinfection occurred so regularly there was little point in making artificial reinfections. While the same difficulty is not encountered in animals exposed to non-siliceous dusts it seemed advisable to adopt a uniform technique for testing so that the results might be compared.

The particular strain employed is known everywhere as R_1. It possesses a limited but rather constant virulence for guinea pigs which has been maintained over a period of forty years or more. Its action after either injection or inhalation is predictable and hence it is a better testing agent than many others which have been tried. When guinea pigs are made to inhale a vapor containing small numbers of R_1 tubercle bacilli, they develop a multiple primary complex comparable to the so-called "childhood infection" in human beings. In normal animals the lesions consist of a variable number of isolated discrete tubercles, all less than 2 mm. in diameter, located in the subpleural alveoli together with foci of tubercle in the tracheobronchial lymph nodes. Such tubercles almost never spread but after progressing to the stage of caseation they begin to heal. Within two years time even microscopic traces of the lesions may have completely disappeared (1922).[35] The only evidence of the infection may be a persistent hypersensitiveness to tuberculin. (Figures 6 *a* to 6 *f*)

The course of an R_1 inhalation in a guinea pig exposed to dust may be quite different from that just described. The nature of the modified response depends upon the type of the pneumoconiosis concerned and the stage of its development when infection supervenes. Animals infected after several months exposure to dust of any type develop more tubercles and many of them are located in the deeper as well as the subpleural portions of the lungs; the course of the resultant infection is determined by the character of the dust. Under the influence of inert, soluble dusts like gypsum or marble the tubercles rarely spread and most of them heal by the normal process of resolution; a few may persist as localized scars, sometimes surrounding a focus of calcification. (Figure 7 *a*) The silicate, chrysotile asbestos and the hematite mentioned above often cause a temporary local extension

of the infection, but in most animals it subsequently heals with the formation of more extensive areas of fibrosis. (Figures 7 *e* and 7 *f*) The natural mixtures of free silica and iron oxide, chert, and the artificial mixtures of gypsum and quartz produce even more marked spreads of the infection. Such reaction usually heals with extensive scar formation (Figure 7 *d*) but in some of the animals chronic, slowly progressive cavities develop which persist for several years. Granite with its 35 per cent quartz content may also cause chronic progressive tuberculosis but only after prolonged periods of exposure to the dust. Pure silica, and for unexplained reasons, the carbide of silicon (SiC) almost invariably produce a progressive type of infection.

If the tubercle bacilli are inhaled at the beginning of an exposure to pure silica dust the lesions pursue a normal course for a period of about five months. Then they begin to spread, at first by local extension into the adjacent lung tissue, then by ulceration into a bronchus with resultant dissemination through the air passages to all parts of the lung and finally by way of the blood stream to the abdominal viscera. Cavities form at the site of many of the original subpleural foci and often in secondary lesions throughout the lungs. The generalized reaction is at first exudative in character but soon becomes proliferative with the formation of tuberculous granulation tissue. Organization of the latter results in a widespread fibrosis which completely obliterates all of the normal pulmonary architecture. The animals appear well and suffer no loss of weight or appetite for many months but they become increasingly short of breath and finally die emaciated with all the signs of intoxication. Those with widespread pulmonary fibrosis often present the picture of right-sided heart failure at autopsy.

If the infection is administered at the end of a silica exposure and the animals are then removed to a normal at-

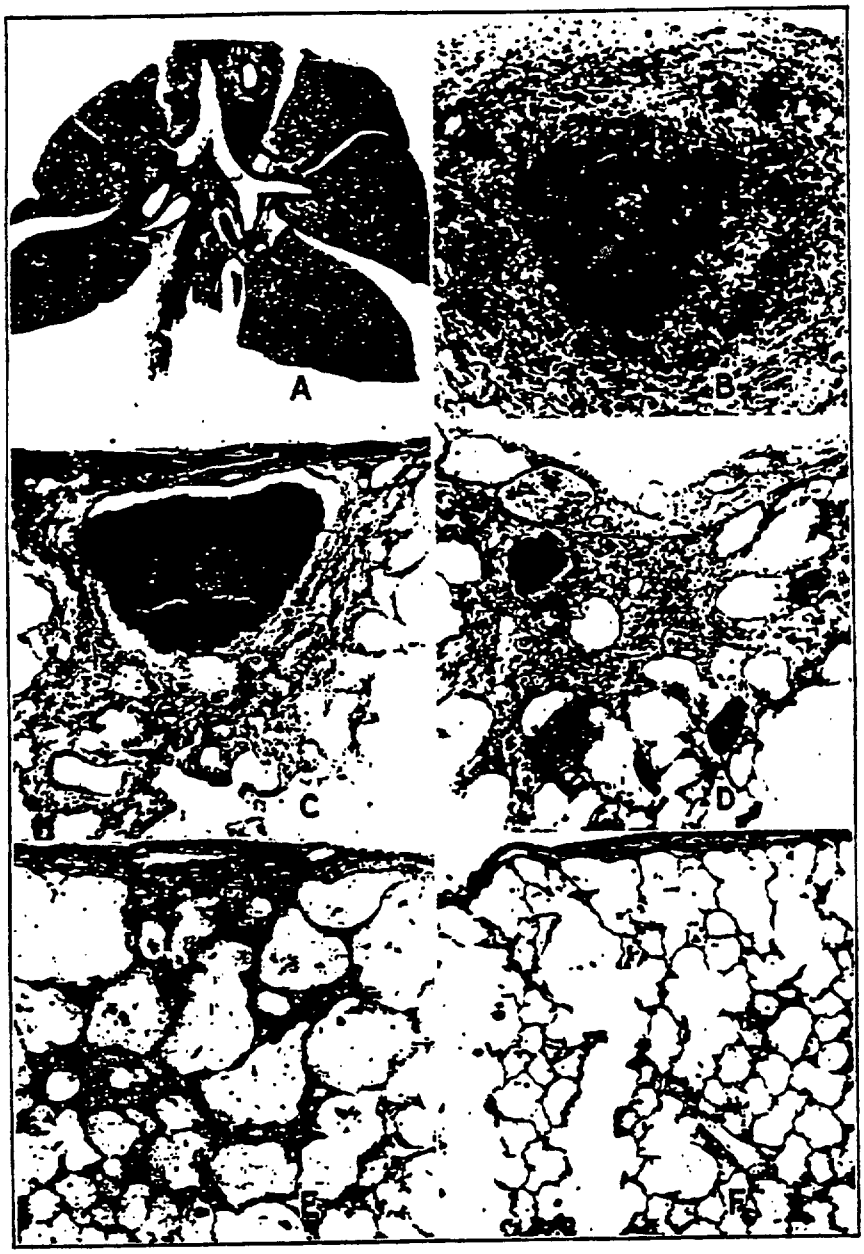


FIGURE 6. See caption on page 333.

mosphere the resultant tuberculosis becomes increasingly acute as more and more silicotic fibrosis develops. Infections after the first four or five months of dusting are generally quite chronic and their course resembles that just described. Administered after six to ten months of dust exposure, the tuberculous infection runs a more rapid course with frequent fatalities ; after twelve to fourteen months in silica dust, R_1 inhalation produces an acute pneumonic tuberculosis which in most cases terminates fatally within a period of three months. (Figure 7 *b*) Occasional resistant members of the last group may survive to develop more chronic lesions with large cavities and tuberculosis throughout their bodies.

If, on the other hand, the inhalation infection is given first and healing is allowed to begin before exposure to silica dust the tubercles are susceptible to reactivation as long as they contain viable organisms (1929).[36] For this to occur it is essential that appreciable quantities of dust be localized in the immediate vicinity of the tuberculous focus. Whenever this occurs mobile phagocytes transport silica particles into the caseous centres of the lesions, the bacilli are stimu-

FIGURE 6

The course of R_1 inhalation tubercle in normal guinea pigs. *a*. Low power photograph to show three small isolated tubercles beneath the pleura on the right side. The tracheobronchial node on the right is slightly enlarged due to simultaneous involvement. *b*. An R_1 tubercle at its maximum stage with a central zone of caseation. *c*. Beginning healing. The tubercle bacilli are largely dead, the caseous zone is shrinking and the proliferative zone has become fibrous and is contracted. The overlying pleura is fibrous. *d*. The caseous zone is reduced to a small area at the upper right. Contraction of the surrounding fibrous tissue is causing emphysema. Note the associated dimpling of the pleura. *e*. All trace of caseation has disappeared. Thickened septa separate considerably dilated air spaces. The pleura is still thick. *f*. Practically all that remains after two years is the localized pleural thickening and some distortion of the underlying air spaces.



FIGURE 7. See caption on page 335.

lated to multiply and an extension of the infection ensues. The result is a chronic spreading tuberculosis whose anatomic manifestations are essentially the same as those in the first example of infection simultaneous with the outset of exposure of silica. (Figure 7 *c*)

It would appear that the bacilli multiply in areas where a sufficient quantity of silica particles has accumulated. But the mere presence of the silica is not the only essential ; the mineral must have had time to react with the tissues and produce an appreciable amount of necrosis. The importance of the latter is well demonstrated by a technique devised by Kettle [37] (1924). In white mice, he showed that blood borne tubercle bacilli, which happened to localize in an area of necrosis that had been produced by subcutaneous injection of finely divided silica, multiplied much more rapidly

FIGURE 7

R_1 inhalation in guinea pigs exposed to various dusts. *a*. Healing of an R_1 subpleural tubercle by calcification in a guinea pig exposed to pure gypsum dust for 5 months, then infected and allowed to remain in the dusting room for 21 months before it was killed. *b*. Acute. tuberculous pneumonia in a silicotic guinea pig infected with R_1 tubercle bacilli. Exposure to pure chalcedony one year, removed from dust room, infected by inhalation, death from tuberculosis in 41 days. *c*. Chronic silico-tuberculosis with cavity formation resulting from reactivation of a partially healed R_1 inhalation infection. The tuberculosis had been present 10 months before the exposure to pure quartz was begun ; the guinea pig died after 7 months in the dust house. *d*. Chronic sidero-silico-tuberculosis in a guinea pig. Animal exposed to ferruginous chert for 3 months ; infected by inhalation of R_1 tubercle bacilli and then returned to dust house for 12 months. *e*. Healing by fibrosis after local extension of R_1 tubercle in guinea pig infected by inhalation and exposed to asbestos dust for 5 months. Note that most of the tubercles are situated in the deeper portions of the lungs rather than in the subpleural regions as in normal control animals. *f*. Higher magnification of one of the fibrous tubercles shown in figure 7e. This lesion is much larger and more fibrous than those produced by either the infection or the dust alone.

than in other portions of the body. No proliferation occurred unless a period of four or five days elapsed between the 2 injections. He also demonstrated the specificity of the silica reaction by producing subcutaneous foci of necrosis with other irritants, like turpentine, and showing that in them there was no unusual multiplication of the bacteria. Vorwald and Landau [20] (1937) used the same method and demonstrated that the injection of non-siliceous dusts would not cause tubercle bacilli to multiply. With various silicate dusts their results were so inconstant that they could draw no conclusions as to the effect of any of these minerals.

Other experimental methods are applicable to demonstrate the stimulating action of silica upon tuberculous infection. Silicotic rabbits injected intravenously with human type of tubercle bacilli, which are ordinarily of low virulence for this species, develop progressive tuberculosis. The infection localizes in and about the preexisting silicotic nodules and produces a collateral zone of tuberculous reaction. Caseation invades and often destroys the dense silicotic fibrosis. White rats, which are naturally immune to tuberculosis and rarely develop localized tubercles, become susceptible after they have inhaled enough silica dust. Tubercles form in their lungs, both in the immediate vicinity of the nodules and in the intervening tissues. Intratesticular subcutaneous and intraperitoneal injections of both tubercle bacilli and various dusts have been tried but the resultant lesions are so complicated that analysis is difficult.

It now seems apparent that the reaction of silica upon the tissues furnishes a medium upon which tubercle bacilli grow with unusual rapidity. But such growth is not necessarily continuous; in newly-formed lesions the organisms are very numerous and readily demonstrated in stained sections or smears, but in old foci bacilli are often rare or entirely absent. Subinoculation into guinea pigs usually demonstrates

their presence in experimental lesions. The writer has studied four advanced human cases with typical cavities and every histologic indication of tuberculosis in which even guinea pig inoculation of caseous cavity contents failed to reveal evidence of living bacilli.

Several investigators have attempted to demonstrate that the addition of silica in various forms to artificial culture media enhances the growth of the tubercle bacillus. Price [38] (1932) reported favorable results but Kettle [3] (1930) and the writer have both failed to note any result other than an early acceleration of growth. More recent experiments by Vorwald, Dworski and Steenken in the Saranac Laboratory have indicated that under certain conditions the amount of growth in the presence of silica is excessive. However, it has not been possible to obtain the same effect in every series of tests and these investigators are still attempting to discover the conditions responsible for their favorable results.

The exact cause of the stimulation awaits demonstration. Some, like Cummins [39] (1934) have ascribed it to obstruction of lymphatics which interferes with free elimination of the bacilli from the lungs. Others have believed that the silica itself directly stimulated the bacteria. The writer is of the opinion that the chemical products liberated by action of silica on the tissues provides a medium particularly favorable for growth. This view is based upon the presence of such large numbers of bacilli in fresh, necrotic silicotic foci and their paucity in lesions which are old and without degenerative changes.

The application of these experimental results to the interpretation of tuberculous manifestations in human silicotic subjects may be somewhat as follows: Activation of a preexisting primary complex of first infection such as has been described in animals does not often occur in human beings because such lesions are generally healed and sterile in per-

sons who have reached the age of industrial employment. However, very occasional examples of such reactivations have been followed in young persons, presumably ones infected for the first time in late adolescence. Such cases prove the possibility of affecting the primary complex but their infrequency makes it at least debatable as to whether the presence of the calcified primary complex constitutes reasonable grounds for rejection from employment. It seems most unlikely that the small calcified primary tubercle in a man over twenty-five should contain living tubercle bacilli.

The acute reactions obtained when a primary infection is administered to an animal with fully developed silicosis have anatomic counterparts in the so-called "perinodular" type of human tuberculosis, a rare form which runs a rapid course with a fatal outcome. The cases usually occur in young subjects who appear to have little resistance to infection. From the animal experience it is assumed that they are nonimmune subjects whose first contacts with the tubercle bacillus were made after silicosis had developed.

The chronic forms of the infection are more apt to occur in individuals possessing some resistance by virtue of previous infections at an earlier age. Such persons may enter employment involving an exposure to silica dust already reinfected and carrying either a healed or a latent but potentially active focus of reinfection in the upper portion of their lungs. Inhaled silica accumulates in unusual concentrations in and about the scars of infection. There its action accentuates the existing tendency to fibrosis and the scar becomes still thicker and heavier. If the focus is sterile and contains no living organisms, more fibrosis is the only outcome. If, on the other hand, viable tubercle bacilli are sequestered within areas of caseation it is altogether probable that in time the phagocytes will transport silica into them. When enough reaction has occurred the organisms will begin to multiply

again, as was observed in the experimental animals. Here are the potentialities for spreading tuberculosis but unlike the focus in the animals, the human lesion is old, dense and often very thick. The proliferating organisms spread into an environment of scar tissue with a deficient blood and lymph supply and a low oxygen tension. Consequently the stimulating effect of the silica is more or less neutralized and the bacilli are barely able to maintain themselves. Enough remain alive so that in combination with the silica they continue to cause proliferative reaction. The resultant area of silico-tuberculosis slowly increases in size but the toxic symptoms of infection are slight or absent because the opportunities for absorption are limited. Ordinary doses of tuberculin fail to elicit reactions in the skin, but larger amounts will produce them. (This has been amply demonstrated in an unreported series of such tests by Dr.L.E.Hamlin,[40] 1936.) In time enough bacilli make their way to the surface of the involved area where they find more normal conditions for growth. Then they multiply more rapidly, toxic products are absorbed and the ordinary clinical symptoms of infection are manifest. The bacilli, no longer bound in the scar tissue, reach the bronchi and the sputum may become positive for the first time. Now the nature of the process becomes clinically obvious.

Not all the chronic cases of silico-tuberculosis result from the reactivation of preexisting latent apical foci. Individuals, resistant by virtue of previous infections, may become reinfected early in the course of their exposure to dust. If conditions are such that the focus of reinfection is encapsulated and does not spread immediately, chronic disease may again develop. Such perhaps are the lesions found in the middle or lower parts of the lung which are unusually common in silicotic subjects. The evolution of this type of silico-tuberculosis is essentially the same as that just described. Its coun-

terpart is not found in the animals for none of them have received exogenous reinfections. However, the principle of resistance acquired by virtue of previous non-progressive infection is illustrated in the animal whose primary infection remains quiescent for a time but when it is activated the resultant endogenous reinfection is of a chronic type.

There are also human cases of tuberculosis on a background of silicosis which behave as do those in the general population. They generally occur when the exposure to silica has not been severe or prolonged. One might assume that insufficient quantities of silica have established contact with the tuberculous focus to affect its behavior since in animals such contact seems to be the essential requirement.

The influence of inhaling other types of dust upon pulmonary infection with R_1 tubercle bacilli have already been mentioned. Detailed discussion of their individual effects is unnecessary except to state that in general the results are comparable to clinical experience in industries where the dusts concerned are generated. One notable exception exists in the case of the carbide of silicon which in animals caused the infection to progress almost as regularly as free silica. This was true in several guinea pig experiments where the dust was inhaled (1923) and the infection was administered either by inhalation or by injection at remote points. It was not confirmed by the white mouse tests performed by Vorwald and Landau[20] (loc. cit.). An unusual incidence of tuberculosis has not been discovered in persons engaged in the manufacture of silicon carbide (Clark, 1929[41]).

Perhaps the most striking feature of the experiments dealing with the combined action of different dusts and tuberculous infection is the variability of the response in the members of the different series. While most of them exhibit a tendency to react in the same general manner, exceptional individuals behave atypically. The same observation is, of

course, constantly being made in human beings. The result could hardly be otherwise when dealing with two living variables.

There remains for discussion the effect of the infection upon the pneumoconiosis. It has already been stated that infection favors the development of nodule-like lesions in the case of granite dust. It has also been intimated that some of the silicates may possibly become more active in the presence of infection. It has been shown that infection is not essential to the formation of nodules by pure silica but that their development is accelerated when infection modifies the tissues of the host.

The significance of the healed fibrous tuberculous lesions associated with the modified forms of silicosis needs special emphasis. Anatomically the experimental lesions consist of wide areas of obliterating fibrosis whose evolution has been that of an organizing pneumonia. In its earlier phases the various manifestations of tuberculous granulation tissue are obvious but later the specific evidences of the infection tend to disappear. In the tuberculous animal, exposed to ferruginous chert in particular, the healing is often so complete that the cause of the fibrosis would not be suspected without the evidence from previous members of the series. The fact that human cases of sidero-silicosis have sometimes presented lesions which were obviously tuberculous in origin but in which living bacilli could not be demonstrated by guinea pig inoculation indicates that in them the causative organisms may die. This suggests that at least some of the areas of massive fibrosis without histologic evidence of their etiology may also have originally been caused by tuberculous infection. In several instances the position of the lesions in the upper portions of the lungs and their gross appearance have supported such a view. Obviously more human autopsy material from persons exposed to many kinds of dust must be

studied before generalizations are possible. Nevertheless, it would now appear that many mineral dusts either alone or in combination with free silica, may favor ultimate healing of tuberculous infections with the formation of scar tissue from which all the specific characteristics have disappeared. Confirmation of this hypothesis would be most useful in explaining the etiology of many of the areas of massive fibrosis found in human silicosis.

Attention is called to the fact that much of the material presented in this chapter has never been published. The writer has borrowed freely from the observations of his coworkers in the Saranac Laboratory. It is his pleasure to acknowledge his debt to Mr.D.E.Cummings, Dr.A.J.Vorwald, Mr.T.M.Durkan, Mr.M.Dworski and to all his other associates who are collaborating with him in the study of these problems. He also is indebted to the Journal of Industrial Hygiene and Toxicology, and the American Review of Tuberculosis for permission to reproduce numerous illustrations that have previously appeared in these journals.

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VI. OCCUPATIONAL, PREVENTIVE AND LEGISLATIVE ASPECTS

GREAT BRITAIN

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SILICOSIS as an industrial malady is probably of great antiquity in Great Britain. Collis [1] has quoted references to prehistoric factories where flint implements and weapons were made, and has found their modern counterpart in the workshops of Brandon, in Suffolk, where the few remaining flint-knappers make gun-flints for barter amongst the native races of Africa. In less remote times flints were used as building material, and, it may be presumed, the masons of the period suffered from the disease. "Stonemasons' phthisis" has been well known for generations amongst workers in sandstone, "grinders' rot" amongst metal grinders, "potters' asthma" amongst pottery workers, and "miners' phthisis" amongst metalliferous miners. These were all trade names for the same disease, silicosis or silicosis accompanied, as it frequently was, with tuberculosis.

The exact extent of the disease in modern industry is not accurately known, but there is an increasing tendency amongst medical men to make use of the term silicosis to indicate the disease in certificates of the cause of death, and from this source an approximate estimate can be made of the annual number of deaths occurring from this cause in England and Wales. During the seven years 1930 to 1936, the average number of deaths recorded in this way was 325 per annum. The principal occupations from which these fatal cases were derived are briefly described.

TABLE 1

Industry	1930.	1931.	1932.	1933.	1934.	1935.	1936.	Total.
Sandblasting	10	17	5	10	5	12	10	67
Steel foundry work	1	4	1	1	—	1	5	13
Metal grinding	35	37	31	21	18	28	24	194
Metallurgist	—	1	—	—	—	—	—	1
Metal drilling	—	—	—	—	—	—	1	1
Stone, pebble flint and sand crushing	1	1	2	4	1	—	1	10
Railway construction (desert sand in Africa)	—	—	—	—	—	—	1	1
Refractories Industries	11	19	5	7	9	12	5	68
Abrasives Manufacture	—	1	3	—	1	3	2	10
Enamel Manufacture	—	—	—	—	1	—	1	2
Sandstone quarrying and dressing	17	25	11	26	33	40	43	201
Sandstone masons	35	45	44	75	55	61	59	374
Grave diggers	1	—	—	—	3	1	—	4
Tunnel mining (sewage works)	—	1	—	3	1	3	—	8
Granite quarrying and dressing	2	1	—	3	—	1	1	8
Slate quarrying and dressing	1	2	3	3	3	3	6	21
Slate dressing, with sand	—	—	1	—	—	—	—	1
Glazier's diamond setter	—	—	—	1	1	—	—	1
Pottery Manufacture	53	57	63	53	44	58	48	376
Leather dressing	1	—	—	—	—	—	—	1
Mining—Gold	24	28	16	18	18	16	4	124
Tin	10	18	28	17	15	35	24	140
Lead	2	4	6	1	—	2	1	16
Copper	—	2	1	—	—	—	—	3
Hematite	—	10	7	6	13	12	9	57
Coal	41	50	76	74	85	111	120	557
Fireclay	—	—	—	1	—	—	—	1
Barytes	—	1	—	1	1	2	1	6
Fluorspar	—	1	—	—	—	—	—	1
Mining engineers	2	2	1	2	2	—	1	10
Totals	247	330	308	329	307	391	369	2,281

Annual average for the period of 7 years 325.86

SANDBLASTING

This is the process of projecting sand, crushed flint or other grit, by means of compressed air, against a surface. It is used: (1) in metal works, to remove adherent sand from castings and to produce a surface suitable for treatment by coating with enamel or another metal: (2) for etching glass and treating other non-metallic articles, such as wood and ivory. The process is carried on in many industrial centres throughout the country.

It can be carried out in various ways. For large metal castings the operator works in a specially constructed chamber, moving about and directing the sand-blast as required. The



FIGURE 1
A gun flint from Brandon. Photo by S.H.Wilkes.

atmosphere of the chamber is filled with a dense cloud of fine dust of the abrasive sand, which becomes finely comminuted in the process. The operator wears protective clothing and a helmet supplied with pure air under pressure through a tube. Exhaust draught is provided for removing the dust-laden air from the chamber. Smaller articles are treated in a closed cabinet before which the worker stands, passing his arms through guarded holes to direct the sand-blast, while watching the process through a glass panel. A modification of this type of apparatus is that generally used for treating pottery. For etching glass a stencil may be used, the glass being pressed against it while the stream of abrasive etches the pattern on

the exposed parts of the glass surface. Other types of apparatus for treating metal articles are the turntable and revolving barrel in which the sand-blast is directed from one or more fixed points, and close attention by the worker is not necessary.

A more recent process is the use of the sand-blast for applying sand to the surface of bricks and tiles in the plastic state. It is done in a special apparatus, the bricks or tiles passing on a conveyor band through a chamber in which they meet moving jets of sand, the sand adhering to the surface of the articles. Exhaust draught is applied within the chamber, and the openings are guarded with rubber or canvas flaps.

The sand-blast has also been used to clean the outside walls of buildings and the hulls of ships.

The abrasives in general use for sand blasting have been quartzose sand, which contains a high proportion of free silica ; and crushed flint, a hydrated form of free silica. Owing to the high incidence of severe silicosis amongst sand-blasters an increasing tendency has been evident, on the part of employers, to replace sand and flint by non-siliceous abrasives Instead of sand or flint, metal grit is being used for cleaning metal castings and surfacing metal for enamelling or metallisation : for glass, pottery and other articles alumina or other abrasives containing no free silica are used with satisfactory results.

With the use of quartz sand and flint, risks are incurred by workers through defects in the appliances or lack of maintenance, and by faulty or careless methods, particularly, opening the door of the cabinet or removing the helmet before the dust cloud has been removed by the exhaust draught.

The dust hazard in cleaning castings is from the moulding sand and from the abrasive, when this is sand or flint. Where clean c ·tings or other metal articles are treated, the danger is from the abrasive alone. When metal grit is used on cast-

ings with moulding sand still adhering, siliceous dust is produced from the moulding sand. With clean metal articles and metallic abrasive all danger of exposure to siliceous dust is obviated. Certain objections have been raised to the use of steel grit as the abrasive, owing to technical difficulties which have been met with ; for example, particles of steel becoming embedded in castings of non-ferrous metals or alloys and preventing satisfactory machining afterwards ; or iron staining from particles of the abrasives being left on articles which were later enamelled. Such difficulties have been got over by using non-ferrous and non-siliceous abrasives, or by cutting out the blasting operation altogether. The pressure of the compressed air is varied with the nature of the work ; for metal castings it is from 30 to 60 pounds to the square inch, while for pottery it is from 15 to 30 pounds ; and for glass, wood and other materials it is still lower. The lower the pressure of the air blast the less dust is likely to be formed.

Both sexes are employed on sandblasting small articles, but men only on the heavier metal work. In the census of England and Wales, 1931, the total numbers over sixteen years of age employed on sandblasting are given as : males 1295 ; females 100. The number of deaths certified due to silicosis in England and Wales in the seven years, 1930 to 1936, was 67 or 9.6 per annum. This gives a mortality rate of 6.9 per 1000 living. The rate is actually higher than this, because the census figures include shot blasters working on clean metal, who are not exposed to siliceous dust.

Silicosis occurs amongst sand-blasters after short periods of employment, compared with other occupations. In 38 fatal cases which were fully investigated, employment was less than twenty years in all of them ; in 8 it was less than five years ; in 15 between six and ten years ; in 11 between eleven and fifteen years, and in only 4 it was over sixteen years.

Prevention. Regulations for the Grinding of Metals (Mis-

cellaneous Industries) 1925[2] provide that (1) sand-blasting shall not be done in any room except in an enclosed chamber or cabinet in which no other work is ordinarily performed and at which efficient means are provided to prevent escape of dust outside of the chamber or cabinet; (2) no person may perform sand-blasting in the open air, or work within 30 feet of such, unless he is wearing a suitable protective helmet and gauntlets; during sand-blasting in a chamber overalls are also required; (3) the protective helmet must be provided with a supply of pure air, means of escape for exhaust air, and it must bear the mark of the person using it; (4) before being used by another person the helmet must be thoroughly disinfected. These Regulations apply to metal works in which grinding of metals and cleaning of castings are done. In other factories and workshops the general provisions of the Factories Act[3] are applicable. Section 4 provides that provision shall be made for rendering harmless, so far as practicable, all dust etc. that may be injurious to health. Section 47 requires means to be taken for preventing the inhalation of dust, and Section 48 requires exclusion of persons from workrooms in which siliceous dust is produced during intervals allowed for meals or rest.

Even with improvements in sand-blasting apparatus the margin of safety is so narrow in this hazardous process that the workers cannot yet be said to be fully protected. The only solution of the problem at present in sight is the abolition of siliceous abrasives in sandblasting and the thorough cleaning free from moulding sand of castings before shot-blasting.

Compensation. The Various Industries (Silicosis) Scheme, 1931[4] provides for payment of compensation in cases of death or total or partial disablement of workmen employed in foundries and metal works on "sandblasting of metals or articles of metal by means of compressed air and with the use of quartzose sand or crushed silica rock or flint."

Grinding of Metals

The processes which cause silicosis in the grinding of metals are confined to those in which grindstones composed of sandstone are used. In addition to actual grinding, certain incidental processes of dressing the surface of the grindstone are very important from the health point of view.

The industries in which metal grinding is important are (1) the cutlery and edge tool trades, and (2) machinery and general engineering works and foundries.

Grinding may be done wet or dry, and the metal being ground may be moved by hand or by mechanical power on a machine. In wet grinding, the grindstone is mounted on a horizontal shaft and is made to revolve rapidly in a direction away from the grinder, except in some special kinds of grinding, such as scythe-grinding, when it revolves towards the grinder. Water is laid on from a tap or spray above the grindstone and is drained away beneath it. Formerly the lower part of the stone dipped into water in a trough in which grit, metal and dirt were allowed to collect. Wet grinding is also done by machines, especially in the manufacture of files, saws and machine-knives, when the metal being ground is fixed to a part of the machine which moves under or across the revolving grindstone.

The processes of dressing the grinding surface of the grindstone are: 'racing', that is, trueing the surfaces of the grindstone before it is brought into use for the first time; and 'hacking' and 'rodding' or 'scaring', which are carried out frequently in the course of the day's work to maintain the grinding properties of the surface.

Grindstones are obtained chiefly from the millstone-grit sandstones of the Derbyshire, Sheffield and Newcastle districts. They vary in size from 1 to 7 feet in diameter and from 1 to 12 inches in thickness.

Dust is produced by attrition of the grindstone in all processes in the grinding of metals, and it varies in amount with the hardness of the stone, the shape of the article being ground and the amount of pressure used. Concentration of dust found at breathing level of the grinder in various processes in wet grinding are as follows (the principal figures being number of particles in 1 cubic centimetre of air, the figures in parentheses being estimated millions of particles in 1 cubic foot of air) : (1) Hand-grinding ; table-blades, 280 (8) ; chisels, 1150 (33) ; scythes, 660 (19). (2) Machine-grinding ; paper-knives. 130 (3.7) ; files, 270 (7.7) ; edge-tools, 120 (3.4). In dry grinding sheep-shears, by hand (with exhaust draught), 240 (7).

The change from grindstones, made from sandstone, to artificial abrasive wheels, made from carbide of silicon and various forms of alumina, has been very marked since 1927. It was estimated that in 1926 about 1600 grindstones were in use for hand-grinding in the Sheffield district. This number was reduced to about 200 in 1933 and many of these were not in regular use. In the Birmingham district there were 480 grindstones in use in 1926 and 452 persons employed. In 1936 only 22 of those sandstone wheels were in use and 18 persons were employed.

Owing to this rapid and extensive change in the method of working it is not possible to estimate the numbers of persons on whom the present incidence of silicosis is falling. It must be presumed that the deaths in these later years are the result of conditions which existed between twenty and forty years ago. The numbers of deaths certified to be due to silicosis amongst metal grinders is showing a tendency to fall. In the seven years, 1930–36 the annual figures were 35, 37, 31, 21, 18, 28 and 24; average 27.7 per annum. This gradual fall in incidence of silicosis is chiefly due to the change from sandstone to abrasive wheels. At the coming into force

of the Workmen's Compensation (Silicosis) Scheme for the grinding of metals industry on 1st July, 1927, there was a widespread departure from the use of sandstone wheels and a corresponding adoption of artificial abrasives to which the Compensation Scheme did not apply.

Prevention. Another influence in reducing silicosis in this industry is the stringent preventive measures enacted in two codes of Regulations in 1925 : the Grinding of Metals (Miscellaneous Industries) Regulations,[5] and the Grinding of Cutlery and Edge Tools Regulations.[6] These two codes replaced a single code of Regulations made in 1909, and followed a technical and medical inquiry[7] in the industry. The general provisions of the Regulations may be summarised thus : —

(1) Localised exhaust draught for 'racing,' dry-grinding or glazing.
(2) Separation of the process of 'racing' grindstones in the cutlery and edge tool trade; and of wet-grinding.
(3) General ventilation sufficient to provide 12 changes of air per hour, and 15 changes in cutlery and edge tool shops ; and continuous movement of air in a direction from the grinder to the outlets.
(4) Suppression of dust at 'hacking' and 'rodding' by water or other means.
(5) The rooms must be a certain minimum height, windows must be adequate and kept clean ; floors and walls must be so constructed as to be capable of being cleaned, and all shafts, belts, etc. efficiently covered.
(6) Adequate drainage for water.
(7) Periodical cleaning of floors, walls, ceiling and fixtures.
(8) Spitting prohibited.
(9) Cloakroom accommodation to be provided.
(10) Grindstones must not be less than the prescribed distance apart.

Compensation. The Metal Grinding Industries (Silicosis) Scheme, 1931,[8] made under the Workmen's Compensation Act 1925, and the Workmen's Compensation (Silicosis and Asbestosis) Act, 1930, replaces a Scheme made in 1927. It provides for compensation in cases of death or total or partial disablement certified to be due to silicosis or silicosis accompanied by tuberculosis, in workmen employed in

(i) grinding of metals (by means of a grindstone);
(ii) any work incidental to such grinding, and glazing, done in the same room as grinding;
(iii) racing of grindstones for the grinding of metals.

Refractories Industries

For purposes of legislation it has been necessary to define this industrial group, as meaning the following processes carried on at mines, quarries, factories and workshops at which refractory material containing not less than 80 per cent total silica is got or manipulated with a view to manufacture or sale, namely: —

All processes in or in connection with the getting, handling, moving, breaking, crushing, grinding and sieving of such material, and all processes in the manipulation of such material in the manufacture of bricks or other articles containing not less than 80 per cent. total silica. The processes include the quarrying or mining of the raw materials, usually sandstones of the coal measures (called ganister), which occur in open quarries and in mines; in some localities, sands or 'pocket-clays' are used. They contain usually from 92 to 98 per cent of silica. The material is crushed, mixed with suitable bonding substances, and made into silica bricks, silica cement, steel-moulders' composition, and similar products for use as refractories in the manufacture of metals, especially steel and steel-castings, and in the construction of gas-retorts and flues.

Quarrying and mining of the solid rock, drilling, blasting and breaking it with hammers are processes attended with exposure to silica dust. Dust is also produced in crushing, grinding, sieving and mixing the material and in moulding bricks. Moving the bricks to and from the drying floors and setting them in and withdrawing them from the kilns in which they are fired also cause evolution of dust. The character of the dust varies with the composition of the raw materials. When these contain clayey matter the finest particles tend to form aggregates, thus reducing the risk. No process in this industry, however, appears to be entirely free from danger.

About 3,000 persons, including a small proportion of women, are employed in the industry, which is distributed in the coal measure districts, especially in the north of England, South Wales and central Scotland.

During the seven years, 1930–1936, the numbers of deaths from silicosis in the industry show a yearly average of 10, with little tendency to fall. Most of the deaths occur amongst ganister miners and quarrymen.

Prevention. In the factory processes there is an increasing use of mechanical methods, and these will have the effect of reducing exposure to dust, particularly in the use of kilns which are not entered by the workmen.

Refractory Materials Regulations 1931 [9] are a revised form of the code which was in force in factories since 1919. They require the enclosure and provision of exhaust draught for machinery were dusty material is crushed, sieved or moved; the use of water for suppression of dust, and the removal and disposal of debris from floors and passages.

Section 78 of the Coal Mines Act, 1911, requires generally that mechanical drills used for drilling in highly siliceous rocks shall be provided and used with an efficient means to prevent the escape of dust into the air. Under the same Act

general Regulations have been made for ganister mines, and under the Metalliferous Mines and Quarries Acts, special rules have been established in tin mines and in many quarries where ganister, sandstone and other silica rocks are worked.

Compensation. The first scheme of compensation for silicosis was made for the Refractories Industries under the Workmen's Compensation (Silicosis) Act, 1918, and it came into force on February 1, 1919. It provided for initial and periodical medical examination of all workers, suspension from the industry on a diagnosis of simple silicosis, as well as of silicosis with tuberculosis; and compensation in respect of disablement or death from silicosis or silicosis with tuberculosis.

The Scheme was revised in 1925, following an Inquiry by a Departmental Committee, and again in 1931 [10] to provide for examinations being made by a Medical Board.

Manufacture of Abrasive Soap Powders

These products are used chiefly as domestic abrasive cleansers. They consist of ground silica, pumice or similar abrasive substance, mixed with smaller quantities of anhydrous sodium carbonate (soda ash) and powdered soap, and sometimes other substances.

Except in a few of the largest works the abrasive mineral is obtained already finely ground. When silica is used it is generally a highly siliceous quartzite rock containing 96 to 98 per cent of silica, and it may be calcined before it is ground. The silica 'flour', as it is called, is mixed with the soda ash, soap, etc., either by hand, with a shovel, or in a mixing machine. The cartons may be filled by hand, or the mixed powders are conveyed and filled mechanically.

A few years ago a considerable number of small undertakings were started, sometimes as a branch of another business, the proprietors and workers having little or no knowledge of

the risk to health or the means necessary for avoiding it. The result has been that some of the most rapidly developing cases of silicosis on record have occurred before adequate measures could be taken to deal with the danger.

In all the fatal cases of silicosis recorded in England from the manufacture of these abrasive powders, the dust has contained a highly siliceous quartzite rock, finely powdered and mixed with soda ash and soap powder. The number of deaths certified due to silicosis contracted in this manufacture was 10 during the seven years 1930–36. This is probably less than the actual number. In one factory where the manufacture was carried on to a substantial extent for seven years, 13 persons are known to have died from silicosis with or without tuberculosis, out of a total of 59 persons who had been employed during that period for longer than two months on the process. All except one had commenced the work between fourteen and sixteen years of age.[11] The unusual characters of the rapid onset and course of the disease in most of these cases may be connected with the early age of the subjects. Attention has been drawn to the presence of free alkali in the powders to account for these characters.

Mention may be made here of siliceous materials used in polishing compositions. The best known are Tripoli, Neuburg chalk and Diatomite.

Tripoli is regarded as a chalcedonic form of silica containing 96–99 per cent silica. The substance generally known by the name is obtained from Seneca, Missouri. The name is derived from Tripoli in North Africa, where the product is diatomite.

Two fatal cases of silicosis with tuberculosis have been recorded from exposure to dust of tripoli. The two men had been employed for ten and eleven years respectively mixing the ingredients in the manufacture of a foundry sand in one case, and of polishing-composition in the other case.

Neuburg chalk is a natural deposit of siliceous material at Neuburg on the Danube. The silica content is variously given as from 65 to 97 per cent. Definite cases of pulmonary disease have occurred from exposure to the dust of Neuburg chalk in Britain and in Germany.

Diatomite (kieselguhr, diatomaceous earth) is formed from the siliceous skeletons of minute aquatic plants and when pure it contains up to 96 per cent of silica. It is used as a polishing medium, as filtering material and for its insulating properties. Radiological examination of 6 workers exposed for ten years to the dust of kieselguhr in Britain showed evidence of a slight degree of fibrosis in 2 of them and none in the others.[12]

Prevention. Suppression of all dust in the processes of mixing and packing of abrasive soap powders is difficult to attain, even with the use of exhaust draught, owing to the dryness and fineness of the powders. Reliance is best placed on the fullest use of mechanical methods, enclosure of the machinery and the application of exhaust draught so as to maintain an inward directional air current at all points where feeding or discharging takes place. In some factories alternation of occupations is practised, and in a few cases periodical medical examinations are made with a view to suspension on the earliest sign of respiratory trouble.

Compensation. The Various Industries (Silicosis) Scheme, 1931[4] applies to the "breaking, crushing, grinding, sieving, mixing or packing of silica rock, or of dried quartzose sand or any dry deposit or dry residue of silica or any dry admixture containing such materials; or any process ancillary thereto." The Scheme provides for compensation in respect of workmen certified to be suffering from silicosis or silicosis accompanied by tuberculosis to a dangerous or disabling extent, or to have died from the disease.

The Sandstone Industry

This industry comprises all processes in getting sandstone from a quarry or mine, and in cutting and dressing it.

The sandstones include the sedimentary silica rocks, and they are chiefly used in the construction of buildings, bridges, reservoirs and roads, and in the manufacture of grindstones and pulpstones. The industry is principally carried on in the districts where the quarries are situated, but stone-dressing takes place to some extent over the whole country, and every town has its stonemasons' yards. About 12,000 men are employed in the processes in quarries and, in addition, about an equal number of masons are employed in builders' and sculptors' yards.

The workers include rock-getters who work at the stone face in quarry or mine ; quarrymen or stone-cutters who hew the blocks ; masons who shape and carve the stone to dimensions or patterns ; drillers with hand or pneumatic-tools or steam-drills ; crushermen ; labourers and cranemen ; and builders "fixers" or "wallers", who frequently do some dressing of the stone.

The siliceous sandstones consist essentially of quartz grains, mixed with a variety of other minerals and held together by a cement of varying composition and proportion. The proportion of silica in sandstone varies in amount up to over 99 per cent.

All the processes give rise to dust, and the risk of silicosis depends on the concentration at breathing level. The following are average concentrations of dust found at breathing level in different classes of work in the sandstone industry (the higher numbers indicate number of particles in 1 c.c. of air, the numbers in parentheses are calculated as millions of particles in a cubic foot) : masons, 545 (16) ; rock-getters, 319 (9) ; drillers, 939 (27) ; quarrymen, 1956 (56) ;

crushermen. 1132 (32). Factors which appear to influence the concentration were determined by Green and Watson: [13]

'The highest concentrations of dust are obtained when the mason is punching or roughing. The following figures show the order of the number of particles produced:

2,150 per c.c.: mason in closed yard; almost dead calm.
1,322 per c.c.: mason in open yard on threshold of shed; almost dead calm.
537 per c.c.: mason in open yard; almost dead calm.
313 per c.c.: mason in closed yard; strong draught.
396 per c.c.: mason in open yard; gusty wind.

'It would be difficult to assess the average exposure of a mason over a long period of time. Even though 40 samples were taken each for periods of one hour upwards, it has not been possible to obtain sufficient data to yield a value on which any reliance can be placed. Extreme values can be stated, viz., 2,150 per c.c. to about 200 per c.c. for the closed yard and 1,300 per c.c. to 150 per c.c. for the open yard.

'In contrast to the large variations in numbers, the size-frequency figures show a remarkable degree of constancy. They emphasize the preponderance of the small particle and the relative infrequency of particles over 5 μ in diameter.'

In an investigation into the occurrence of silicosis in the sandstone industry, Sutherland and Bryson [14] found the disease amongst masons, rock-getters, quarrymen, planers and wallstone dressers. Roentgenological evidence of the disease was most frequently found after forty years of age and after twenty years in the industry. Ferguson [15] found clinical evidence of pulmonary fibrosis in 433 sandstone workers out of 1,000 consecutive routine examinations of men continuing at work. Roentgenographic examination of 173 of the most definite of these showed silicosis in 109.

During the seven years 1930–1936 the number of deaths certified due to silicosis amongst sandstone workers in Eng-

land and Wales was 574, the annual average being 82 deaths. Estimating the number employed at 25,000 this gives an annual death-rate of 3.3 per 1000. The numbers for the consecutive years over the period show no tendency to fall, the last four years being above the average.

Prevention. In processes carried on in quarries in which the stone contains not less than 80 per cent. of silica, Special Rules made under the Quarries Act, 1894, are applied by the Mines Department. The Special Rules provide that: —

(1) Rock drilling by mechanical power is done with an efficient water jet, or other efficient means to prevent escape of dust.
(2) Stone breaking by manual labour is to be done only in the open air, and respirators provided if workers are exposed to the inhalation of dust.
(3) Machines for crushing and grinding of stone to be (a) provided with exhaust draught and dust collecting appliances, or sufficient water or steam spray, or other arrangement to prevent escape of dust, or (b) entirely enclosed.
(4) Stone to be kept wet in sawing, planing and turning.
(5) Workmen dressing stone not to work nearer than 6 feet from each other.
(6) Stone dressing not to be done in any closed shed unless exemption is granted on the ground of exhaust ventilation being provided.

The stone mason who dresses the stone by hand is the most frequently affected in the industry, and preventive measures are neither easily applied to this work nor readily adopted by the masons themselves. Progress has been made in the development of an efficient type respirator which will protect against the finest dust to the extent of 80 per cent while affording a reasonable degree of comfort, at least for intermittent wear. If such respirators were worn regularly during

certain phases of the work which have been shown to be most productive of dust, many lives would be prolonged. Two methods are available for applying localised exhaust draught to the process of hand dressing either with hammer and chisel or with a pneumatic tool. In one of these a flattened tube of gutta-percha is fixed to the back of a glove or mitten worn on the left hand, and this is connected with a flexible tube leading to an injector arrangement on a compressed air supply. In the other a small metal hood connected with a flexible duct is placed as near as possible to the chisel point and is moved about as the work progresses. The tube is connected with a dust-collecting appliance.

Compensation. The Sandstone Industry (Silicosis) Scheme, 1931 [16] applies to workmen employed in the "Sandstone Industry", defined as follows, — all processes in or incidental to the getting or manipulation of sandstone with a view to manufacture, sale, or use, which are carried on at or within the close or curtilage of any mine or quarry or at any premises worked in conjunction with a mine or quarry, wherever situate.

Exemptions from this Scheme are provided for : places to which the Refractories Industries Scheme applies ; premises not being a mine or quarry for the making of silica flour ; any mine or quarry worked occasionally only and where no explosive or mechanical power is used in the processes ; workmen employed exclusively as craneman, engineman, fitter or blacksmith ; manufacture of artificial stone except as regards breaking, crushing or grinding sandstone.

The financial and administrative structure of this Scheme resembles that for the Refractories Industry, in that all claims for compensation and all expenses under the Scheme are paid out of a General Compensation Fund maintained by means of levies payable by all employers in the Industry. The Fund is managed by a Company representative of the Employers,



FIGURE 2. See caption on page 365.

but cannot be wound up without the Secretary of State's approval: all levies have to be approved by the Secretary of State. A large proportion of the workmen engaged in the processes of dressing or manipulating sandstone, e.g. building and monumental masons, are not covered by this Scheme because their employers, not being owners of a mine or quarry, are not contributors to the funds of the Company. All such workmen are covered by The Various Industries (Silicosis) Scheme 1931.[4]

The Silicosis and Asbestosis (Medical Arrangements) Scheme 1931,[26] and the Scheme as amended in 1934[27] provides, with certain exceptions, for initial and periodical medical examinations of workmen employed in prescribed processes in the industry. The intervals between periodical examinations are eighteen months in the more hazardous processes, and three years in those in which the risk of contracting silicosis is considered to be less. The periodical examinations are made by the Medical Board, and in most cases at the place of employment.

Granite Industry

The granites are igneous rocks of crystalline structure, in which the amount of free silica as quartz rarely exceeds 1/3 of the total, and in some granitic igneous rocks frequently included in the commercial term, the proportion of free silica is much less than 1/3, the other constituents being silicates. The granites and allied rocks occur chiefly in the Counties of Cornwall, Devon, Leicester, Cumberland and Westmorland, and in several parts of the west and north of Scotland.

Figure 2

Localised exhaust for dust removal at stone-dressing. The expanded end of the duct is made of rubber and is attached to the back of a glove worn by the operator. By kind permission of the Home Office Industrial Museum.



FIGURE 3. See caption on page 367.

The processes are carried on for the most part at or near the places where the quarries are situated. In getting and dressing the rock the processes resemble those in the sandstone industry, but owing to the greater hardness or toughness of the granites, pneumatic tools are much more frequently used, and one of these, the surfacing machine known as the 'dunter', is not met with in sandstone work. Some of the dressing of granite for monumental and architectural purposes is carried on in partly enclosed sheds, but generally most of the work is done in open sheds or in the open air. Workmen who have worked both in Britain and America believe that the risk is greatly increased in the latter country with the use of closed sheds made necessary by severe weather. Owing to the qualities of the granitic rocks they are largely used for road material and for concrete, and almost every granite quarry has its crushing plant, while in some quarries the whole output is in the form of setts, kerbs, and other road material.

Dust is produced in the various classes of work in granite. Average concentrations of dust found, expressed as particles in 1 c.c. of air (and in parentheses millions of particles in a cubic foot of air) were: masons' work 412 (12); rock getting 343 (10); drilling 1935 (55); stone-crushing 1834 (52).

In the roentgenograms of granite workers the prevalent type of shadows indicating fibrosis of the lungs is somewhat different from that found in workers who have been exposed to dust containing a high proportion of free silica. It is a finer type of mottling, with more linear striation and reticulation, but nodulation of silicotic type is also met with in some cases.

FIGURE 3

Showing attachment of the expanded end of the duct and its connection with the suction apparatus. By kind permission of the Home Office Industrial Museum.



FIGURE 4. See caption on page 369.

Pulmonary fibrosis of granite workers in this country is neither so prevalent nor so severe as amongst sandstone workers, and the same features have been noted in other European countries by Teleky, Gutzeit and others.

An investigation was made by Sutherland and others,[17] in which 494 workers were clinically examined and 211 of these were examined roentgenologically. Clinical evidence of fibrosis of the lungs was found in 260 cases (52.6 per cent), and roentgenological evidence of silicosis was found in 36 (17 per cent) of these. Comparing the results of the medical examinations made by these workers in the granite and sandstone industries, the number of cases of fibrosis is seen to be of the same order, 52.6 and 59 per cent respectively. Of those examined by roentgen-ray in the two industries, only 17 per cent of granite workers showed evidence of silicosis, compared with 49 per cent in the sandstone industry.[14] During the seven years, 1930–1936, 7 deaths were certified due to silicosis amongst granite workers in England and Wales, and 1 in Scotland.

Prevention. The processes in the granite industry are similar to those in the sandstone industry, and the same methods of dust suppression can be employed in both. The dust from drilling can be dealt with by the application of water or by the use of a dust trap with exhaust. For cutting, turning and surfacing, specially adapted methods of application of exhaust draught have been devised.

Compensation. The Various Industries (Silicosis) Scheme, 1931 [4] provides for the payment of compensation only in the case of workmen employed in one specified process in the getting and manipulation of granite (including any igneous rock), namely: "the dressing of stone by masons."

FIGURE 4

- Movable hood connected with exhaust apparatus by a flexible tube. By kind permission of the Home Office Industrial Museum.

Slate quarrying and Dressing

The industry is concerned with quarrying or mining the rock, and making and shaping the slates for roofing and other structural work. Powdered slate is used to some extent in the manufacture of roofing felt for road material and as a 'filler.'

The industry is widely distributed in this country, but about 9,000 of the 11,000 wage earners in the industry are employed in North-West Wales.

In the open quarries of North Wales the rock is quarried by blasting and wedging. The large blocks are conveyed to the mills where they are sawn to sizes with power-driven saws cutting across the grain. The blocks are then split with chisel and mallet and cut to required sizes by hand or machine. In some small quarries there are no mills and splitting is done in the open air. Slate makers, who do the splitting and cutting, usually number 3 or 4 times as many as the rock getters.

Slate is the typical cleaved rock. Its most important constituent quantitatively is silica, free as quartz and combined as silicates of aluminum, iron, alkalis and other bases. In Penrhyn (Welsh) slates quartz amounts to 34.66 to 43.26 per cent, while total silica (free and combined) is 57.75 to 63.01 per cent.[18]

Dust is produced in drilling in the quarry: the average of a series of samples taken with Owens' Jet Dust-counter showed a concentration of 560 particles in 1 c.c. of air (16,000,000 in 1 cubic foot). In the mills the concentration of dust varied widely, in a series of samples, from 241 particles in 1 c.c. (7,000,000 in a cubic foot), to 3,325 in 1 c.c. (99,000,000 in a cubic foot); the average count was 1,463 in 1 c.c. (42,000,000 in a cubic foot).

Sutherland and Bryson[19] made clinical examinations of 120 workers and found severe fibrosis of the lungs amongst

the older millmen. 3 of the 14 men with fibrosis had worked between thirty and thirty-nine years in the industry. Radiological examination of 52 millmen showed signs of silicosis in 14 men. The rockmen were found to be less severely affected ; while fibrosis was found amongst the older rockmen, no silicosis was found, although the average age of the rockmen (52.5) was higher than that of the millmen (46.4). During the seven years 1930–36, 23 deaths were certified due to silicosis amongst slate quarrymen and dressers.

In view of the ages reached by many of the workmen while still remaining fit for work, it may be assumed that there is no general disability occurring amongst these workmen from exposure to dust in their occupation.

Prevention. The risk of injury to health in open slate quarries is not great. In confined spaces in quarries and in slate-mines water may be used to suppress dust in drilling. In the mills dust can be controlled by means of localised draught, or where this is not practicable, by a high standard of general ventilation, and sawing can often be done with copious application of water.

Compensation. The slate quarrying and dressing industry is not specifically covered by the Workmen's Compensation (Silicosis) Acts.

Pottery Industry

This industry includes several distinct branches, subdivision being determined by the nature of the article being manufactured and the materials entering into the composition of the ware. The principal divisions are : earthenware, which includes general earthenware, tiles, sanitary earthenware and electrical fittings : china ; jet-and-Rockingham ; sanitary fireclay ; stone-ware ; coarse ware. The occurrence of silicosis is especially associated with the first two groups, namely, earthenware and china. The great centre of the in-

dustry is at Stoke-on-Trent in North Staffordshire, where all branches of pottery manufacture are represented.

In the manufacture of earthenware, the ingredients, — ball clay, china clay, china stone, and flint — in a ground state, are mixed together in the form of liquid slip, from which excess water is removed by pressing. The resulting plastic material is used by throwers, pressers, jiggerers and jolliers, handlers and modellers, in the potters' shops. Increasing use is made of the method of 'casting' ware. For this process the slip or body is made into a liquid, which is allowed to flow by gravity from a reservoir, or is poured from a vessel by hand, into moulds made of plaster-of-Paris. After a period, to allow the porous mould to draw liquid from the slip, the excess slip is poured off, the mould is separated into its component parts, and the article removed for fettling, drying and finally, firing. For the making of earthenware tiles and electrical fittings by pressure, the slip is made into a semi-dry powder, called "dust," which is pressed in moulds. So long as the clay remains moist it is harmless, but in the process of manufacture fragments fall on benches and floors or adhere to the clothing of the workers, become dry, and give rise to dust. After the article has been made in the plastic form, partly dried, it is frequently subjected to the processes of towing on a revolving disc, and fettling by hand, to remove irregularities of surface and edges. The articles are then placed in fireclay saggers with some sand, and fired in the oven. They are then termed "biscuit ware." Subsequent processes of decoration and glazing do not give rise to silicosis ; but, after the ware has been decorated and glazed, blemishes are removed by polishers who frequently use powdered flint, mixed with water, as a finishing abrasive on a rapidly revolving wheel.

In the manufacture of china, the ingredients are calcined bone, china clay and china stone, but it contains no added

flint. The processes of making the articles are similar to those employed with earthenware in a general way, but in the process of firing the articles require much more support than do earthenware articles, and to provide this they are placed in saggers with finely powdered flint. When the saggers of china ware are taken from the oven the flint which was used in placing them is removed by a series of processes known as "scouring."

For use in the manufacture of pottery, flint is calcined by burning the flint pebbles with coal fuel in kilns. The calcined flints are washed or sieved to free them from ashes, and crushed in a stone crushing machine. If the flint is required for making slip for earthenware it is then ground with much water in buhr-stone mills. This process is frequently carried on at the pottery where the flint is to be used. If the flint is required for placing china biscuit ware it is reduced to fine powder, in the dry state, in crushing mills.

It will be seen that the exposure to flint dust in the pottery industry, in addition to the preliminary processes of the preparation of the flint by milling and grinding and the final process of polishing, occurs amongst those manipulating the earthenware body in the plastic and semi-dry states, and, in the manufacture of china, amongst those employed in placing the biscuit ware and in removing the flint from it after firing. It is in those processes that the highest incidence of silicosis occurs.

Estimations of atmospheric dust were made by H.H.Watson [20] with the thermal precipitator at various processes in pottery manufacture. The following are typical examples of the concentrations found at breathing level, unless otherwise stated, and expressed in the number of particles in 1 c.c. of air (and, in parentheses, millions in a cubic ft. of air): — flint-grinding, dry with exhaust draught: 150 (4.3); flint-milling, wet (general air of the room): 109 (3); placing

china biscuit ware (general air of the room), 121 (3.4); earthenware plate-making: 176 (5); fettling, damp: 168 (4.8); fettling, dry: 201 (5.7); pressing tiles: 213 (6); fettling tiles: 275 (8); casting sanitary earthenware (general air of the shop), 164 (4.7).

In a clinical and Roentgenological investigation in various occupations in the pottery industry, Sutherland and Bryson [21] found that of 182 males, 76 showed roentgenological evidence of silicosis, and of 68 females, 11 showed such evidence. Silicosis was diagnosed in flint millers, workers in the earthenware sliphouse and potters' shops, and in china biscuit placers, oddmen and scourers, and in polishers. Their findings were confirmed later by mortality experience in the industry. The figures for the seven years, 1930 to 1936, are given in the Table, together with the mortality rates

TABLE 2

POTTERY INDUSTRY. Mortality rates for silicosis in certain occupations calculated on fatal cases investigated by the Factory Department in the seven years 1930 to 1936.

Occupation.	Estimated numbers employed.		Deaths in 7 years.		Annual mortality rates per 1000 employed.	
	Males.	Females.	Males.	Females.	Males.	Females.
Flint millers and mill labourers	240	–	9	–	5.4	–
Earthenware—sliphouse	698	–	19	–	3.9	–
" throwers	24	–	1	–	–	–
" turners	132	–	3	–	3.3	–
" handlers	113	336	4	–	7.1	–
" platemakers	364	108	19	1	7.5	1.3
" dishmakers	113	6	7	–	8.8	–
" saucermakers	52	156	4	1	11.0	1.3
" cupmakers	46	248	2	5	6.2	2.9
" jolliers	261	122	25	–	13.7	–
" pressers and casters	221	592	29	1	18.7	0.4
" (sanitary) " " "	736	–	39	–	7.6	–
" (tiles) " " "	229	492	9	6	5.7	1.7
" hollow-ware pressers	248	–	30	–	17.3	–
China biscuit ware placers	152	–	18	–	16.4	–
" " odd men	70	–	8	–	15.7	–
" " scourers	–	223	–	8	–	4.9
Polishers	330	–	21	–	9.1	–
Totals	4,029	2,283	247	22	8.8	1.4

calculated on the estimated number of persons employed in each occupation.

Prevention. Regulations were made in 1913, under the Factory and Workshop Act, for the Manufacture and Decoration of Pottery.[22] A Departmental Committee on Compensation for Silicosis dealing with the Pottery Industry reported on the working of the Regulations in 1928 [23] and, following their recommendations, another Code. The Pottery (Silicosis) Regulations, 1932 [24] was made. This Code deals entirely with the risk from the inhalation of siliceous dust, and it covers not only potteries but also factories in which flint is ground for use in the manufacture of pottery. The two Codes together provide a comprehensive measure for the control of dust in the industry. Special use is made of localised exhaust draught at specified processes, unless the material is so damp that dust is not produced; conveying machinery must be enclosed as well as being provided with exhaust draught: dust discharged from the exhaust fans must be collected in suitable apparatus; floors and benches must be freed from scraps and debris and cleaned daily, by a moist method after working hours, or by vacuum cleaner, and floors must be kept in good repair and clear of obstacles so as to facilitate thorough cleaning. The employer must appoint one or more competent persons whose duty it shall be to carry out systematic inspection of the working of all the Regulations, and to record any breach of the Regulations or any failure of the apparatus needed for carrying out the provisions, and the steps taken to remedy the defects or to prevent recurrence.

With a view to removing the danger from the use of powdered flint for firing china ware and the exposure to flint dust in removing it after firing, manufacturers experimented with various substances in the search for a safe substitute for flint. They found that sufficiently satisfactory results were obtained with alumina, and the Medical Research Council were

eventually asked to determine whether there would be any risk of pneumoconiosis from exposure to alumina dust. As no satisfactory data on the effects of alumina were available an investigation [25] was carried out on 50 workers who had been exposed to dust of alumina for periods varying from five to forty years at the furnaces in aluminium works. As a result of clinical and radiological examinations of these men, and a statistical report on sickness rates amongst a larger group of similar workers, no evidence was found that alumina dust had caused fibrosis of the lungs. Following this finding it seems probable that alumina will be used to replace powdered flint for the placing of china biscuit ware, and thereby the risk to china placers, oddmen and scourers will be removed. Alumina is also being used instead of flint as an abrasive for polishing finished ware.

Compensation. The Silicosis and Asbestosis (Medical Arrangements) Scheme, 1931 [26] and the Scheme as amended in 1934,[27] made under the Workmen's Compensation (Silicosis and Asbestosis) Acts, provide, with certain exceptions, for initial examination, within two months of employment in the industry, and periodical examinations at prescribed intervals of persons employed in certain processes in the pottery industry, which may be summarised as follows: — (1) milling and grinding of flint or quartzose material; (2) in the manufacture of china, placing the ware in flint for firing and removing the flint after firing; (3) male workers in certain processes, carried on in potters' shops, in the manufacture of general earthenware, sanitary earthenware and earthenware tiles, and (4) polishers who use flint or quartz.

The Various Industries (Silicosis) Scheme 1931 [4] provides for the payment of compensation to workmen employed in the following processes and *potteries*: — (a) the milling of flint or crushing or grinding of silica rock or dried quartzose

sand ; (b) any process in or incidental to the manufacture of china or earthenware including sanitary earthenware, electrical earthenware or earthenware tiles, up to and including the preparation for glazing but excluding underglaze decorating, and modelling and mould-making where these processes are carried on in separate rooms ; (c) polishing, sorting or grinding on a power driven wheel in connection with the grinding of glost ware, and tile-slabbing.

Tin Mining

In this country tin is mined almost entirely in Cornwall. The numbers employed vary with the economic condition of the industry ; thus in 1928 there were 2,800 wage earners, and in 1934, 1,645.

The ore occurs in lodes which traverse granite, or an argillaceous schist called 'Killas.' Dust is derived from the lodes which consist of hard stone (containing the binoxide of tin) , and from the containing rock of granite or Killas.

In the Report on the Health of Cornish Miners [28] the high mortality from respiratory disease is referred to. Out of 142 deaths of rock drillers, 120 were certified as from various forms of phthisis or "miners' disease," and 13 from other respiratory diseases. The majority of these rock drillers had worked in other countries, 90 of them in the Transvaal, but 38 of them had worked only in Cornwall.

During the seven years, 1930 to 1936, silicosis was certified as the cause of death of 140 tin-miners, a mortality rate of 12 per 1,000 on the number of wage earners in 1934. It is not known how many of these tin-miners had worked in other mines, though no mention was made of such on the certificates.

Compensation. The Various Industries (Silicosis) Scheme 1931 [4] applies to all workmen employed *underground* in Tin

Mines, and in the breaking or crushing of the ore or the containing rock above-ground or any handling or moving incidental thereto.

Hematite Iron-ore Mining

The industry is concerned with the mining of the anhydrous ferric oxide, haematite, Fe_2O_3. The numbers employed vary widely with the economic state of the industry, and during the present century fluctuations between 10,000 and 3,000 have taken place. The great majority of these are employed in the West Cumberland and North Lancashire iron-ore field, where the ore is used for metallurgical purposes; small numbers are employed in the haematite deposits in the South-West, the product of which is used in the manufacture of paints.

Much of the hematite deposits are precipitates from ferruginous solutions which must have been in most cases charged with CO_2, and such solutions would carry dissolved silica which would be simultaneously precipitated with iron, generally in the form of finely divided quartz. Also in cases where the calcium carbonate of calcareous rocks has been replaced by iron compounds, all the insoluble siliceous constituents of the original calcareous rock will find their place in the newly formed iron ore. Further, quartzose rocks may form one side of a lode of ore and these have often to be blasted or cut in order to work the ore-deposit. Insoluble residue of the better class ores amounts to 5 per cent to 7 per cent, but rises to 15 per cent, mostly in the form of free silica. In lower grade ores the insoluble residue may reach a much higher figure. Examination of thin sections of hematite ores reveals grains of quartz, secondary silica and oxides of titanium, in addition to the various oxides of iron and carbonates. The dust produced by drilling and blasting in haematite mines, therefore, will contain silica.[29] A series of samples of dust from mine work-

ings, yielded on analysis from 2.76 per cent to 7.0 per cent free silica, and drillings from the ore body yielded 1.5 per cent to 6.8 per cent.

H.H. Watson [30] found the following dust concentrations in a hematite mine at a distance of 50 yards from the working face, without dust suppression; after an average of 6 shots with 9 lbs. explosive: 222,000 particles in 1 c.c. of air (6,343,000,000 in a cu. ft.); after an average of 4 shots, with 6 lbs. explosive: 105,000 (3,000). With the use of a dust-suppressing device the air was apparently free from dust, but actually, the thermal precipitator showed a concentration of 30,000 (867). At wet drilling apparently no dust was produced, but actually there were over 2,000 (57) very small particles.

Methods of working have been changed by replacing, about 1913, the slow hand drilling by machine drilling and the more frequent blasting operations which this change permitted. This may be the reason why silicosis had not been generally regarded as an occupational risk until the last few years. Collis [31] pointed out the higher mortality for respiratory diseases amongst the Cumberland-Lancashire iron-ore miners, compared with the iron-stone (carbonate) workers, in the Registrar-General's statistics for 1910–1912, and Cronin [32] found symptoms and signs of impaired respiratory function in a clinical examination of 100 hematite drillers in 1925. Stewart and Faulds [33] have described 15 fatal cases of pulmonary fibrosis in hematite-miners, and fatal cases have more recently occurred in a haematite mine in the South-West of England.

During the six years, 1931–1936, 57 deaths from silicosis were certified, an average of 9.5 per annum.

Prevention. At one time both management and workmen were generally sceptical about the harmful effects of the dust in haematite mines, and accordingly preventive measures

were carried out reluctantly. Since the occurrence of silicosis has been established beyond doubt, strong measures have been taken by the industry to secure suppression of dust in the mines. In one large group of mines a medical officer was appointed to make initial and periodic examinations of the workmen.

The methods relied on include good general ventilation ; machine drilling only with the use of axial water feed or other approved method, and hand drilling with the use of water ; exclusion of workmen from places after shot-firing until they have been cleared of dust and smoke ; the suppression of dust by water where it is liable to be produced in breaking and shovelling rock ; and removal of dust from machines used for crushing and dressing.

Compensation. The Various Industries (Silicosis) Scheme, 1931 [4] as amended by The Various Industries (Silicosis) Scheme 1935 [34] provides for payment of compensation for disablement or death from silicosis to workmen employed in underground operations in *Hematite Iron Ore Mines.*

Coal Mining

This is one of the most important industries in the country. The situation of the coal-fields and the numbers of wage earners employed at a given date are indicated in Table 3.

While the dusty conditions to which many workers are exposed underground in coal mines has been reflected in the incidence of pulmonary disease in the industry for many years, it is only comparatively recently that the disease now known as silicosis has been identified amongst these workers. Silicosis follows especially those processes underground which expose the worker to siliceous dust. These processes are : driving a hard heading or cross measure drift, and ripping or brushing, that is, cutting the roof, floor and sides of a roadway. They involve drilling, shot-firing and loading debris.

The following dust-counts are of samples taken by H.H. Watson [35] with the thermal precipitator, in studying the movement of a dust cloud from the point of production along the roadways in a coal mine, while means were not being taken to suppress the dust. The samples were freed from carbonaceous matter before counting. Drilling, usually in sandstone, at 15 yards distance, 10,860 particles in 1 c.c. of air (310,000,000 in 1 cu. ft.); at 65 yards, 860 (25); at 160 yards, 650 (18). Shot-firing (with 24 ozs. explosive), at 65 yards, 2,000 (57); (with 40 ozs. explosive) at 160 yards, 2,300 (65); near the bottom of the upcast shaft, 550 (15).

In 1909 the Royal Commission on Mines [36] referred to the possible danger from dust produced in drilling in siliceous rock in coal-mines, and since 1921 silicosis was found amongst rock-drillers in the coal-mines of Somerset and South Wales, and later in other coal-fields. The distribution of the disease in the different coal-fields has been very unequal, as can be seen from a geographical classification of the certificates issued by the Silicosis Medical Board during the period of four and a half years to the end of 1935. (Table 3) The numbers of certificates issued in respect of fatal cases, if calculated on the number of wage earners at the end of the period is 22.37 for Great Britain; 4.13 for England; and 112.59 for South Wales and Monmouth. No completely satisfactory explanation of this distribution of the disease has yet been reached.

In order to find out the effects on the lungs of coal dust, by itself, the Medical Research Council's Committee on Industrial Pulmonary Disease [37] carried out a clinical and roentgenological examination of 40 coal trimmers employed in loading ships with anthracite coal. The men had been exposed to high concentrations of coal dust for various periods from three years to over forty years, but the Committee did not find any evidence that the inhalation of anthracite or

TABLE 3

District.	Number of wage-earners on Dec. 14th 1935.	Number of certificates issued for—		Suspension.
		Death.	Total disablement.	
England.				
Northumberland	43,865	..	1	..
Durham	104,244	..	2	..
Cumberland and Westmorland	4,862	..	..	..
South Yorkshire	94,427	4	8	10
West Yorkshire	41,991	..	3	1
Lancashire and Cheshire	59,607	3	5	5
North Derbyshire	41,623	..	..	..
Nottingham	44,852	1	2	..
South Derbyshire	3,179	..	..	..
Leicestershire	9,055	..	..	..
Cannock Chase	21,366	1	2	..
North Staffordshire	22,543	3	16	6
South Staffordshire and Worcestershire	4,460	..	1	..
Shropshire	2,623	..	1	..
Warwickshire	16,391	..	..	..
Forest of Dean	5,075	..	2	2
Bristol	838	..	..	..
Somerset	3,410	3	17	7
Kent	7,303	3	6	4
Total	531,694	22	66	35
Wales.				
South Wales and Monmouth	130,552	147	511	195
North Wales	8,676	..	1	..
Total	139,228	147	512	198
Scotland.				
Fife and Clackmannan	21,625	..	..	1
Lothians (Mid and East)	12,472	..	2	..
Lanarkshire	38,830	..	1	3
Ayrshire	11,311	..	..	..
Total	84,238	..	3	4
Great Britain	755,160	169	581	237

other coal dust had caused fibrosis of the lungs in this series of cases.

Fisher [38] has shown that there is no constant relation between the amount of drilling and the incidence of silicosis. The same is true of the practice of stone-dusting. It is held by some that a risk of bronchitis is incurred by the men, overheated, travelling out of certain pits by slants through chilling currents of air which reach a velocity of 2500 ft. per minute with a temperature drop of 20° to 40° F. T.David Jones [39] found that four times as many cases of silicosis were certified

from collieries with slants as from those without slants. W.R. Jones [40] stated that the mineral sericite is present in the sandstones of the anthracite coal-field, while in those of well-known Scottish collieries, sericite is either absent or rare. According to Cooke [41] sericite is constantly present in the atmosphere of the Lancashire coal-mines, but he found that silicosis was extremely rare amongst the coal-miners there. That "prolonged exposure to the working conditions incident to coal mining is frequently associated with the gradual development of alterations in the radiological appearances of the lungs" is a conclusion reached as a result of a roentgenological study of certain groups of industrially healthy South Wales coal-miners.[42] The distinction in the degrees of change found between workers in anthracite coal and in bituminous coal agree with those reported by Russell. In the Welsh study the anthracite group showed a degree of "mottling" greater than that found in the semi-bituminous group. Harper [43] found no roentgenological difference between cases of silicosis in South Wales and those seen by him in the Belgium coal-fields. Lyle Cummins [44] directed attention to the variety of occupations included in the coal-mining industry.

In the report of a study made in the Anthracite Region of Pennsylvania by the United States Public Health Service,[45] the results of examination of a total number of 2,711 workers in 3 anthracite coal-mines are described. Anthraco-silicosis was found in 23 per cent, and the incidence varied with the period of employment, and the concentration and nature of the dust to which they were exposed. Böhme [46] described the results of examination of 3318 rock-drillers working in the Ruhr coal-mines for periods from five to twenty-five years. Of these, 19.44 per cent showed changes, due to dust, of varying degrees of severity from slight, 14.7 per cent, to grave, 0.18 per cent.

From a study of systematic examinations of 9807 stone-

workers in the coal-mines of the Ruhr district Reichmann and Schürmann [47] found the prevalence and degree of severity to be 1048 (10.6 per cent) slight, 89 (0.9 per cent) moderate, and 14 (0.16 per cent) severe. In 493 cases of severe silicosis the duration of employment was, on the average, 18.3 years. Death was due to simple silicosis with heart failure in 37 per cent and to an accompanying tuberculosis in 63 per cent.

Courtois [48] made a study of pulmonary disease in 136 coal-miners at Charleroi. Roentgenological examinations of these workers are classified as negative 33, positive (nodular opacities 30, confluent opacities 61) 91, other conditions (bronchitis, emphysema, and deformities) 12. Post-mortem examination showed that the nodules were typical, simple, silicotic nodules. In the massive fibrotic areas the nodular arrangement had disappeared except at the periphery. Leclercq [49] has described the occurrence of silicosis amongst coal-miners in the north of France. Magnin [50] found that the disease produced amongst workers underground in the coal-mines of Central France is silicosis, which occurs in nodular and pseudo-tumoral forms. Badham and Taylor [51] found in the coal-miners of New South Wales several different types of pulmonary fibrosis. One type was thought to be either a silicatosis due to silicates, or a pure anthracosis due to coal dust.

Prevention. The Coal Mines Act, 1911, enforces the use of water sprays or jets or other efficient means when drilling in ganister, hard sandstone or highly siliceous rock "the dust from which is liable to give rise to fibroid phthisis." The preventive measures in general use include (1) water, alone or containing substances to increase its wetting power, sprayed over the exposed surfaces in the mines and on dumps of broken material; drilling with hollow or other special drills to which is fed a supply of water, alone or mixed with a foam-producing substance: (2) a device known as a dust-trap, of

which there are large numbers of several types in use, by means of which the dust produced in drilling is drawn by suction into a collecting bag made of dust-proof material: (3) respirators, which can be worn where means for suppression or removal of dust are not practicable: (4) efficient ventilation of all parts of the mine workings especially those at which dust is produced by drilling, and fumes and dust are produced by blasting: (5) protection from currents of cold air of workmen while being brought out of hot pits on tramways.

Compensation. The Various Industries (Silicosis) Scheme, 1931 [4] as amended by the Order of 22nd October, 1934 [52] provides for the payment of compensation in respect of disablement or death from silicosis for all workmen employed in *"any operation underground in any coal mine."*

Asbestosis

Asbestosis is described in the Official Memorandum on Silicosis and Asbestosis [53] as a disease of the lungs produced as a result of the inhalation of asbestos dust, usually over a period of several years, and occurs in workers in occupations associated with production of asbestos dust in a fine state of division. It is characterised by a special type of fibrosis of the lung tissue which resembles silicosis in its general features of causation and development, but differs from it in some of its clinical and pathological manifestations.

Asbestos, which causes the disease, is defined in the Asbestos Industry Regulations 1931 [54] as follows: — *"Asbestos* means any fibrous silicate mineral, and any admixture containing any such mineral, whether crude, crushed or opened."

This somewhat wide definition is limited in practice, by commercial and industrial usage, to a group of silicates having the common properties of finely fibrous structure and flexibility. There are two principal varieties, serpentine asbes-

tos or chrysotile, the 'white' asbestos, which is a hydrated silicate of magnesium with a small proportion of iron ; and the hornblende minerals, the most important of which are crocidolite, or 'blue' asbestos, and amosite, a brown coloured variety ; blue asbestos and amosite consist largely of iron silicates, with a small proportion of magnesium.

Asbestos is imported into Great Britain in increasing quantities, year by year, owing to a remarkably rapid expansion of its uses in industry. The chief sources of supply are Canada, Cape Province, Italy, Rhodesia and Russia. The valuable properties of the fibrous minerals include the facility with which they can be disintegrated into flexible fibres and spun into yarn and woven into cloth ; their resistance to heat and electricity confers valuable properties for insulation, and the resistance to acids, of some varieties, favours their use for chemical processes.

The numbers of persons employed in the asbestos manufacturing industries is difficult to compute, but it is probably between 3,000 and 5,000, and they include both sexes. The largest section of the industry is engaged in the manufacture of asbestos textiles and the products into which these enter : the processes include the preliminary disintegration of the crude mineral, carding the fibre, spinning, plaiting and weaving the yarn ; the making of insulating mattresses of asbestos cloth filled with loose fibre ; making brake-linings, fire-proof curtains, clothing, etc. These branches of the industry are largely centred in Lancashire and Yorkshire, and in and near London. Other branches of the industry are connected with building, engineering and shipping, and are spread over the centres where these are carried on. The non-textile products of manufacture include asbestos mill-board ; asbestos-cement sheets, tiles and pipes ; brake and clutch-linings ; packings and jointings ; electrodes and switch-board panels. Mixtures of asbestos with magnesia, kieselguhr and other materials are

used as cements or fillings for insulating boilers, engines, pipes and other parts. Many persons are employed in handling and applying these mixtures in buildings and ships in course of construction or repair.

The dust given off from asbestos in the processes of manufacture consists of fragments of fibres and small rounded or angular particles. The concentration of the dust-cloud varies within wide limits, the most important factors being the nature of the process and the variety of asbestos in use. In a series of samples of atmospheric dust taken by H.H. Watson [55] with the thermal precipitator the following concentrations were noted :

TABLE 4

Process.	Asbestos.	Position.	Particles. Fibres. (in 1 c.c.)		Total.*
1. Carding	White.	B.L.	235	180	415 (12)
2. do.	do.	G.A.	120	95	215 (6)
3. Doubling	Blue.	G.A.	105	95	200 (6)
4. Spinning	do.	G.A.	115	120	235 (7)
5. Weaving (cloth)	White.	B.L.	240	85	325 (9)
6. do.	do.	G.A.	55	40	95 (3)
7. Weaving (brake-lining)	do.	B.L.	140	70	210 (6)
8. do. do.	do.	G.A.	130	55	185 (5)
9. Winding	Blue.	B.L.	200	240	440 (13)
10. Plaiting	White.	B.L.	120	50	170 (5)
11. do.	do.	G.A.	120	85	205 (6)
12. Mattress making	Blue.	B.L.	405	820	1,225 (35)
13. do.	Various.	G.A.	35	25	60 (2)
14. Bagging	Amosite.	G.A.	210	210	420 (12)
15. Disintegrating	do.	G.A.	190	260	450 (13)
16. Making sections	do.	B.L.	690	1,630	2,320 (66)
17. do.	do.	G.A.	150	170	320 (9)
18. Pipe making	Blue.	B.L.	90	190	280 (8)
19. do.	Amosite.	B.L.	110	215	325 (9)
20. do.	do.	G.A.	80	135	215 (6)

B.L. = breathing level of worker ; G.A. = general air of the room.
* The figures in parenthesis represent the number of millions of particles in a cubic foot of air.

The median length of the *fibres* in 5 counts was between 2.65 μ and 3.5 μ ; from 8 per cent to 16 per cent less than 1 μ and 8 per cent to 13 per cent over 10 μ. In one sample the thickness of the fibres had a median diameter 0.56 μ, 5 per cent were less than 0.2 μ and 98 per cent less than 2 μ. The median sizes of the rounded or angular particles in 5 counts

varied between 0.46 μ and 0.8 μ diameter ; 32 to 54 per cent. were less than 0.5 μ and 96.6 to 99.9 per cent. were less than 3 μ.

The history of the recognition of asbestosis as a serious industrial disease, and the increase of knowledge regarding it, are described elsewhere, but it may be stated here that the first case recorded in England was that of a card room worker, who died in 1899, the last survivor of 10 men employed in the same room. The case was described by Dr. Montague Murray in 1906.[56] During the same period a similar state of affairs existed in France, when in 1890 a textile asbestos factory was established at Condé-sur-Noireau (Calvados) and 16 workers died of pneumoconiosis between 1890 and 1895.[57]

Merewether [58] examined 363 workers in various processes in the asbestos industry and found in 95, or 26.2 per cent, definite fibrosis due to asbestos dust. Roentgenological signs of a diffuse fibrosis were found in 52 out of 133 persons examined. These figures do not represent the average incidence in the industry as a whole, because, for the clinical examinations, workers with longer terms of service were selected, and for the radiological examinations those with some clinical or other suggestive sign were given preference. There was, however, no undue proportion of workers from the more dusty processes. Age, considered apart from duration of exposure, and sex, appeared to have no influence on the onset of fibrosis.

During the seven years 1930 to 1936, 78 deaths were certified due to asbestosis in England and Wales. 40 of these were women and 38 were men. The numbers vary between eight and sixteen in the individual years, but they show no tendency towards diminution in the later years of the period. This is due to the delayed development of the disease, which in 42 fatal cases showed an average of twelve years exposure, and the fact that the gravity of the danger from asbestos dust

was not realised until 1924, although, as already mentioned, Montague Murray had recorded a fatal case and referred to others in 1906.

Prevention. The Asbestos Industry Regulations 1931 [54] were made following a medical and engineering inquiry into conditions in the industry by Merewether and Price.[38] The Regulations apply to all factories and workshops in which any of the following processes are carried on : —

(i) breaking, crushing, disintegrating, opening and grinding of *asbestos*, and the mixing or sieving of *asbestos*, and all processes involving manipulation of *asbestos* incidental thereto :

(ii) all processes in the manufacture of *asbestos textiles*, including preparatory and finishing processes ;

(iii) the making of insulation slabs or sections, composed wholly or partly of *asbestos*, and processes incidental thereto ;

(iv) the making or repairing of insulating mattresses, composed wholly or partly of *asbestos*, and processes incidental thereto ;

(v) sawing, grinding, turning, abrading and polishing, in the dry state, of articles composed wholly or partly of *asbestos* in the manufacture of such articles ;

(vi) the cleaning of any chambers, fixtures and appliances for the collection of *asbestos* dust produced in any of the foregoing processes.

The Regulations require that machinery, used for processes in the manufacture of asbestos giving rise to dust, be so constructed and maintained that dust cannot escape otherwise than by mechanical exhaust draught which prevents the escape of dust into the air of a workroom. Mechanical exhaust draught is also required at processes in which asbestos is manipulated.

Special requirements apply to the making and repair of

insulating mattresses, one of the most dangerous processes in the industry owing to the difficulty of controlling the finest dust. Ventilation of the room must be approved in writing by the Chief Inspector; whilst filling, beating and levelling are being done, persons not actually employed on such work are excluded from the room; damping of floors, benches and material is prescribed.

Cleaning of the cylinders of a carding machine is no longer allowed to be done by hand tools, and persons not engaged in the work are excluded from the room. In practice, suction apparatus is now used and this is one of the most important preventive measures.

A breathing apparatus or approved respirator must be provided for and worn by persons employed in chambers containing loose asbestos, in cleaning dust collecting apparatus, and in filling insulating mattresses. Persons under eighteen years of age must not be employed in any of these processes, or in sack-cleaning or blending asbestos by hand.

In all rooms in which the processes are carried on, floors, benches and plant must be kept clean and free from obstructing material or articles not immediately required, and every room must be adequately lighted.

Initial and periodical medical examinations may be of great value as a means of preventing or arresting the development of asbestosis. Such examinations are prescribed under the Silicosis and Asbestosis (Medical Arrangements) Scheme, 1931 [26], as amended in 1934 [27], for workmen employed in the processes of breaking, crushing, disintegrating, opening or grinding asbestos, and in mixing or sieving of asbestos or any admixture of asbestos, and in making asbestos textiles and insulating mattresses. The periodic examinations are carried out by the Silicosis Medical Board at the prescribed intervals of twelve months.

Compensation. The Asbestos Industry (Asbestosis)

Scheme, 1931 [59] provides for the payment of compensation by employers of workmen who contract asbestosis due to employment in those processes in the industry in which the disease is liable to occur. The processes are as follows : — breaking, crushing, disintegrating, opening and grinding of asbestos, mixing or sieving of asbestos or any admixture of asbestos : the manufacture of asbestos textiles ; the making of insulation slabs or sections or mattresses composed wholly or partly of asbestos ; other manufacturing processes carried on in the same room as any of the foregoing processes ; the cleaning of machinery and plant used in the processes, and of chambers, fixtures and appliances for the collection of asbestos dust ; the sawing, grinding and turning in the dry state of articles composed wholly or partly of asbestos, except articles composed wholly or partly of woven asbestos impregnated with bitumen or other bond of an adhesive nature.

The Prevention of Silicosis

Silicosis, like every occupational disease, is preventable. The long latent period between first exposure and the appearance of symptoms, and the chronic course of the disease tend to obscure the connection between the fatal result and the conditions which brought it about. This leads to the argument that the conditions which existed in this or that industry thirty or forty years ago were responsible for most of the silicosis mortality of today. That may be true of some industries but conditions do still exist which are capable of producing silicosis and new processes have been introduced without due regard to this danger.

The most important measures for preventing silicosis are (1) abandonment of the process ; (2) finding a safe substitute for a dangerous material ; (3) suppression of dust immediately on its production ; (4) removal of dust near its point of origin so that it does not reach breathing level ; (5)

exclusion of persons from the room where a dusty process is being carried on, except those actually and necessarily employed in it; (6) protection of individual workmen by respirators or breathing apparatus; (7) medical supervision.

(1) A safe process may be adopted in place of a dangerous one; for example, cleaning metal castings with adherent sand by a wet method instead of by sand- or shot-blasting.

(2) Notable examples of replacing a dangerous substance by a safe substitute are the use of artificial abrasive wheels for sandstone in metal-grinding; the use of alumina for placing china-biscuit ware and for polishing and grinding in the pottery industry; metal grit or aluminous abrasive for sand or flint in sand-blasting. These measures have altered the outlook in their respective industries.

(3) Suppression of dust at the point of origin has been achieved to meet the hygienic needs of rapid drilling and other mechanical methods; water alone or combined with foam producers and with suitably modified drills have improved the outlook in mining and quarrying in sandstone, granite and other siliceous rocks and siliceous deposits.

(4) Localised exhaust ventilation by mechanical means is one of the most widely used measures for dust removal. To be effective the plant must be designed to remove the required quota of dust as near as possible to the point of origin and to admit of effective collection and removal. It is a special engineering problem, and its efficiency should be checked at its installation and periodically afterwards by approved scientific instrumental methods of dust estimation. Standards of permissible air dustiness are still lacking, but with standardisation of methods these can be evolved, and for the present reasonable arbitrary standards can be maintained. Localised exhaust must usually be combined with some degree of enclosure of machinery which gives rise to dust.

(5) Exclusion from the room of persons not actually en-

gaged in the dusty process is necessary where dust suppression cannot be complete. The principle has been incorporated in Regulations and is now specifically included in the Factories Act, 1937, Section 48, as regards periods allowed for meals or rest.

Section 48 of the Act provides that where in any room a process prescribed by Regulations is carried on which gives rise to siliceous dust or asbestos dust, a person shall not be permitted to remain in that room during the intervals allowed to him for meals or rest, and suitable provision must be made to enable such persons to take their meals elsewhere in the factory.

Some processes can be carried on mechanically without the presence of any person in the room while the machinery is in motion ; for example, crushing and screening of road material. Certain dusty processes required intermittently can be carried out by a minimum number of persons outside ordinary working hours, the persons employed being suitably protected.

(6) Individual workmen can be protected by breathing apparatus providing pure air through a tube or by self-contained oxygen apparatus. A certain degree of protection can be secured by efficient respirators ; these should, however, have a high filtering efficiency against fine dust, should fit accurately, have a low resistance, and be reasonably comfortable and cheap. Protection of this kind cannot be regarded as a substitute for dust suppression or dust removal where such is practicable.

(7) Medical supervision of personnel may take the form of selection by initial examination of persons proposed for employment in the dusty process and exclusion of those of deficient respiratory physique or showing any signs of tuberculosis. Subsequent periodic medical examinations of persons employed, with roentgenological examinations and the keep-

ing of records of the serial examinations; this enables persons showing the earliest evidence of pulmonary changes due to dust, or the onset of tuberculosis, to be suspended from further work in the process. This form of supervision can be used as a means of determining the relative dangers of the various processes and the value of measures in use for dust suppression.

Section 4 (1) of the Factories Act, 1937 [3] requires that effective and suitable provision shall be made for securing and maintaining, by the circulation of fresh air in each workroom, the adequate ventilation of the room, and for rendering harmless, so far as practicable, all fumes, dust and other impurities that may be injurious to health, generated in the course of any process or work carried on in the factory.

Section 47 (1) requires that in every factory in which, in connection with any process carried on, there is given off any dust or fume or other impurity of such a character and to such an extent as to be likely to be injurious or offensive to the persons employed, or any substantial quantity of dust of any kind, all practicable measures shall be taken to protect the persons employed against inhalation of the dust or fume or other impurity, and to prevent its accumulating in any workroom, and in particular, where the nature of the process makes it practicable, exhaust appliances shall be provided and maintained, as near as possible to the point of origin of the dust or fume or other impurity, so as to prevent it entering the air of any workroom.

Compensation for Silicosis and Asbestosis

A beginning was made in providing compensation for these diseases in 1918, when the Workmen's Compensation (Silicosis) Act was passed. This Act gave power to the Secretary of State to make schemes for the payment of compensation by the employers of workmen in any specified industry or