ASBESTOS PNEUMOCONIOSIS

Experimental Studies
by
The Saranac Laboratory

Report to the Johns-Manville Corporation
January 31, 1949

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A S B E S T O S I S

Experimental Studies

by

THE SARANAC LABORATORY
SARANAC LAKE, NEW YORK

Report to the

JOHNS-MANVILLE CORPORATION
NEW YORK, NEW YORK

January 31, 1943

Submitted by:

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A B S T R A C T

1. Various forms of asbestos fibers produce a peribronchiolar fibrosis of the lungs of guinea pigs, rats, cats and rabbits but not of mice and dogs.

2. The mode of action of the asbestos fiber is primarily mechanical rather than chemical in nature.

3. Long asbestos fibers are essential in the production of peribronchial fibrosis; short fibers are incapable of producing this reaction.

4. Typical experimental asbestotic fibrosis was produced by the inhalation of an atmospheric suspension containing an average of 138 million particles per cubic foot of air of which only 0.6 per cent consisted of fibers longer than 10 microns.

5. The duration of exposure required to develop the pulmonary reaction to inhaled asbestos dust is inversely proportional to the concentration of long fibers in the atmosphere, viz. as the concentration is increased, the reaction develops in shorter time.

6. Established experimental asbestosis ceases to progress on discontinuing exposure to the dust.

7. The formation of asbestosis bodies represents a coating of the fibers by blood and tissue elements which results in loss of ability of the fiber to produce fibrosis.

8. Aluminum hydroxide failed to neutralize the fibrosing action of the long fiber asbestos (Section 35).

9. Inhalation of asbestos dust did not alter significantly the final outcome of experimental tuberculosis in two series of guinea pigs exposed.

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2. Introduction

Asbestosis is a form of pneumoconiosis resulting from prolonged inhalation of asbestos dust. The name asbestos, literally "unburnable," is not that of a particular mineral but is a term applied to a number of different minerals whose characteristic feature is a structure composed of long, parallel, flexible fibers. This structure is unique because the fibers are capable of repeated longitudinal subdivision to units of molecular proportions. In length the fibers vary from a few microns to six or more inches. Some varieties are stiffer than others but many are sufficiently flexible to be spun into yarn and woven on modified textile machinery.

3. Asbestos Minerals

The asbestos minerals are silicates of variable composition and belong to the serpentine and the amphibole groups. Listed below are the more common varieties.

Amphibole Group	
Anthophyllite	(Mg, Fe) silicate
Amosite	(Mg, Fe, Al) silicate
Amphibole	(Ca, Mg, Fe, Al, Na, K) silicate
Tremolite	(Ca, Mg) silicate
Actinolite	(Ca, Mg, Fe) silicate
Crocidolite	(Na, Fe) silicate + Fe silicate
Serpentine Group	
Chrysotile	Mg silicate (hydrous)

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The bulk of the asbestos of commerce is chrysotile, $3MgO.2SiO_2.2H_2O$, which is mined in the Thetford region of the Province of Quebec. Crocidolite and amosite are also used commercially but in much smaller amounts. Chrysotile occurs as veins in serpentine, a mineral similar in chemical composition to chrysotile but which exists in massive form and is made up of microscopic fibers without the parallel orientation characteristic of chrysotile. The massive blue black serpentine, which is smooth and soapy to the touch, is traversed by veins of fibrous chrysotile varying in width from a barely perceptible line to six or more inches. The fibers run across the vein and not lengthwise with the formation.

Attention is directed to the mineral brucite, $MgO.H_2O$, which is often found in the same formations with serpentine and chrysotile and may be fibrous in structure. It has no commercial value at present because its fibers are not sufficiently flexible to be used in textiles but they are capable of repeated longitudinal subdivision. Unlike other asbestiform minerals, brucite is not a silicate and for this reason it has been a valuable tool in an experimental evaluation of the action of fibrous minerals upon lung tissue.

IV
E X P E R I M E N T A L A S B E S T O S I S

For many years studies have been carried on by the Saranac Laboratory in an investigation of the cause, nature and development of asbestosis. The present report is devoted to Experimental Asbestosis. In it are described the animal experiments with various kinds of asbestos dust. Another report, to be prepared and issued later, will be concerned with Human Asbestosis and will cover the health aspects of workers who have been exposed to asbestos dust in an industrial environment.

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Although asbestosis in man is a chronic disease which requires years to develop, it is possible to reproduce in one or more species of animal characteristic tissue changes which are similar to the lesions of human asbestosis. Since the life-span of the experimental animal is relatively short, it is not possible to develop the characteristic lesions in animals under the usual industrial conditions. Consequently, to obtain a complete evaluation of the tissue response to inhaled particulate and fibrous material, it is necessary to accelerate the reaction by employing higher concentrations of dust than would ordinarily be encountered in industry. While conditions of exposure are thus different, the information yielded by experiments with animals is invaluable in furnishing a better understanding of the reaction of the human organism to inhaled asbestos dust.

7. Experimental Methods

For investigating the biological reaction of the experimental animal to the various asbestos minerals, two types of technique have been employed, namely, the inhalation method and the injection method. In inhalation experiments, groups of animals - 40 to 100 or more guinea pigs and sometimes smaller numbers of rabbits, cats, dogs, rats or mice - are kept for eight hours a day in a cubical dust room, eight feet in dimension, in which a cloud of asbestos dust is maintained. At intervals during the experiment, a few animals are sacrificed and the tissue examined to determine the nature and extent of the dust reaction. Some animals are exposed for periods up to three years. The injection experiments, in which the dust, either dry or suspended in fluid, is introduced into the animal by the intravenous, intraperitoneal or intratracheal procedure, are used to determine whether or not a particular dust has a potential capacity to produce tissue reaction.

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Long-term inhalation experiments furnish information upon which great reliance is placed when estimating the degree to which a dust might be hazardous to industrial workers. Whether or not atmospheric dust, even though potentially dangerous, can be inhaled, pass the natural defense barriers and reach the pulmonary tissue in quantities sufficient to cause damage can be determined only by inhalation procedures. Injection experiments are useful because in them contact between the dust particles and tissues is assured and the potential capacity of the dust to produce reaction can be estimated accurately. When dealing with fibrous minerals like asbestos, the intratracheal method is valuable since it permits observing the effect of the fibers on pulmonary tissue.

6. Species Susceptibility

Unlike free silica, asbestos does not exert its specific effect in all organs of all species of animal (Table 1). Injection of fine quartz into various organs of the guinea pig, rabbit, rat, mouse, cat, dog, chicken and even tadpole will produce silicotic nodules. However, similar injections of long or short fiber asbestos have resulted in a fibrous reaction in the lung and, to a lesser extent, in the peritoneum but not in other organs of the guinea pig, rabbit, cat and white rat. The dog and white mouse failed to respond. This variation in species is yet to be accounted for.

7. Peculiar Characteristics of Asbestos

Experience has demonstrated that most of the particulate matter inhaled into the lungs of man and animal is 10 microns or less in maximum diameter. Larger particles apparently are excluded by the protective mechanism of the upper respiratory tract. In the case of fibrous materials, however, this restriction does not apply and fibers 100 and even 200 microns in length have been found in the terminal air spaces of human lungs. In small laboratory animals exposed to asbestos dust the maximum length of fiber found in the lung rarely exceeds 60 microns. Not every kind of fibrous material is inhaled with equal readiness; for example,

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the cylindric fibers of glass wool apparently are too inflexible to pass easily through the nose, pharynx, trachea and bronchi and seldom reach the terminal bronchioles and alveoli.

Inhaled particulate matter comes to rest throughout the terminal air spaces (alveolar duct, atria, alveoli) in all parts of the lungs; inhaled asbestos fibers are first restrained in the respiratory bronchioles. These very small tubes are immediately distal to bronchioles lined by ciliated epithelium. Their own essential lining is a low cuboidal type of epithelium but, as their name implies, they usually function in respiration through lateral alveoli given off as pouches along their walls. Either these pouches, or the abrupt change in the character of the lining epithelium, or the decrease in diameter of the tube, or perhaps the combination of all these factors is responsible for local retention of the inhaled fiber. Only after asbestosis is well established are appreciable numbers of fibers carried into the more peripheral air spaces.

3. Rate of Tissue Reaction to Asbestos Fibers

The rate of tissue reaction to asbestos is much more rapid than to an active dust like quartz. Evidences of tissue response appear as soon as fibers have localized in sufficient concentration in specific areas. In rats receiving asbestos fibers by intratracheal injection this evidence is visible as early as two weeks after injection; for quartz dust the latent period might be two months or more.

The behavior of the tissue reaction to inhaled dust after the termination of exposure is not the same in silicosis as in asbestosis. In silicosis, the young nodules become larger; in asbestosis, young scar tissue, that may have formed, contracts and becomes more dense but the area of involvement decreases in size. If exposure to asbestos dust is terminated after a brief period, the recently-inhaled

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fibers in the lung may cause the fibrous tissue response to continue for a short time, until the fibers have been coated. This progression is of only a slight degree and of little significance.

9. Asbestosis Bodies

The peculiar structure known as the asbestosis body or curious body is a specific concomitant of asbestosis. The typical body is a golden-yellow, beaded or haustrated rod which may be either straight or curved. Often one or both ends are bulbous like a dumb-bell. The bodies vary considerably in length, and dimensions up to 250 microns have been recorded.

It is believed that asbestosis bodies are due to a deposit of protein and iron pigment upon the surface of inhaled fibers. In guinea pigs they form after about 60 days of contact with the tissue. They are abundant in man and the guinea pig (see Table 1) but are much larger in the former, probably because the larger-sized air tubes admit fibers of greater dimension. In cats, rabbits and mice there is an atypical coating of a few of the fibers after much longer residence in the lungs. In rats and dogs no bodies could be discovered. Although the evidence is incomplete, it appears that the formation of the asbestosis body prevents damage to the tissue by the fiber.

E
INHALATION EXPERIMENTS

Four comprehensive inhalation experiments have been conducted at the Saranac Laboratory with various forms of asbestos dust. In each of these investigations more than 100 animals were used and the experiments were carried on for periods ranging from 2 to more than 5 years. The four kinds of asbestos dust employed are identified as Ring's floats, short-fiber, 100 per cent ball-milled, and long-fiber asbestos dust.

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XI

INHALATION EXPERIMENT WITH "KING'S FLOATS" ASBESTOS DUST

The first inhalation experiment conducted at the Saranac Laboratory with asbestos dust was begun in 1928. Animals inhaled the dust for periods up to nearly three years and some guinea pigs lived for about four years after their first exposure to dust. A preliminary report giving observations after 29 months of exposure appeared in the February, 1931, issue of THE JOURNAL OF INDUSTRIAL HYGIENE.* At that time observations covered a period of only 2-1/4 years and the conclusions as to the ultimate effects of inhaled asbestos dust were provisional. Results of the completed study show that most of the conclusions drawn in the preliminary report were substantiated. A complete review of this experiment follows:

12. The dusting material was a commercial variety of asbestos dust known as King's floats and was composed of short fibers and particles of variable size. It was obtained from the Thetford, Quebec plant of the Asbestos Corporation of America.

13. The dust composition (Table 2) reveals that the amount of fibrous chrysotile was only 14 per cent, a rather low value. However, there was sufficient fibrous material to produce a characteristic fibrosis.

14. The dust concentration at first was quite low and for impinger samples taken soon after the experiment was started, the average light field count by the standard technique was only 6.0 million particles per cubic foot of air. An appreciable number of large particles (or fibers) also were present, as

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*[illegible] ON EXPERIMENTAL PNEUMONOCONIOSIS. VI. Inhalation of Asbestos Dust. Gardner, [illegible] and Cummings, F.J. J. Ind. Hyg., 13: 65-81, 97-114, 1931.

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shown by an average count of 0.8 million for particles greater than 10 microns. After the inhalation experiment had been under way for about two years, the speed of the rotating paddle in the dusting machine was increased and for the remaining 5 or 10 months of the experiment considerably more dust was dispersed into the atmosphere. Average dust counts for impinger samples collected after this change were 53.7 million for the usual light-field method, and 1.6 million for particles larger than 10 microns.

13. Reaction in Animals to Inhaled "King's Floats" Asbestos Dust. Results of the investigation, briefly summarized in Table 3, show that inhalation of King's floats asbestos dust produced a typical peribronchiolar fibrosis in guinea pigs but not in rabbits or rats.

14. Guinea Pigs. Seven groups of guinea pigs were used. In three groups the effect of a continuous and of an interrupted dust exposure was studied; in two other groups the relationship between infection and dust exposure was investigated. The remaining two groups were infection controls.

15. Rate and Type of Reaction. Guinea pigs inhaling this dust for periods up to 33 months developed a characteristic fibrosis occurring in conical patches about the respiratory bronchioles. During this exposure the peripheral alveoli were not involved. The particulate elements of the dust were transported to the lymphatic system where they caused no significant reaction; the fibrous elements remained fixed at the site of original localization and were seldom detected in the lymphoid tissue. Pleurisy and fibrosis in the lungs were observed only when infection complicated the process.

After exposure of approximately a year, a small amount of cellular reaction had been produced about many respiratory bronchioles. As more dust was inhaled, it continued to accumulate in the same location and later stages of the disease

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consisted of extensions of the original lesions. New areas were not involved.

Apparently, the inhaled fibers were caught in the pocket-like alveoli that are given off from the lateral walls of the respiratory bronchioles. There they were phagocytized and many of them were carried into the wall by migratory cells. Mononuclear leucocytes attracted to the area caused an appreciable thickening of the bronchial wall. After 16 months a delicate fibrosis made its appearance. The process evolved so gradually that mitotic division of fibroblasts could rarely be discovered; nevertheless, the number of fine intercellular collagenous fibers (fibrosis) steadily increased. As this fibrosis contracted, it partially closed the alveoli, and with this atelectasis the lining epithelium assumed its characteristic cuboidal form. The result was the adenoma-like appearance that Willis described in guinea pigs inhaling silicon carbide. The longer exposures resulted only in more thickening of the walls of the air spaces, largely due to an increase in the amount of fibrosis. The fibrous tissue always remained cellular and never showed the hyalinization characteristic of silicosis.

b. Regression. The reaction produced in exposed guinea pigs did not progress significantly during a subsequent period of 37 months when the animals lived in a normal atmosphere. Between 8 and 11 months after exposure ceased, the cellular reaction had been completely replaced by thin strands of fibrous tissue. Observed still longer, the scar tissue decreased in extent but in the last animal sacrificed, 37 months after discontinuing dust exposure, some fibrosis was still visible.

c. Infection Coincident with Dust Inhalation. Of the group of 40 guinea pigs infected with attenuated tubercle bacilli (Rh strain) 31 died or were sacrificed before two years of dust exposure and were reported in the paper by Gardner and Cummings mentioned

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above. Seventeen of these died from intercurrent pneumonia. Briefly, the results were as follows: 10 revealed some evidence of spread of the tuberculous process; in 6 of these it was confined to the lungs and in the other 4 the abdominal viscera also were involved. Usually a slight local extension of the tuberculous infection had occurred but subsequent healing had resulted in fibrosis of both the pulmonary lesions and the secondary lesions in other organs. The healed pulmonary lesions showed more fibrosis than is characteristic of either tuberculosis or asbestosis alone.

The 9 animals which were still alive after two years of dust exposure were sacrificed at intervals during the following year. In 4 of them the primary foci of infection had healed with fibrosis and even calcification and there was no evidence of progression. In the other 5 the tuberculous foci showed evidence of having previously spread locally: in 4 of them it had healed, by the time of autopsy, with excessive fibrosis; in the other animal there was a generalized chronic tuberculous pneumonia in one lobe and isolated primary tubercles, which were still active but had not spread in the other lobes.

Evidence of extension of the infection was first seen after 7 months of dust inhalation; during the next 20 months more than half of the animals showed an actively spreading tuberculosis and in 3 of them small cavities had developed. During the last 3 months no animals exhibited any evidence of active infection although in half of them the healed fibrous scars of previous extensions were obvious. Sixty per cent of the guinea pigs with spreading pulmonary tuberculosis showed tuberculosis of the spleen and liver.

10. Infection Superimposed Upon an Established Asbestosis. Twelve guinea pigs, after inhaling asbestos dust for nearly 26 months, were infected with tubercle bacilli and then returned to normal air. The subpleural tubercles in the dusted animals were

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ore numerous than in non-dusted controls, but a considerable number were nd in the depths of the lung about foci of asbestosis. The reaction to infec- on showed only slight local extension about the original sites in the lungs d tracheobronchial lymph nodes. The abdominal viscera were involved in only e animal. Caseation was found in tubercles 1-1/2 months old but by 5-1/2 nths it had completely disappeared, leaving only scar tissue. The latter still existed in the last animal, which was killed 14 months after infection.

11. Asbestosis Bodies. Moderate numbers of asbestosis bodies occurred in the lungs of the guinea pigs, becoming more numerous nd more distinctly segmented in later months.

12. Rabbits. Rabbits exposed to the asbestos dust for periods up to 19 months developed a low-grade foreign-body type of reaction but o fibrosis. Although their lungs contained particulate elements of the dust, fibers were not present, indicating that the upper respiratory mechanism of the abbit is adequate to exclude fibrous foreign bodies. Two rabbits, after inhaling ust for 5 and 18 months, lived in normal air for more than two years. At autopsy ither animal showed any evidence of cellular reaction or fibrosis in the term- na bronchioles nor were there any asbestosis bodies.

13. Rats. All the white rats had acquired an infection, resulting in the formation of pulmonary abscesses, before they came to autopsy. Apparently, so much heavy mucus obstructed their bronchi that very few fibers could have entered their lungs. In a few of the rats, an occasional asbestosis body was discovered but there was no fibrosis.

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Summary and Interpretation of Inhalation Experiment with King's Floats Dust.

The findings in the experiment with King's floats dust can be summarized under three headings.

1. Effect of the inhaled dust on normal animals. The King's floats dust caused a characteristic peribronchiolar fibrosis in guinea pigs but not in rabbits or rats. The lesions did not progress after the dust exposure was discontinued and the guinea pigs transferred to normal air

2. Effect of the inhaled dust on tuberculosis in guinea pigs. In guinea pigs infected with attenuated tubercle bacilli and then placed in the dust room, the results were more variable than is usual in an experiment of this type. A few animals showed no sign of progression; in most of them there was evidence of tuberculous progression with subsequent healing; in one animal there was continuous progression to death. In contrast, when guinea pigs, after being infected, are exposed to a similar amount of asbestos dust, the infectious process continues to progress and usually causes the death of the animals. On the other hand, exposure of infected animals to a harmless dust like calcite or gypsum does not alter the progression of the infection. Guinea pigs infected with attenuated tubercle bacilli following the termination of about two years' exposure to asbestos dust showed no signs of progressive disease. The only modification of the infection was a slight reduction in the number of viable bacilli being retained in the fibrous terminal granulomas and a scarcity of tubercles there in addition to the usual foci beneath the pleura.

In view of this variability, the unusual nature of the response and the high incidence of deaths from intercurrent pneumonia it is felt that definite conclusions regarding the influence of asbestos on the course of tuberculous infection are not justified.

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XXV

INHALATION EXPERIMENT WITH SHORT-FIBER ASBESTOS DUST

Since hazardous dusts like quartz are most effective in producing fibrosis when the particles are 3 microns and less in size, an inhalation experiment was carried on to determine whether this condition is true also for asbestos dust. It was thought that by using a short-fiber asbestos dust consisting almost entirely of fibers and particles smaller than 3 microns an accelerated tissue response might be initiated and an advanced reaction obtained in a short time. The previous inhalation experiment with King's floats asbestos, which contained fibers from 1 mm. to 1 micron or less in length as well as a great deal of particulate matter and which produced a typical peribronchiolar fibrosis in exposed guinea pigs, served as a basis of comparison.

86. The dusting material for this experiment was forwarded from the Manville plant of the Johns-Manville Corporation. It was the remains of fibers collected in dust bins after a carding operation and screened to pass the mesh. Since the material as received contained many long fibers, it was ground in a steel ball mill to reduce practically all the particles to 3 microns or less in size. When used alone in a standard dusting machine, this finely-ground asbestos tended to pack in the hopper and it became necessary to mix one volume of the unground material with three volumes of the ground to generate a satisfactory dust cloud. The addition of the small quantity of unground asbestos was unfortunate because it confused the interpretation of results. Probably the minor amount of reaction that developed was due to the long fibers in the mixture although the data of this experiment do not prove the point.

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27. The composition of the short-fiber asbestos as received is disclosed by the chemical and petrographic analyses given in Table 4. Samples taken before and after grinding yielded about the same values on analysis, indicating that there was no contamination from the mill or loss of water content.

28. The dust concentration varied somewhat during the experiment and light field counts for atmospheric samples collected inside the animal cages with the impinger apparatus ranged from 83 million to 182 million. The average of counts was 130 million for the first year of the experiment, 134 million for the second year and 140 million for the third year.

29. Size-frequency measurements of air-floated dust from inside the cages at a magnification of 1300X revealed a great preponderance of fine particles (Table 5). Nearly 90 per cent of the particles seen were smaller than 3 microns.

30. Reaction in Animals to Inhaled Short-Fiber Asbestos Dust. Four species of animals - guinea pigs, white rats, cats and rabbits - were used in this experiment. The results of the dust exposure, which are summarized in Table 6, will be considered more in detail below.

31. Guinea Pigs. Eighty guinea pigs were originally placed in the dust room but 21 of them were later eliminated from the experiment and killed because of enlarged lymph nodes. Of the other 59 animals, 46 remained in the dust room until they were sacrificed or died from natural causes and 13, after being exposed to dust for 20 months, were transferred to a normal atmosphere.

32. Rate and Type of Reaction. The type of tissue reaction to the inhaled

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short-fiber asbestos was essentially the same as that already observed in the experiment with King's floats asbestos. The rate of reaction also was approximately the same but the extent of involvement with the short-fiber dust was very much less and after 16 to 24 months of exposure only a very few small foci of reaction, which generally required microscopic examination for detection, were produced in the guinea pigs.

Until exposures had continued for approximately one year, there was little tendency for dust-containing phagocytes to collect into clumps. By 16 months macrophages had begun to collect about the walls of a few of the respiratory bronchioles with a little proliferation or infiltration of mononuclear cells in these walls. There were also some multinucleated cells but they were always of the giant foreign-body type. At 20 to 24 months the cellular clumps were sometimes quite marked and sometimes changes in the epithelium resulted in the adenoma-like or "adenomatoid" appearance previously described in Section 17. In most of the subsequent members of the series, the reaction remained cellular in type. In a few, however, fibrous elements dominated the picture. In the latter case, the collagen was pale in color and tenuous with no heavy swollen hyalinization. As in the rats described below, the alveolar walls might be made up of a band of collagen supporting a layer of epithelium, but with no contained capillaries. In the tracheobronchial lymph nodes the reaction was more pronounced in this experiment than in the previous one with King's floats asbestos, probably because of the preponderation of an excess of fine particles to the nodes in animals inhaling short-fiber asbestos. The reaction was essentially an increase in reticulum, rather than a fibrosis, with preservation of the original cells between the thickened reticular fibers. Diffuse chronic pleurisy without evidence of pulmonary infection was present in a few animals.

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3. Progression. In the 13-3/4 months following the cessation of 20 months' exposure to dust, progression of disease was not definitely nstrated but neither could it be absolutely disproved, owing to the varia- ty of the response in different animals. At the end of the dust exposure of onths two pigs were read as + and one as 2+. Among the 13 removed from dust findings were variable: in 2 the reaction was ±; in 4 it was +; in 3 it was ; in 2 it was 4+; and in one animal it was 5+. It is quite possible that those h the most marked changes had already developed more reaction than the remain- r by the time exposure ceased. Since the more severe reactions occurred spora- ally and bore no relationship to the length of time after cessation of expo- re the differences were attributed to variation in individual susceptibility. his view received support from the chemical analyses (Table 7), which often re- ealed comparable amounts of ash and silica in lungs with widely different amounts tissue change. For example, the ash and silica values were quite similar for three animals in dust 20 months and then in normal air 13-3/4 months, yet the tis- sue reaction for one animal was 4+; for another, +; and for the third, only ±.

4. Asbestosis Bodies. The formation of asbestosis bodies was at first extremely limited. After 5 months' exposure only a very rare short body could be found, usually inside of cells. Around the finest intracellular particles there were yellow deposits having the same color as the asbestosis body. Exposure of one year had permitted an accumulation of many longer fibers about which the asbestosis-body coating developed. Most of these were still short enough to be partially or entirely within phagocytic cells. By the 20th month and thereafter, they were comparatively numerous although still rare in comparison with the findings in the King's Floats experiment.

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15. White Rats. Seventy-three white rats were exposed to atmospheric short-fiber asbestos dust for periods up to 32 months. Sacrifices during the first 10 months were made bimonthly and for the remainder of the experiment at less frequent intervals.

16. Rate and Type of Reaction. The dust cells until 8 months were widely scattered and existed in foci only sporadically. Reaction was limited to occasional slight thickenings of the septa about small accumulations of dust cells. In a few rats at 10 months, there was a suggestion of early fibrosis but the change was so slight that it would probably be overlooked without the clump of dust cells to attract attention to the area. Six animals were exposed from 12 to 32 months. In each of them the lungs showed minute patches of well-defined fibrosis distributed like that of asbestosis but without asbestosis bodies. The lesions, visible only at a magnification of 50 diameters or more, consisted of patches along alveolar ducts in which the walls of the air spaces were very thick, due to swollen collagen framework. Connective tissue and Fox-Weisenowski silver preparations revealed complete loss of capillaries involved locally. Outside the collagen was a thin layer of epithelial cells. This did not resemble the "adenomatoid" change characteristic of guinea pig asbestosis. No pleurisy was present. Near the lesions the air spaces were filled with macrophages containing gray to yellow particulate dust and a rare long naked asbestos fiber. Careful search failed to reveal even a suggestion of an asbestosis body. The bronchobronchial nodes showed compact focal collections of monocytic cells at 12 months and, at 20 months, some diffuse thickening of the reticulum. In a few rats there was definite fibrosis along the margins of the nodes and extending into the mediastinal areolar tissue. Compared with the response to native dusts like quartz and chert the reaction to short-fiber asbestos was negligible.

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Results of chemical analyses made on the white rats are given in Table 8 and average values have been tabulated in Table 9 for comparison with similar data for rats inhaling other dusts. The concentration of atmospheric particles to which the animals were exposed was approximately the same for asbestos and quartz; for the gypsum-quartz mixture, it was about twice as high and for chert about 3 times as high. It will be noted that the percentages for asbestos are lower than those for quartz or chert but are similar to those for the gypsum-quartz mixture, in which atmospheric agglutination tended to reduce the amount of dust inhaled. It might be inferred that the total quantity of asbestos dust inhaled was low or that it had been eliminated from or dissolved within the lungs. In the present state of our knowledge evaluation of these hypotheses is not possible.

7. Cats. Twenty cats were used in this inhalation experiment with the short-fiber asbestos. Eighteen were kept in the dust room until death, the exposure period ranging from one month to nearly 4-1/2 years, and two, after a dust exposure of 31-1/2 months, were removed to normal air. One of these was sacrificed 5 months, and the other 24 months, later.

8. Rate and Type of Reaction. The reaction was essentially that to an inert dust, even after more than 4 years of exposure. The tissue response in this species was confined to microscopic foci of fibrosis in the walls of groups of subpleural alveoli, rather than in the peribronchiolar areas. In one animal the change was extensive enough to be visualized in gross inspection of the section.

9. X-ray Changes. Only in the animal with the longest exposure did the X-ray reveal definitely abnormal shadows. After 29-3/4 months the picture was negative; after 45 months a faint mottling could be detected in the right lung. At autopsy, 8 months later, there was only microscopic

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fibrosis in the subpleural zone plus heavy lymphocytic infiltration about small bronchioles.

10. Asbestosis Bodies. On prolonged search a few yellow atypical asbestosis bodies, smooth and without haustrations, were found in animals exposed for more than a year.

11. Rabbits. Eight rabbits were exposed to dust for periods extending from one to more than five years. The last animal was removed from the dust room and left in normal air 6 months before being sacrificed.

12. Rate and Type of Reaction. There was never enough fibrosis to be detected grossly and there was no chronic pleural pleurisy. Microscopic evidence of alveolar wall thickening was first noted after about 3 years of exposure and was seen in all five animals examined thereafter. In one animal that died of paralysis after nearly four years of exposure the reaction was extensive enough to be visible on gross inspection of the thoracic [illegible]. The possibility of pulmonary infection in this animal could not be excluded. However, in another animal dying two years later the focal fibrosis was not nearly as obvious or as advanced. Areas of involvement, which were readily visualized because of phagocytic reaction within the air spaces, tended chronologically to become more fibrous with the passage of time but there was little if any encroachment upon the lumen of air spaces and the architecture of the lung was preserved.

13. Asbestosis Bodies. Asbestos bodies were not detected in rabbits that died early in the experiment but were seen in all animals that had been exposed to the dust for more than three years.

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44. Summary and Interpretation

The original purpose of the experiment was to evaluate the chemical theory of the pathogenesis of asbestosis. It was felt that if the tissue reaction to asbestos were chemical in origin an accelerated or accentuated response would result from exposure to finely-divided asbestos, as is the case with quartz. The experiment, in which the reaction was slower and less extensive than with lung floats, indicates that the reaction is not primarily chemical in nature.

Of the four species exposed in this experiment only the guinea pig has not reacted with characteristic peribronchiolar fibrosis. The cat reacted with atypical sub-pleural fibrosis and in the rabbit the fibrosis which occurred could not be positively attributed to the dust because of a strong possibility of pulmonary infection.

XLV

INHALATION EXPERIMENT WITH 100 PER CENT BALL-MILLED ASBESTOS DUST

In the inhalation experiment with short-fiber asbestos dust a small quantity of unground asbestos was mixed with ground material in order to produce a suitable dust cloud. When evidence of a dust reaction appeared in the guinea pigs during the experiment, it was not clear whether this was a tissue response to the small number of long fibers in the unground asbestos or was a delayed effect of the more abundant fine dust. Consequently, another inhalation experiment was started in which no unground material was used.

The dusting material was the ground short-fiber asbestos used in the previous inhalation experiment but no unground material was mixed with it. To obtain a sufficient amount of atmospheric dust, the design of the dusting apparatus was changed to an open type of hopper and fresh dust was added daily,

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due to the tendency of the material to form small spherules which prevented all of the fibrous portion from floating out of the hopper, the dispersal of dust was not entirely satisfactory and after 7 months of operation, the dusting machine was reconverted to its original design. To prevent "pilling" or the formation of spherules of asbestos, steel wire brushes were attached to the interior surfaces of the hopper and to the rotating paddle. This arrangement gave satisfactory results and was used for the remaining 21 months of the experiment.

The composition of the raw material (short-fiber asbestos) and of atmospheric dust liberated from the ball-milled product in the dusting machine is given in Table 10. These values are based upon petrographic study and x-ray diffraction analysis. The atmospheric sample was collected with an electrostatic precipitator after wire brushes had been installed in the dusting machine. Previous to this, the chrysotile content of the air-suspended material was probably less than the 15 per cent value given in Table 10. In an interview, it was stated that the air-borne dust contained about 5 per cent of chrysotile. Two of the wire brushes were used and up to 8 per cent afterwards, but these values were probably low. Quantitative estimates on ball-milled asbestos will be somewhat inaccurate because it is difficult to determine how much of the sample is fibrous chrysotile and how much is non-fibrous serpentine.

The dust concentration for the first 7 months of the experiment was about 400 million particles per cubic foot of air. After the wire brushes had been installed, the dust counts were a little higher and the overall average for the first year was 406 million. The average of counts for the second year was 141 million and for the third year 145 million.

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The size-frequency of the components of atmospheric dust collected inside the animal cages with the electrostatic apparatus is reported in Table 11. Two samples were taken, one before the wire brushes were installed and one after. It will be noted that after the wire brushes were in use a greater proportion of very fine particles and also of longer fibers was released into the air.

3. Reaction in Animals to Inhaled 100 Per Cent Ball-Milled Asbestos Dust. Guinea pigs, rats and mice were used in the inhalation experiment with 100 per cent ball-milled asbestos dust. The results are summarized in Table 12.

1. Guinea Pigs. The experiment was started with 100 guinea pigs. As the dust exposure proceeded, there were 39 accidental deaths, chiefly from pneumonia in an epidemic. After 28 months of dusting the 16 surviving animals were transferred to normal air.

2. Rate and Type of Reaction. For the first year of exposure practically the only reaction to the dust was the presence of scattered phagocytes and an occasional minute asbestosis body. At 16 months no gross response was visible on the tissue section but microscopically there were slight foci of inflammatory cells could be seen. At 24 months there were visible lesions large enough to be seen with a hand lens although microscopic examination revealed cellular accumulations about terminal bronchioles and many small asbestosis bodies, chiefly within cells.

Chemical analyses of the lungs (Table 13) reveal that in spite of the limited tissue reaction considerable dust had been retained in the lung.

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53. Progression. The lungs of animals exposed for the full dusting period (28 months) and then living in normal air for 2 months revealed the changes described above and also very slight peribronchiolar fibrosis. After 8 months in normal air the findings were similar but at 12 months 3 of 4 animals showed grossly-visible characteristic peribronchiolar fibrosis with nodular change.

54. Lymph Node Involvement. The tracheobronchial nodes were essentially negative until exposure had been continued for more than a year and a half. Animals sacrificed at 12 months and 16 months revealed a few minute collections of phagocytes containing particles but practically no fibers large enough to be recognized as such. After 20 months of exposure many monocytes filled with yellow granules were present. At 30 months there had been a slight increase in reticulum but no fibrosis. No further changes occurred in the nodes. Asbestosis bodies were not seen in the nodes of any of the guinea pigs.

55. Asbestosis Bodies. Minute asbestosis bodies were observed as early as 3 months after exposure began, but they did not become numerous until 16 months had elapsed. The bodies were short and practically all were intracellular, although at 20 months some were long enough to project beyond the cell borders.

It is important to note that in the later months of exposure there was a distinct increase in the number of long fibers up to 70 microns in length in the lungs and that after exposure ceased characteristic long asbestosis bodies were seen.

56. White Rats and Mice. In this experiment 40 rats were exposed for periods up to 20 months and 24 mice for periods up to 12

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rabbits. Neither species developed even a suggestion of asbestosis and reaction was limited to phagocytosis of inhaled particles by widely-scattered dust cells which remained free in air spaces or were transported to the tracheobronchial lymph nodes. No asbestosis bodies were found in the rats but in the mice there were a very few small non-haustrated forms within phagocytes.

In 21 mouse lungs sectioned there were 3 instances of pulmonary adenoma (14%).

17. Summary and Interpretation.

The tissue reactions observed in this experiment were much less extensive and slower in development than in the previous investigation with short-fiber amosite. Since presumably there were fewer fibers longer than 3 microns in the material used in this experiment, the results tend to confirm the interpretation made in Section 44 of the short-fiber experiment that the reaction is not primarily chemical in nature.

The finding of long asbestosis bodies in animals inhaling the ball-milled material is an example of the difficulty of completely eliminating long fibers from an asbestos preparation.

In regard to progression of reaction after removal from dust, which was observed in this experiment but not in the others, the following interpretation is offered: When the reaction is well-developed at the termination of exposure, the contraction of the fibrous tissue would obscure any possible progression. In this experiment, however, since only the earliest stage of reaction was present at the time of removal from dust, its subsequent progress was apparent. It should be noted that the degree of progression was so slight that it can have little, if any, practical significance.

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LVIII

INHALATION EXPERIMENT WITH LONG-FIBER ASBESTOS DUST

After animals inhaling short-fiber asbestos dust for more than a year had failed to develop significant reaction, the hypothesis that asbestosis is produced by the mechanical irritation of long fibers was given added support. Since the King's floats asbestos used in the first inhalation experiment had a rather low content of fibrous chrysotile and contained considerable serpentine and other impurities, it was decided to conduct a new inhalation experiment with a purer form of chrysotile which would be richer in long fibers.

1. The dusting material employed in this investigation was obtained from the Manville plant of the Johns-Manville Corporation. Samples of several varieties of asbestos dust were first submitted to the Saranac Laboratory for examination and one kind, identified as Lot D, which was low in magnetite and dolomite and had a fibrous content estimated to be about 75 per cent, was selected as most suitable. Steel wire brushes were fastened to the inside surface of the hopper and to the rotating paddle in order to open up the bundles of asbestos and liberate more fibers into the atmosphere.

2. The composition of the long-fiber asbestos used in this experiment is indicated by the chemical and petrographic analyses given in Table 14. It appears that this material was a much purer form of asbestos than the short-fiber dust used in other experiments. This is borne out by comparing the approximate analyses of the long-fiber and short-fiber dust in Table 15.

3. The dust concentration as revealed by impinger samples taken inside the animal cages was much lower than the concentration for the experiments with short-fiber or ball-milled dust. For the first year of the experiment with long-fiber asbestos the average of the light field counts was 32 million; for

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...second year, 48 million; for the third year, 39 million; and for the fourth ..., 13 million. Examination of the impinger samples with dark field illumination disclosed that many fine particles less than one micron in size accompanied the larger particles and dark field counts were, on the average, about 5 or 6 ...s larger than the light field counts.

...2. The size-frequency of atmospheric samples of the long-fiber asbestos dust and of the ball-milled dust is shown in Table 16. Both samples were collected with the electrostatic precipitator. It will be noted that there ... more fibrous material in the long-fiber dust.

...3. Reaction in Animals to Inhaled Long-Fiber Asbestos Dust. Guinea pigs, cats, rats and mice were employed in the inhalation experiment with long-fiber asbestos. Results of the experiment, summarized in Table 17, are discussed in greater detail below.

...a. Guinea Pigs. The experiment was started with 100 guinea pigs. After exposure had been carried on for a year, a severe epidemic of pneumonia arose in the dust room and about one-third of the animals died or were killed. To replace them, 38 more guinea pigs were added to the surviving ones in the dust room.

...b. Rate and Type of Reaction. Histological examination revealed grossly visible lesions in the lungs after 8 months of exposure to dust, consisting of cellular infiltration about the terminal bronchioles. At 12 months, there were adenomatoid changes in the air spaces and ... the 16th month a definite fibrosis was present in these areas in half the animals. The fibrous lesion could be seen macroscopically at 20 months. From this time on the reaction increased in extent and in the amount of collagen and

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[illegible] month, it had fanned out into the parenchyma. The lesions were [illegible]ly localized and the extensions from different bronchioles showed [illegible]ency to fuse, even in animals exposed for the maximum period (3 years). [illegible] the intra-pulmonary reaction sometimes reached the pleura, there was no [illegible]ment of that membrane. No emphysema was visible at any point. Some [illegible]ng of the larger bronchi with a chronic inflammatory infiltration was re- [illegible]ut it probably was no more than would be produced by a similar exposure [illegible]ust. For the first 5 months the phagocytes consisted of monocytes or [illegible]l giant cells; later, giant cell formation was more prominent. After [illegible] the giant cells were large, filled with yellowish-brown pigment and [illegible] vacuolated. An occasional animal showed an admixture of polymorpho- [illegible] leukocytes and, in guinea pigs exposed for a considerable period, [illegible]cells. The reaction was at first entirely cellular but by 15 months fi- [illegible] tissue formation was definite. However, it never attained a stage of [illegible]ation suggestive of silicosis.

[illegible]derate individual variation occurred among the exposed animals, both in [illegible] of developing lesions and in the stage of development attained at the [illegible] exposure.

[illegible]lyses of the lungs (Table 18) disclosed that although the tissue response [illegible] much greater in these guinea pigs than in those exposed to either short-fiber [illegible] ball-milled asbestos, the amount of mineral matter in the lung ash was less.

[illegible]. Progression. In guinea pigs exposed to the dust for 20 months and then removed to normal air, there was a marked tendency for [illegible]ellular inflammatory reaction to clear. This effect, accompanied by contraction [illegible] the fibrous tissue, resulted in a diminishing size of the focal lesions. None

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[illegible] animals, killed at various periods up to 14 months after exposure, [illegible] lesions as large as those in the group sacrificed at the end of the [illegible] exposure period, or those in animals which remained in the dust room [illegible] more than 20 months. Fourteen months after dust exposure ceased, the foci [illegible] four of the six remaining guinea pigs were so small that they were visible [illegible] with a hand lens.

Reaction in the group exposed for 27 months and then transferred to a normal atmosphere was quite similar to the response in the 20-month exposure animals mentioned above. However, small foci were always visible on gross inspection of sections of all guinea pigs of the 27-month series but in no instance was there evidence of extension of the reaction.

67. Lymph Node Involvement. Reaction in the tracheobronchial lymph nodes was first visible at the third month of exposure. At the 8th month patches of cellular connective tissue began to appear in the medulla and by the 14th month most of the node had been replaced by cellular connective tissue. This picture, which resembled that in early silicosis, persisted to the end of the experiment. Some animals, as a variant, showed heavy sheets of diffuse monocytes and large active giant cells but there was never any necrosis or hyaline formation. The spindle-shaped new cells were yellowish in color from fine pigment granules that stained for iron. No fibers or asbestosis bodies were seen.

68. Asbestosis Bodies. Although asbestosis bodies were seen in the lung as early as one month after exposure began, they were rare and hard to find. At 5 months more were visible, chiefly coiled inside giant cells, and at 8 months many bodies were free in connective tissue. They became fairly abundant as exposure continued although in some later animals the asbestosis bodies were only moderately numerous.

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73. Rate and Type of Reaction. All four animals sacrificed at 25 months showed a well-marked peribronchiolar fibrosis. In the 19-month animal, reaction was just beginning. Asbestosis bodies were practically absent at both 19 and 25 months although two small smooth bodies were found in the 19-month animal after a long search. Thus, these animals exhibited fibrosis without asbestosis bodies.

74. Mice. Out of 20 white mice used in this experiment, 11 lived a year or more in dust and died or were killed without showing an appreciable degree of pulmonary infection.

75. Rate and Type of Reaction. Reaction was limited to phagocytosis by mononuclear cells. Usually these were widely scattered through the air spaces; a limited number were grouped about the terminal bronchioles producing some thickening of their walls. There was no suggestion of fibrosis.

Numerous asbestosis bodies were observed in animals killed late in the experiment. Thus, these animals exhibited asbestosis bodies without fibrosis.

76. Summary and Interpretation.

The purpose of this experiment was to evaluate the importance of long fibers in the tissue response to inhaled asbestos. The results indicate strongly that long fibers are chiefly responsible for the reaction. Thus, in guinea pigs reaction developed earlier and became more extensive than in previous experiments in spite of a smaller concentration of atmospheric dust and a lower mineral content in the lungs. Furthermore, a typical peribronchiolar fibrosis was produced in cats although in a previous experiment with short-fiber dust it did not develop in this species.

The cause of the cellular fibrosis in the lymph nodes of the guinea pigs is not clear. It did not occur in other inhalation experiments with asbestos.

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LXXVII

I N J E C T I O N E X P E R I M E N T S

In order to determine to what extent the various fibrous minerals possess the capacity to produce tissue damage, numerous injection experiments were performed. In these experiments guinea pigs and rabbits were used and the mineral dust was injected by the intratracheal, intraperitoneal and intravenous techniques. For the purpose of simplification the findings in each series of tests have been condensed and reported in tables, to which reference will be made later.

78. Experiments Using Intratracheal Technique.

Since the asbestos minerals do not cause a typical advanced fibrosis in extra-pulmonary tissue, the intratracheal technique is the preferred way of introducing fibrous dust into the experimental animal. In this method the dust suspension is injected by means of a special needle or catheter deep into the trachea, from which it flows into the lungs.

79. Comparison of Fibrous and Non-Fibrous Dusts. To demonstrate that the ability of asbestos to produce fibrosis resides in its fibrous character, the series of injection experiments reported in Table 19 were performed. The tests were made with unheated long-fiber chrysotile and with chrysotile that had been ignited to destroy its flexible structure or ball-milled to reduce the length of fiber to 3 microns and less. At the same time control tests were made with serpentine, which has the same chemical composition as chrysotile but is non-fibrous. A review of the findings reveals that only the unheated long-fiber chrysotile produced fibrosis. Fibers subjected to ignition or shortened by ball-milling had lost their capacity to cause serious tissue damage. Ignition produced important changes in the

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chrysotile fibers, among them being loss of water, an alteration from a flexible to a brittle structure and possibly other changes.

80. Comparison of Various Long-Fiber Dusts. Some very interesting findings are disclosed by the results of the experiments included in Table 20. First, all the long-fiber asbestos minerals tested, with the exception of anthophyllite, produced a typical fibrosis. It is not entirely clear why anthophyllite behaved differently from the other asbestos minerals. Unfortunately, 5 of 8 animals died of pneumonia within the first two weeks of the experiment and the remaining animals were sacrificed at 1, 8 and 12 months; thus observations were not made at the optimum periods of 2 and 4 months.

Second, with the mineral brucite, which is not a silicate but is a fibrous form of magnesium hydroxide, a characteristic fibrosis like that of the asbestos minerals was obtained. Since the brucite used contained only 0.90 per cent silica (as an impurity), it is obvious that a siliceous component is not an essential factor in the development of asbestosis.

Third, no fibrosis resulted from the injection of glass wool fibers, even though glass wool resembles asbestos in some ways. There are fundamental differences, however. A glass wool fiber 3 microns in diameter is a solid rod and, in short lengths, is fairly rigid, while an asbestos fiber of the same diameter is a bundle of extremely fine filaments which impart to the fiber a high degree of flexibility. It would seem that this structure and the associated flexibility are important factors governing the capacity of a mineral to produce peribronchiolar fibrosis.

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61. Comparison of Long-Fiber and Short-Fiber Dusts. With quartz dust it has been demonstrated that the smaller the particles, the more intense is the tissue reaction, and that there is little reaction to particles larger than 3 microns in diameter. In the case of asbestos, however, the reverse is true and apparently only long fibers have any specific effect. This is confirmed by the data of Table 21, in which a series of tests with fibrous minerals is reported. When the injected dust consisted of fibers 20 to 40 microns long, all the minerals tested (except anthophyllite, as noted in Section 30) produced a fibrosis; when the material was prepared by first grinding the fibrous dust until the length of fibers was reduced to 20 microns and less (or, in some cases, 3 microns and less), none of the injected mineral dusts caused fibrosis.

62. Experiments Using Intravenous Technique.

The experiments, described in Table 22, in which the intravenous method of injection was employed, show that the asbestos minerals are far different from quartz in their action on tissue. It has been repeatedly demonstrated that intravenous injection of quartz particles 3 microns and less in diameter will cause a typical tissue reaction with the development of hyalinized fibrotic lesions in extra-pulmonary sites, such as the liver and spleen. Asbestos minerals, however, on intravenous injection generally produce only an inert type of reaction, as is revealed by the results given in the table. The reason for the early deaths in the experiment with chrysotile particles is not clear: it may have been caused by silicic acid liberated by the finely-ground mineral.

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Intratracheal Daily Intraperitoneal Technique.

The results of injection experiments with the intraperitoneal technique are given in Table 28. It will be noted that the long-fiber dusts produced a fibrous reaction while dusts composed of particles shorter and less in size caused only the inert type of response. These experiments indicate also that the fibrosis produced by the irritation of asbestos fibers is not restricted to the lungs, as was formerly assumed, but can be produced in the peritoneum as well.

XXIV

THE EXPERIMENTAL ASBESTOSIS MINERALS

A number of additional experiments were conducted to throw more light on specific phases of the asbestosis problem.

1. Protective Action of Aluminum Compounds.

Intratracheal injection of a suspension of long-fiber chrysotile to which colloidal aluminum hydroxide had been added revealed that the addition of the aluminum compound did not prevent the tissue irritation produced by chrysotile. If anything, the acute inflammatory response to the injected fibrous mineral was accelerated. One month after the last injection of the dust suspension the bronchiolitis was becoming fibrous.

2. Formation of Asbestosis Bodies.

The iron in the coating of the asbestosis bodies appears to be derived from dietary or tissue elements and not, as has been suggested, from the mass of fiber. Following subcutaneous injection of two kinds of chrysotile into the groin of guinea pigs - one kind containing 2 per cent and the other 0.2 per cent iron - the asbestosis bodies were equally numerous in both sites of injection.

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[illegible] attempt to produce asbestosis device in guinea pigs by implantation of [illegible] sack bags containing fibrous chrysotile was unsuccessful. One bag planted [illegible]aneously in the abdominal wall disappeared; the other two bags, placed in [illegible] peritoneal cavity, produced a little foreign body reaction but no asbestosis [illegible] in a year.

[illegible] intratracheal injection into guinea pigs of asbestosis bodies recovered from [illegible] lung tissue failed to produce the typical tissue reaction to asbestos [illegible]. The injected material was obtained by digesting with sodium hypochlorite [illegible] lung tissue removed at autopsy from an asbestos worker. The asbestosis [illegible] could be seen in the guinea pigs for at least a year after injection. [illegible] experiment shown that the asbestosis body has a rather resistant coating [illegible] is not destroyed by moderate hypochlorite treatment and may be maintained [illegible] alive for a year or longer.

LXXXVII
THEORY OF INERT ACTION

Two hypotheses have been proposed to explain the tissue irritation and reaction caused by asbestos fibers: the chemical and the mechanical. In the chemical theory, which is based upon experience with quartz, it is assumed that the asbestos minerals dissolve in the body fluids and that in this process their bases are leached away to leave silica in a form capable of irritating tissues. According to this hypothesis, asbestosis would be merely an indirect silicosis. Several facts make the chemical theory untenable: (1) Intratracheal injections of brucite fibers, which have a silica content of only 0.70 per cent, caused a typical fibrosis like that produced by the asbestos minerals; (2) Precipitin particles increase in potency as the particles size becomes less, but asbestos fibers shorter than about 10 mu do not produce a detectable fibrosis; (3) aluminum

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...oxide neutralizes the irritating effect of quartz but not of asbestos; ...serpentine has the same chemical composition as long-fiber chrysotile but ...does not produce the same kind of tissue reaction; (5) there is a wide range ...in the chemical composition of the minerals which do cause asbestosis (see ...Table 24). In view of this evidence it seems more likely that asbestosis is ...caused by an unusual mechanical irritation from long asbestos fibers; this ...irritation being related to the peculiar filamented structure of the fiber and ...its associated flexibility, which are possessed by no other foreign body. For ...example, ignition of chrysotile fibers changed their structure and made them ...inert while the same fibers, before being heated, produced fibrosis (see Table ...). Further support for the theory of mechanical irritation is that asbestosis ...occurs in an organ of high mobility - the lung - and that a fibrous reaction can ...be produced by injection of asbestos fibers into the peritoneum, where there is ...also a degree of mobility, but not in other extra-pulmonary organs.

LXXXVIII
C O M P L I C A T I O N S

The experimental investigation with asbestos minerals was concerned primarily with the effect of the dust on normal tissue but some attention was given to other phases, such as susceptibility to infection and occurrence of malignancy.

1. Infection.

The only experiment in which the effect of inhaled asbestos dust on a pulmonary infection was studied was the first inhalation experiment, carried on with "King's floats" dust. It is, perhaps, unfortunate that infection studies were not made in the other inhalation experiments also.

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90. Susceptibility to Tuberculous Infection. The development of a tuberculous process initiated at the beginning of exposure to asbestos dust, and also of an infection superimposed on an established asbestosis, was described in Sections 19 and 20 of this report. It will be noted that asbestos, when classified according to the effect of dust on tuberculous infection, would be placed below an active dust like quartz but above inert dusts, such as calcite and gypsum. In animals infected with attenuated tubercle bacilli, quartz will cause the infectious process to progress until the animal dies of tuberculosis. Inert dusts will have no effect on the infection and the lesions will usually heal and the disease disappear. Asbestos dust is in a different category. When the fibrous dust was being inhaled during the evolution of the infection, there was a spreading of the tuberculous process for a time but usually the stimulus for continued proliferation of the tubercle bacilli was not sustained, the progression was arrested and healing followed. In guinea pigs infected with attenuated tubercle bacilli following the inhalation of nearly three years of exposure to asbestos dust, progressive disease did not develop. The only modification of the infection was one of localization, a few bacilli being retained in the fibrous terminal bronchioles and forming tubercles there in addition to the usual foci beneath the pleura. Such tubercles healed in a few months and there was nothing to suggest any influence on the course of the disease.

91. Susceptibility to Non-Tuberculous Infection. There was no pointed experiment concerning the effect of inhaled asbestos dust on non-tuberculous infection. Intercurrent pneumonia among animals exposed to asbestos dust was rather common, the frequency in guinea pigs exposed in the four inhalation experiments ranging from 16 to 39 per

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...at. This incidental evidence suggests the possibility of an effect of ...bestos dust on non-tuberculous infection. Nevertheless, since such epidemics ...re not uncommon in inhalation experiments with other dusts and even in the ...olony of normal animals, it is felt that the inhalation of asbestod dust does ...ot exert a significant effect on the susceptibility to non-tuberculous ...ulmonary infection.

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S U M M A R Y

Owing to the vast amount of data included in this report it seems most convenient to state as precisely as possible the various points which emerged from the investigations and, when necessary, follow each with a brief resume of the evidence.

A. Various forms of asbestos fibers produce a peribronchiolar fibrosis of the lungs of guinea pigs, rats, cats and rabbits but not of mice and dogs.

Both inhalation and injection experiments provide ample support for this statement. Figures 5 and 6 show the reaction to two different kinds of asbestos mineral in the guinea pig lung. Similar but less extensive fibrosis occurred also in rats, cats and rabbits (Table 1). Mice and dogs failed to respond. This variation in response of different species to identical dust exposures is still to be accounted for.

B. The mode of action of the asbestos fiber is primarily mechanical rather than chemical in nature.

The evidence for this is given in Section LXXXVII. Figures 1, 2, 3, 4 and 7 illustrate the important points. The fibrous filamented structure of asbestos plays an essential part in the irritating action, since the solid fibers of glass wool do not produce fibrosis (see Figure 8).

C. Long asbestos fibers are essential in the production of peribronchial fibrosis; short fibers are incapable of producing this reaction.

Experimental evidence discloses that fibrosis develops following the injection of asbestos fibers between 20 and 50 microns in length, but not following injection of particles less than 20 microns, (Tables 21 and 23). This shows that the capacity to produce fibrosis develops somewhere between 20 and 50 microns.

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studies have not been carried out to determine the upper
of effective fiber length. It appears, however, that that
will be determined by the inhalability of the fiber.

Experimental asbestotic fibrosis was produced by the inhalation of
an aeroscopic suspension containing an average of 135 million particles
per cubic foot of air of which only 0.6 per cent consisted of fibers longer
than 10 microns.

In the inhalation experiment with 100 per cent ball-milled
asbestos dust containing 0.6 per cent of fibers longer than 10
microns (Section 46 to 57 inclusive) a typical fibrosis was ob-
tained (see Table 12). The evidence presented shows at least that
an atmospheric concentration of asbestos dust containing 0.8 mil-
lion (0.8% = 133,000,000) fibers greater than 10 micronsper cubic
foot of air is capable of producing experimental asbestosis. The
actual lower limit of concentration of long fibers necessary to
produce asbestosis cannot be established on the evidence available.

The duration of exposure required to develop the pulmonary reaction to in-
haled asbestos dust is inversely proportional to the concentration of long
fibers in the atmosphere, viz. as the concentration is increased, the
reaction develops in shorter time.

Evidence for this statement is presented in the inhalation
experiment with Long-fiber Asbestos Dust (Sections 58 to 76
inclusive). Study of the size-frequency of the long-fiber dust
discloses that it contained 8.7 per cent of fibers greater than
10 microns in length (Table 16). The lungs of animals exposed to
this dust revealed that the pulmonary reaction developed in approx-
imately one-half the exposure time required for its development in
animals subjected to the ball-milled dust, which contained only 0.6
per cent of long fibers.

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...ained experimental asbestosis ceases to progress on discontinuing ...ure to the dust.

...idence shows in fact that on discontinuing exposure there was ...preciable clearing of the mature pulmonary lesions due to ...raction of the fibrotic reaction. In contrast, an immature ...me response consisting primarily of cells with little or no ...osis continued to progress. It is assumed that following at- ...ment of fibrotic maturity, the same process of contraction ...ld ensue (Section 57).

...ormation of asbestosis bodies represents a coating of the fibers by ...t and tissue elements which results in loss of ability of the fiber ...educe fibrosis.

...ntratracheal injection of asbestosis bodies failed to produce ...typical asbestotic tissue reaction in experimental animals ...ction 86). The cessation of progressive reaction to inhaled ...estos dust soon after exposure terminates may be due to the ...mation of asbestosis bodies.

...inum hydroxide failed to neutralize the fibrosing action of the long ...er asbestos (Section 65).

Inhalation of asbestos dust did not alter significantly the final outcome of experimental tuberculosis in two series of guinea pigs exposed.

This interpretation is in distinct contrast to the stimulating effect of inhaled quartz upon a tuberculous process in the lung. It must remain tentative, however, since it is based upon evidence limited to two series of guinea pigs exposed to only one kind of asbestos, namely "King's floats" (Section 19-20, 90). Reference to Table 3 shows that when infection was coincident with onset of dust exposure, there was temporary progression of the infectious process with subsequent healing; when infection was initiated after 25-3/4 months of dust exposure the course of the tuberculosis was not

(Continued on Page 42a)

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...ably altered. This latter finding is in marked contrast with ...mal experience involving quartz dusts or mixed dusts containing ...in wherein the adverse influence of quartz upon a tuberculous ...ion is most strikingly manifested where infection is initiated ... a period of dust exposure, viz. superimposed upon a background of ... hed silicosis. As indicated above, application of this more ...tive test to asbestos dust failed to demonstrate that such dust ... adverse influence upon a tuberculous infection. Thus, there ...ong evidence in support of the interpretation. However, it is ...mended that further investigation be undertaken to establish ... point.

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Table 1

REACTION TO LONG-FIBER CHRYSOTILE

IN LUNGS OF MAN AND OTHER SPECIES OF ANIMAL

Species	Mode of Exposure	Fibrosis	Asbestosis Bodies
Man	Inhalation	4+	4+
Guinea Pig	Inhalation and injection	2+	3+
"	" " "	+	±
"	" " "	+	±
White Mouse	Inhalation	0	±
White Rat	Inhalation and injection	+	0
"	Injection	0	0

± Very small atypical asbestosis bodies.

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Table 3

ANALYSES OF KING'S FLOATS ASBESTOS

Chemical		Determinable*	
[illegible]	38.22%	Chrysotile	145
[illegible]	43.24	Serpentine	40
[illegible]	2.37		
[illegible]	12.38	Magnetite	12
[illegible]	2.37	Carbonates	13
[illegible]			
[illegible]	1.24	Talc	12
	100.00	Others	4
			100

*Values given are based on the number of particles, except chrysotile, smaller than 10 microns; for chrysotile fibers the maximum dimension was 300 microns.

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Table 3

SUMMARY OF INHALATION EXPERIMENTS

WITH

"KING'S FLOATS" ASBESTOS DUST

...e of ...riment	Number of Animals	Maximum Dust Exposure	Maximum Survival after Dust Exposure	Results
...posure con- ... through- ...	34 g. pigs	33 months	0 months	Typical peribronchiolar fibrosis.
	9 rabbits	19	0	Foreign body bronchitis.
	13 rats	6	0	Little or no reaction.
... exposure ... ed by a pro- ... residence ... nal air.	25 g. pigs	3 months	35 months	Nonprogressive fibrosis.
	25 g. pigs	3-3/4	37	Nonprogressive fibrosis.
	1 rabbit	6	30	Absorption of foreign body reaction.
	1 rabbit	16-2/3	34-1/3	
...neous in- ...ons at start ... dust exposure.	40 g. pigs	33 months	0 months	Temporary progression of infection followed by healing with fibrosis.
...rols to in- ...ion; no dust ...sure.	23 g. pigs	0 month	33+*	Healing by resolution (one exception).
...neous in- ...ion" after ... 3/4 months of ... exposure, ... residence in ... nal air.	12 g. pigs	33-3/4	14	No appreciable increase in susceptibility to tuberculous infection. Healing with fibrosis.
...rols to in- ...ion; no dust ...sure.	12 g. pigs	0 month	13-1/2+*	Healing by resolution.

* With low-virulent strain of tubercle bacillus
** After infection.

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Table h

ANALYSES OF SHORT-FIBER ASBESTOS (CHRYSOTILE)

(as received)

Chemical		Petrographic
SiO_2	37.17%	The material contains a predominance of fibrous chrysotile and platy (non-fibrous) serpentine. Accessory minerals are dolomite, chromite, magnetite and a little tremolite and actinolite. Non-uniform size distribution. Fibrous bundles vary from about 45 microns to 1 micron. More fibers than in Ring's floats.
Fe_2O_3	9.03	
Al_2O_3	1.10	
Cr_2O_3	0.14	
MnO	0.09	
CaO	0.35	
MgO	35.96	
Na_2O	0.14	
K_2O	0.10	
Co	0.93	
H_2O (ignition loss)	14.03	
	100.12	

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Table 1

DISTRIBUTION OF ASBESTOS DUST

ACCORDING TO SIZE GROUPS

FOR

VENTILATION EXPERIMENTS WITH STEAM-JET AGITATION

Size	North wall	East wall	South wall
microns	per cent	per cent	per cent
< 1	10.1	11.0	10.0
1-3	54.5	38.0	14.0
3-5	10.4	10.4	5.5
5-10	7.4	6.1	4.2
5-10	5.0	5.7	3.4
> 10	1.7	1.3	3.4
	100.1	100.5	100.0

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Table 3

SUMMARY OF INHALATION EXPERIMENT

WITH

SHORT-FIBER ASBESTOS (CHRYSOTILE)

Nature of Experiment	Number of Animals	Maximum Dust Exposure	Maximum Survival After Dust Exposure	Results
Dust exposure continuous throughout	46 g pigs	33 months	0 months	Rate of reaction about the same as in experiment with King's floats asbestos but extent of involvement very much less. See Note Below. **
	73 rats	32	0	Only slight reaction: no asbestosis bodies.
	18 cats	33-2/3*	0	Reaction essentially that to an inert dust.
	7 rabbits	46-3/4*	0	No fibrosis seen grossly; microscopic evidence of alveolar wall thickening after 40 months exposure.
Dust exposure followed by a prolonged residence in normal air.	13 g. pigs	30 months	13-2/3 months	Progression after removal from dust doubtful; neither clearly established nor definitely excluded.
	2 cats	31-1/2	24	Same as for continuous exposure.
	1 rabbit	42*	6	Similar to continuous exposure; evidence of slight regression.

* Exposure after 33 months was to 100 per cent ball-milled asbestos.

** Reaction probably due to [illegible] fibers in the unground material which was mixed with the ground asbestos dust to produce a satisfactory dust cloud. Refer to text, page 14

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Table 7

ANALYSES OF LUNGS OF GUINEA PIGS AFTER PROLONGED INHALATION OF SHORT-FIBER ASBESTOS (CHRYSOTILE)

		Time from beginning of dust exposure					
		[illegible] 12	[illegible] 15	[illegible] 20	[illegible] 21	[illegible] 20	[illegible] 33 3/4
	Exposure to dust Period in normal air	12 0	15 0	20 0	21 0	20 0	33 3/4 0
Dust Exposure Continuous During Life	Amount of ash (per cent of dried lung)	per cent 5.02 4.58 5.16	per cent 5.00 4.86 4.95	per cent 5.06 5.43	per cent 5.42 5.50	per cent 5.85 5.85	per cent 6.06 6.05
	Total SiO_2 (per cent of dried lung)	0.51 0.45 0.64	0.49 0.43 0.53	0.85 0.80	0.73 0.78	0.85 1.17	0.75 0.96
	Total SiO_2 (per cent of ash)	10.23 10.08 10.54	9.86 9.00 10.60	14.66 14.07	11.43 11.20	17.00 19.00	12.37 15.11
	Tissue Reaction*	±	±	2+	3+	[illegible]	[illegible]
Dust Exposure Followed by Prolonged Residence in Normal Air	Exposure to dust Period in normal air	months - -	months - -	months - -	[illegible] months 20 4	[illegible] 20 10	months [illegible] 10 3/4
	Amount of ash (per cent of dried lung)	per cent -	per cent -	per cent -	per cent 5.16 5.11	per cent 5.11 3.00	per cent 4.77 5.13 4.71
	Total SiO_2 (per cent of dried lung)	-	-	-	0.48 0.16	0.60 0.34	0.25 0.20 0.22
	Total SiO_2 (per cent of ash)	-	-	-	9.30 3.16	10.21 8.51	5.31 5.00 4.60
	Tissue Reaction*	-	-	-	2+	3+	2+

*The symbols merely represent the relative degree of reaction, ranging from ± (questionable) to 4+ (the maximum for this experiment). The relationships apply only within this table, and cannot be compared with symbols in other tables.

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Table 6

ANALYSES OF LUNGS OF WHITE RATS

THAT HAD INHALED

SHORT-FIBER ASBESTOS (CHRYSOTILE)

	Duration of Exposure					
	0 months*	2 months	4 months	6 months	8 months	10 months
	per cent	per cent	per cent	per cent	per cent	per cent
Amount of ash (per cent of dried lung)	3.0 4.3 2.9 3.8 3.3 3.0 3.4	3.8 3.6 2.9 3.2	3.3 3.6 3.4	3.3 2.4 3.7	3.9 3.6 3.5 4.4 3.7	4.9 4.6 5.3 4.7
Total SiO_2 (per cent of dried lung)	0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.08 0.13 0.09 0.05	0.09 0.11 0.07	0.07 0.05 0.04	0.08 0.12 0.15 0.17 0.13	0.18 0.15 0.15 0.13
Total SiO_2 (per cent of ash)	0.0 0.0 0.0 0.0 0.0 0.0 0.0	2.1 3.6 3.3 1.5	2.3 3.0 2.2	2.1 1.5 1.1	2.2 5.5 3.4 4.0 4.2	3.8 3.3 2.8 2.8

* Normal controls (no dust exposure)

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Table 10

COMPOSITION OF

100 PER CENT BALL-MILLED ASBESTOS DUST

	Short-fiber Asbestos Used in Dusting Machines per cent	Atmospheric Dust Collected with Precipitator per cent
Tremolite	17	15
Serpentine	55	60
Magnetite	10	10
Quartz	2	2
Biotite	5	3
Limonite	0	0
Other Minerals	11	10
	100	100

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Table 11

SIZE-FREQUENCY OF ATMOSPHERIC DUST

COLLECTED INSIDE CAGES

FOR

INHALATION EXPERIMENT WITH 100 PER CENT BALL-MILLED ASBESTOS DUST

		Sample taken before wire brushes installed	Sample taken after wire brushes installed
		per cent	per cent
Distribution of Particles, Clumps and Fibers	Particles and clumps	98.7	98.6
	Fibers	1.3	1.4
		100.0	100.0
Size-frequency of Particles	< 3 microns	86.1	95.0
	3-10	11.9	5.0
	> 10	2.0	0.0
		100.0	100.0
Size-frequency of Fibers	< 3 microns	22	0
	3-10	44	58
	> 10	34	42
		100	100

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Table 13

ANALYSES OF LUNGS OF GUINEA PIGS

EXPOSED TO DUST II

[illegible] STRAIGHT SILICA 100 PER CENT BALL MILLED ASBESTOS DUST

		Time from beginning of dust exposure								
		months 1	months 2	months 3	months 5	months 8	months 12	months 16	months 20	months 24
Dust Exposure Continuous During Life	Exposure to dust Period in normal air	1 0	2 0	3 0	5 0	8 0	12 0	16 0	20 0	24 0
	Per cent of ash (per cent of dried lung)	per cent 1.85 4.30 4.35	per cent 4.00 4.00 5.05	per cent 5.30 5.07 5.74	per cent 4.30 4.93 5.01	per cent 4.05	per cent 5.56 6.24	per cent 5.80 6.03	per cent 5.85 5.79	per cent 5.30 5.50
	Total SiO_2 (per cent of dried lung)	0.21 0.30 0.24	0.23 0.34 0.61	0.70 0.32 0.56	1.31 0.31 0.32	0.52	1.26 1.65	1.02 1.11	1.21 1.79	1.03 1.21
	Total SiO_2 (per cent of ash)	4.23 7.05 5.69	4.90 7.40 12.01	12.47 3.36 9.77	7.51 6.17 7.73	11.86	22.16 23.23	18.26 23.05	22.99 24.62	17.05 21.77
	Tissue Reaction*	0	0	±	±	0	0	±	±	±

		Time from beginning of dust exposure		
		months 30	months 36	months 40
Dust Exposure Followed by Prolonged Residence in Normal Air	Exposure to dust Period in normal air	20 2	28 8	29 12
	Per cent of ash (per cent of dried lung)	per cent 7.25 8.67	per cent 6.25 5.96	per cent 6.30 5.17
	Total SiO_2 (per cent of dried lung)	1.57 2.19	0.68 0.87	0.64 0.64
	Total SiO_2 (per cent of ash)	21.63 25.24	13.39 14.55	13.03 12.41
	Tissue Reaction*	+	+	2+

*The symbols merely represent the relative degree of reaction, ranging from 0 to ±(questionable) to 2+ (the maximum observed in this experiment. The relationships apply only within this table and cannot be compared with symbols in other tables.

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Table 14

ANALYSES OF LONG-FIBER ASBESTOS DUST

(as received)

Chemical	
SiO_2	38.40%
Fe_2O_3	1.82
Al_2O_3	0.78
MnO	0.02
CaO	0.31
MgO	40.16
Na_2O	0.06
K_2O	0.06
CO_2	0.37
H_2O	14.00
	99.76

Petrographic

The material contains about 75 per cent of fibrous asbestos, probably chrysotile, with some serpentine and small amounts of calcite, magnetite and chloritic or micaceous minerals. Only a trace of quartz was seen. There were shreds of non-separated fibers 10 to 50 microns long and 5 to 15 microns wide.

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Table 25

COMPARISON OF APPROXIMATE ANALYSES OF

LONG-FIBER AND SHORT-FIBER ASBESTOS DUST

	Long-Fiber		Short-Fiber	
	Original Material	Atmospheric Dust	Original Material	Atmospheric Dust**
	per cent	per cent	per cent	per cent
›tile	75	80	17	15
›atite	15	10	55	60
›tite	5	3	10	10
›z	tr	3*	2	2
›ite	2	4	5	3
›atite	0	10*	0	0
›or	3	-	11	10
	100	100	100	100

* Contamination from other dusts.

** Atmospheric sample was 100 per cent ball-milled dust.

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Table 16

COMPARISON OF SIZE-FREQUENCY OF ATMOSPHERIC LONG-FIBER AND BALL-MILLED ASBESTOS DUST COLLECTED INSIDE CAGES

		Long-Fiber	Ball-Milled
		per cent	per cent
Grains	< 3 microns	65.4	90.6
	3-10	1.1	4.8
	> 10	0.0	0.0
Fibers	< 10	25.8	0.8
	> 10	6.7	0.6
Clumps		1.0	3.2
		100.0	100.0

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Table 17

SUMMARY OF INHALATION EXPERIMENT

WITH

LONG-FIBER ASBESTOS

Nature of Experiment	Number of Animals	Maximum Dust Exposure	Maximum Survival After Dust Exposure	Results
Dust exposure continuous throughout life	117 g. pigs	36 months	0 months	Definite fibrosis in 16 months.
	4 cats	42	0	Slowly developing fibrosis first seen at 24 months.
	20 rats	35	0	Marked peribronchiolar fibrosis first seen at 24 months.
	20 mice	35	0	Limited reaction; no fibrosis.
Dust exposure followed by a prolonged residence in normal air	12 g. pigs	20 months	24 months	Clearing of inflammatory reaction and definite contraction of fibrosis.
	9 g. pigs	37 months	9	Clearing of inflammatory reaction and slight contraction of fibrosis.
	2 cats	18	24	Similar to continuous exposure group; suggestion of progression in one of the two animals.

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		Time from beginning of dust exposure												
		[illegible]	[illegible]	[illegible]	month 5	month 8	months 12	months 16	months 20	months 24	months 27	months 30	months 34	months 38
	[illegible]	1	2	3	5	8	12	16	20	24	27	30	34	38
	[illegible]	0	1	0	0	0	0	0	0	0	0	0	0	0
		per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
	[illegible]	[illegible]	[illegible]	[illegible]	4.77	4.12	4.07	2.90	3.54	3.42	3.09	3.53	6.05	4.10
	[illegible]	4.35	[illegible]	[illegible]	4.63	4.02	5.02	2.93	3.60	3.68	3.74	5.05	6.70	2.74
		[illegible]	[illegible]	4.51	5.09	4.34	5.10	3.10	3.69			3.02		
	[illegible]	0.08	0.05	0.05	0.09	0.10	0.26	0.20	0.43	0.36	0.39	0.37	0.60	0.37
	[illegible]	0.07	0.05	0.05	0.12	0.09	0.20	0.05	0.49	0.53	0.49	0.36	0.84	0.55
		[illegible]	[illegible]	0.06	0.09	0.07	0.31	0.06	0.62			0.28		
	[illegible]	1.10	1.07	1.20	1.76	2.21	6.20	12.70	12.32	10.15	11.51	10.66	8.60	8.11
	[illegible]	2.11	1.13	1.13	2.67	1.90	4.09	12.25	13.05	8.60	10.15	11.32	12.47	12.80
		[illegible]	1.10	1.43	1.77	1.68	5.09	10.01	10.69			6.10		
	[illegible]	0	±	±	±	+	+	2+	2+	3+	3+	4+	4+	4+

		Time from beginning of dust exposure								
		[illegible]	months 42	months 46	months 50	months 54	months 58	months 62	months 66	
	[illegible]	39	42	46	50	54	58	62	66	
	[illegible]	0	1	10	14	0	5	7	9	
		per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	
	[illegible]	5.51	2.09	4.16	6.01	3.10	3.66	3.10	3.21	
	[illegible]	5.53	2.10	4.00	5.04	3.74	2.64	3.19	2.76	
		7.36								
	[illegible]	0.13	0.21	0.24	0.21	0.30	0.31	0.25	0.29	
	[illegible]	0.19	0.27	0.22	0.16	0.49	0.19	0.28	0.23	
		0.28								
	[illegible]	12.72	7.23	5.75	4.19	11.61	8.09	7.99	8.93	
	[illegible]	13.65	9.50	5.07	3.68	13.15	8.54	8.72	8.61	
		14.52								
	[illegible]	2+	2+	2+	+	3+	2+	2+	2+	

[illegible] ranging from 0 to ± (questionable) to 4 + (the maximum for this experiment). [illegible] with symbols in other tables.

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Table 19

COMPARISON OF REACTION TO CHRYSOTILE AND SERPENTINE

INJECTED INTRATRACHEALLY

Dose

Each animal was injected intratracheally with 0.5 cc of a 5 per cent suspension of the dust. Two weeks later another similar injection was given. Total amount of dust injected = 50 mg.

Animals Used

Six groups of 9 guinea pigs each (one group for each type of dust).

Sacrificing Periods

One or two animals in each group at 1, 2, 6, 8-1/2 and 12 months after injection.

Preparation of Dust

Chrysotile (ball-milled) unheated: Ball-milled for 1176 hours, dried and reground in agate mortar.

Chrysotile (ball-milled) ignited: Ball-milled chrysotile heated for 2 hours at about 700° C., then ground in agate mortar 2 or 3 minutes.

Chrysotile (fibrous) unheated: Ground in agate mortar to pass 200 mesh.

Chrysotile (fibrous) ignited: 200-mesh material heated for 2 hours at about 700° C. No further grinding.

Serpentine (ball-milled) unheated: Ball-milled for 1438 hours, dried and reground in agate mortar.

Serpentine (ball-milled) ignited: Ball-milled serpentine heated for 2 hours at about 700° C., then ground in agate mortar 2 or 3 minutes.

Mineral	Size of Dust Particles	Results
Chrysotile (ball-milled) unheated	3 microns and less	Grinding destroyed capacity to cause fibrosis. At 1 month considerable inflammatory edema and cellular proliferation and localization of dust particles about bronchioles; at 2 months, only a very slight proliferative reaction; at 6, 8-1/2 and 12 months, widely-scattered small mononuclear phagocytes. At 12 months, a few microscopic patches of thin alveolar wall thickening with some adenomatoid change in portion of air spaces abutting on thickened bronchi. No asbestosis bodies seen.
Chrysotile (ball-milled) ignited	3 microns and less	Reac... limited to large foreign-body giant cells without production of fibrous tissue.

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...erni	Size of Dust Particles	Results
...otile ...ous) ...ted	30-60 microns approx.	...t Pulmonary Fibrosis. Reaction localized to connective tissue about terminal bronchioles; little within those tubes. Contraction caused adenomatoid appearance of air spaces given off directly from terminal bronchioles. Reaction area became smaller with progress of time; no new regions involved. No chronic pleurisy even at points abutting intrapulmonary change. At 1 month considerable inflammatory edema and foci of cellular proliferation; at 2 months well-marked cellular proliferation and fibrosis occurring focally about respiratory bronchioles. This reaction developed before asbestosis bodies had formed and was as advanced as that produced by 2 years inhalation of asbestos dust. At 6 months, reaction less extensive than at 2 months, apparently due to contraction of fibrous tissue; asbestosis bodies were abundant. At 8-1/2 months, reaction still less extensive, confined to the immediate vicinity of the small terminal bronchioles, where the scar tissue was quite dense and was becoming hyaline in character. Sometimes it even obliterated the bronchiole. Asbestosis bodies had become scarce. At 12 months, the well-developed peri- and intrabronchial adenomatoid areas of fibrosis had produced considerable distortion. More peripherally were patches of pneumonitis with eosinophilic infiltration, some of which was being transferred into fibrous tissue. These seemed to be precursors of the localized, diffuse patches of thin alveolar wall fibrosis seen elsewhere.
Chrysotile (fibrous) ignited	20-30 microns approx.	Reaction limited to large foreign-body giant cells without proliferation. Heating the fibers, which made them brittle, destroyed their capacity to produce significant reaction.
Serpentine (ball-milled) unheated	5 microns and less	Dust relatively inactive. At 1 and 2 months, simple phagocytosis without proliferation; at 6 months, no change except possibly lymphoid cell infiltration; at 8-1/2 months, a slight chronic pneumonitis; at 12 months, only a little pneumonitis without suggestion of fibrosis.
Serpentine (ball-milled) ignited	5 microns and less	Dust relatively inactive. Reaction essentially the same as for unheated serpentine. With ignited serpentine, less tendency for dust to be carried to bronchial nodes.

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Table 20

COMPARISON OF REACTION TO VARIOUS LONG-FIBER DUSTS

INJECTED INTRABRONCHIALLY

Dosage

See Table

Animals Used

From 6 to 9 guinea pigs for each dust.

Sacrificing Periods

Usually at 1, 4, 8 and 12 months after injection.

Size of Dust Particles

Separated so that most fibers are from 20 to 50 microns long.

Mineral	Results
Chrysotile (Thetford)	..distinct fibrosis. Additional information given opposite Chrysotile (fibrous) underlined, in Table 19.
Chrysotile (Arizona; low iron content; 0.2% Fe_2O_3)	Reaction virtually identical with that to Thetford Chrysotile. Both fibrosis and asbestosis bodies produced with an asbestos containing very little iron. Fibrosis occurred as plugs within terminal bronchioles and as finer deposits at periphery. Fibrosis developed before asbestosis bodies seen and was in cellular state well-formed at one month. With age, fibrous tissue contracted and occupied smaller area but was more dense. Adenomatoid changes similar to those with Thetford Chrysotile. Pleurisy limited to immediate vicinity of early reaction about areas of massive localization. Asbestosis bodies formed but were few in number. At 1 month after injection, minute foci of mononuclear proliferation about bronchioles and in areas of atelectasis; at 1-1/2 months, heavy peribronchiolar patches of fibrosis often with papillary projections partially closing lumen of bronchiole; adenomatoid appearance marked; connective tissue reaction showed heavy collagen but no hyalinization; at 3 months, minute foci of well-matured fibrosis about bronchioles; at 6 months, mature asbestosis fibrosis with evidence of contraction; considerable chronic pneumonitis with infiltration of lymphocytes and eosinophiles. At 9 months, small intrabronchiolar fibrous plugs with foci of more delicate fibrosis at periphery.
Amosite	...ypical fibrous ...s and peribronchiolitis with formation ...ptoplasmic asbestosis bodies. Accumulation of bodies began before 4th month after injection, well-developed by 8th month. Bodies not lost after 12th month. Reaction at 1 month heavy endo... peribronchiolitis already showing

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Dust	Results
Mosite (contd)	fibrous changes; atelectasis and fibrosis with some necrosis at site of massive localization of dust. At 4 months, heavy, widely scattered endo- and peribronchiolitis, now fibrous, with marked deformity of bronchioles and with an adenomatoid appearance. At 8 and 10-1/2 months, reaction in lung essentially the same as at 4 months. At 12 months, foci of fibrous endo- and peribronchiolitis still large with more dense scar tissue and more deformity of bronchial tube but no extension into, or atelectasis of, peripheral parenchyma.
Crocidolite (Celma)	Advanced fibrous endo- and peribronchiolitis. Beaded asbestosis bodies noted at 3 months. At 1 month, early fibrous endo- and peribronchiolitis; many giant cells and some lymphocytic reaction. At 4 months, small areas of endobronchiolitis scattered throughout the lung; cellular fibrosis. At 8 and 12 months, areas of bronchiolitis smaller because of contraction of dense scar tissue; at 12 months, marked lymphocytic infiltration and adenomatoid appearance.
Crocidolite (S. Africa)	Typical advanced fibrous endo- and peribronchiolitis produced by 0.5% suspension (1 cc total dose); most animals would not tolerate usual 5% suspension. Fibrosis well-developed before asbestosis bodies seen. At 4 months, well-developed fibrous bronchiolitis with lymphocytes and giant cells and adenomatoid change. At 8 months, typical bronchiolitis not quite as extensive or as heavily fibrous as with a 5% suspension, otherwise the same. Many deeply-stained fibers with a good proportion of beaded asbestosis bodies. At 12 months, heavy fibrous bronchiolitis, more peri- than endobronchiolitis, with lymphocytes and giant cells; very marked adenomatoid appearance.
Anthophyllite	Lymphocytic infiltration and giant cells but no fibrosis. A very few atypical asbestosis bodies. At 1 month, many scattered foci of intrabronchiolar dust without massive localization; lymphocytic infiltration of walls and a few giant cells. At 8 and 12 months, little evidence of dust; a few bronchioles and bronchi with giant cells in adjacent alveoli and with lymphocytic infiltration of walls.
Tremolite	Fibrosis about bronchioles. At 1 month, area of dust localization with collapse of alveoli and infiltration with acute inflammatory cells, macrophages and giant cells. Within the next were a few foci of fibrous tissue and numerous areas of hypertrophy of alveolar epithelium. Many bronchioles packed with fibers. At 4 months, general appearance of lesion unchanged; pleura slightly thickened over heavy localizations of dust. An occasional segmented asbestosis body seen. At 8 months, many foci of fibers in bronchioles and extension dust with cellular reaction as before; also

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Mineral	Result
Tremolite (contd)	some foci showed distinct collagen deposition. At 12 and 18 months, reaction as before with fibrosis about bronchioles more apparent because of contraction and decrease of inflammation. Giant cells prominent. Pleura markedly involved.
Trocite	Typical fibrous endo- and peribronchiolitis like reaction to asbestos minerals. At 1 month, extensive endo- and peribronchiolitis with giant cells; dense fibrous loops within bronchioles and cellular fibrosis about them; adenomatoid change present. At 2 months, heavy intrabronchiolar and peribronchiolar fibrosis producing marked deformity with distortion of tubes and obliteration of surrounding air spaces; fibrosis pale without hyalinization but with few nuclei; no necrosis. Typical asbestosis bodies seen. At 4 and 8 months, little change; fibrous tissue contracting. At 10-1/2 months, dense fibrous bronchiolitis with asbestosis bodies. No pleurisy. No extension to surrounding lung.
Glass Wool	No fibrosis within a year. At 1 month, no reaction inside bronchioles; in peripheral air spaces clumps of giant cells packed with fine spicules of glass with lymphocytic infiltration of adjacent walls; no asbestosis bodies. At 2 months, reaction less intense than at 1 month; fair-sized clumps of elongated giant phagocytes containing spicules and particles of glass; no endobronchitis. At 4 and 8 months, reaction still diminishing. At 12 months, focal areas of pneumonitis with no fibrosis or endobronchitis; moderate number of smooth iron-staining fibers.

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	Size of Dust Particles	Results
	Long-fiber 20-40 microns	... Massive fibrosis. Refer to Chrysotile (fibrous) tabulated on Table 12.
	Short-fiber 5 microns and less	No fibrosis. Refer to Chrysotile (ball-milled) tabulated in Table 12.
	Long-fiber 20-40 microns	Typical nodular peribronchiolitis. Refer to Table 10.
	Short-fiber 20 microns and less	Reaction limited to phagocytosis with lymphocytic infiltration of adjacent cells. Short fibers caused foreign cell phagocytes; longer ones (avg. 10 microns) caused typical nodules and bridges. At 1 month after injection, microscopic granuloma giant cells; most phagocytes were within air spaces and had not migrated to cells. At 6 months fine granular fibers had worked themselves into interstitia in case where there was granuloma proliferation of lymphoid cells and monocytes but no fibrosis. At 8 months, foreign body reaction with some pneumonitis, no bronchiolitis. Typical nodulations began to appear.
	Long-fiber 20-40 microns	Advanced fibrosis, nodular and peribronchiolitis. Refer to Table 10.
	Short-fiber 5 microns and less	No fibrosis at 1 month, air spaces compromised and filled with giant cells, lymphocytes and monocytes. Cells mostly infiltrated with monocytes and lymphoid cells. At 6 months, a moderate degree of nodular proliferation of cells; small giant cells were noted with rare epithelioid

Mineral	Size of Dust Particles	Results
Anthophyllite asbestos		At 3 and 6-1/2 months, masses of giant cells, containing mineral particles, in small bronchi but not in respiratory bronchioles; smaller ones widely scattered in terminal air spaces. Numerous asbestosis bodies. No reaction in connective tissue. No endobronchial proliferation. At 12 months, many scattered small monocytes packed with dust. No endobronchitis. No peribronchial fibrosis. In lymph nodes, a slight reticulosis; no fibrosis.
	Long-fiber 20-30 microns	Lymphocytic infiltration and giant cells but no definite fibrosis. Refer to Table 20.
	Short-fiber & microns and less	No fibrosis and practically no asbestosis bodies. At 1 month, focal collections of dust-filled monocytes and a few giant cells; at 4 months, some alveolar epithelial reaction; at 8 months, simple pneumonitis with phagocytosis of short-fibers; at 12 months, isolated and sharply localized collections of dust cells inside air spaces about terminal arterioles. Reaction in walls limited to lymphoid cell infiltration. No fibrosis. In lymph node, reaction limited to slight prominence of reticulum.
Tremolite	Long-fiber 25-30 microns	Fibrosis about bronchioles. Refer to Table 20.
	Short-fiber 20 microns and less	Simple foreign-body reaction. No acute inflammation. No accumulation of dust in or about terminal bronchioles. No endobronchitis. At 1 month, scattered small giant cells and considerable infiltration of adjacent small giant cells and considerable infiltration of adjacent walls with monocytes and lymphoid cells. At 4 months, little change except more cellular infiltration of connective tissue. At 8 months, lymphoid infiltration and thickening of walls about some but not all terminal bronchioles.
Crocidolite	Long fiber .5-30 microns	Typical fibrous endo- and peribronchiolitis-like reaction to asbestos minerals. Refer to Table 20.
	Short-fiber (grains of crocidolite, long fibers with rubber policeman)	Atypical type of reaction. At 1 month after injection, small concentration widely scattered through air spaces; focus of atelectasis with lymphoid infiltration of compressed air space walls. No marked alveolar reaction as with chrysotile. At 4 months, reaction similar to that at 1 month; fibrous peribronchial lesion seen. At 12 months, small clumps of macrophages dust-filled monocytes; no fibrosis. No reaction in lymph nodes.

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SUMMARY OF EXPERIMENTAL DUSTINGS BY INTRATRACHEAL TECHNIQUE

[illegible] dust sample at dust - 1.0 mg, divided into 20 equal doses (each dose was 5 cc of a 1 per cent suspension) which were given twice weekly for 10 weeks

Type of Dust Investigated	Time of Dust Instillation	Animals Used	Maximum Survival After Last Injection	Results
[illegible] (Refined)	Siliceous and Iron (Distilled Water Vehicle)	6 rabbits	-	The rabbits did not tolerate intratracheal injections of finely ground chrysotile and 3 of the 6 died after 1 to 5 injections of even dilute suspensions; the other died after 22 injections of one gm per kilogram suspension (27 days after first injection). Reaction limited to fine large giant phagocytes of dust cells seen in pulmonary capillaries. No deposition for Cantilever discovered but material may have been retained to be not evident [illegible] threshold.
[illegible]	Siliceous and Iron (Ground in Porcelain Mortar)	5 rabbits	17 months	Repeated pulmonary injection killed 3 animals at 5, 11 and 17 months after last injection, showing intended duration of experiment and cumulative effect. The two animals sacrificed earlier (3 and 5 months) showed only local phagocytosis with no progression in the 5 months animal. The last two (11 and 17 months) were probably the most affected focal necrosis of the liver and atrophy of the spleen were both progressive difficult.
Idaite	Siliceous and Iron (Ground in Porcelain Mortar)	5 rabbits	12 months	Reaction was that to an inert substance with no change in 12 months. (Three sacrifices at 3, 4, and 6 months). Simple phagocytosis of particles. No tendency to agglomerate and no change in adjacent tissues. Grinding the dust to place of 3 stones [illegible] destroyed the fibrous structure of this mineral and injected material [illegible] rather than fibers.
[illegible]onbyllite	Siliceous and Iron (Distilled Water Vehicle)	4 rabbits	24 months	Reaction essentially that of an inert mineral. Observations made at 3, 12 and 24 months. Only suggestion of irritating properties manifested in spleen and lymph nodes, but not the liver, of the 24 month rabbit. In this animal there had been proliferation of some nuclear and giant cells that was not present in either rabbit at 12 months animal. The absence of associated fibroblastic reaction in these organs and of any change in the liver condition justifies the classification of anthophyllite as an inert silicate. No fibers were retained in lung to demonstrate whether asbestosis would develop.
[illegible] (Iron Free)	Siliceous and Iron (Dust Milled 100 Hours)	4 rabbits	19 months	Reaction essentially that of an inert mineral. Dust animal sacrificed over 2 a little pro liferation and lymphocytic infiltration in liver, not even cavities (at 3, 6 and 12 months). No evidence of any activity in lesions in other organs.
[illegible] (Iron)	Siliceous and Iron (Dust Milled 48 Hours)	4 rabbits	24 months	An inert foreign body reaction with no change in 24 months. Sacrifices made at 3, 6, 12 and 24 months.

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Table 23

SUMMARY OF INJECTION EXPERIMENTS

B.

INTRAPERITONEAL INJECTIONS

Each animal received a single injection intraperitoneally of 2 cc of a 10 per cent dust suspension. Total amount of dust injected = 0.2 gram.

Material	Size of Dust Particles	Animals Used	Maximum Survival After Injection	Results
Asbestos (Calidria)	5 microns and less (ball-milled 216 hours)	15 g. pigs	36 months	No fibrosis nor asbestosis bodies. Dust particles ingested by phagocytes, chiefly multinucleated variety. Six months after injection fibrous elements of dust appear to have dissolved leaving only the insoluble magnetite, a contaminant. No reaction in surrounding fat or areolar tissue. No transporting of dust to regional lymph nodes. Observations made at intervals from 1 to 36 months after injection.
Asbestos (Calidria)	Long fiber (through 100 mesh)	4 g. pigs	2 months	Definite fibrous reaction produced, delicate and non-hyaline. Atypical asbestosis bodies developed but all were unusually small. No evidence of extra-long fibers seen. Observations only at 2 months.
Asbestos	5 microns and less (ground in agate mortar)	9 g. pigs	12 months	Infection interfered with interpretation. Dust reaction appeared to be of inert type and limited to phagocytosis with a moderate tendency to lymphocytic infiltration. Observations at 1, 4, 8 and 12 months.
Asbestos	5 microns and less; also some long spicules (ground in agate mortar)	7 g. pigs	12 months	Dust foci consisted only of large mononuclear and giant phagocytes surrounded by a minimum amount of cellular connective tissue. The injected dust contained not only fine material that in grinding had been washed into irregular plates but also many long spicules 10 microns, or more, in length. No asbestosis bodies seen although the longer spicules appear slightly swollen and greenish. Observations at 1, 4, 8 and 12 months.
Chrysotile	5 microns and less (ball-milled 1400 hours)	5 g. pigs	25 months	Essentially inert foreign body reaction. In early animals (1, 4 and 8 months) focus of monocytes and small giant cells and a little central necrosis. In the 4 month animal there was also slight peripheral fibrosis. At 12 and 25 months, non-progressive mass of monocytes and giant cells; no fibrosis.
Chrysotile (Original Vein)	Nearly 5 microns and less; some fibers 30 microns or more long (ground in agate mortar)	5 g. pigs	12 months	Reaction, which consisted of very large giant cells surrounded by a variable number of lymphocytes, was much heavier to those unintentionally long fibers than to the fine dust in the experiment above. There was more or less proliferation of fibroblasts producing cellular connective tissue visible in areas where the quantity of foreign particles was not so great that it obscured the reaction. Observations at 1, 4, 8 and 12 months.
Chrysotile (Cassiar)	5 microns and less (ball-milled 15 hours)	5 g. pigs	12 months	Inert type of response never progressing beyond the stage of very slight lymphocytic reaction about masses of dust-filled phagocytes. No fibrosis. Observations at 1, 4, 8 and 12 months.

*Each animal receiving long-fiber chrysotile was injected with 2 cc of a 0.5 per cent dust suspension.

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Mineral	Size of Dust Particles	Animals Used	Maximum Survival After Injection	Results
Ironcliffe (soda)	3 microns and less (ball milled 48 hours)	6 g. pigs	18 months	Mild non-progressive foreign-body type of reaction. No fibrosis. Observations at 1, 6, 12 and 18 months.
Anthophyllite (originally labeled talc)	300 microns and less	35 g. pigs	12 months	Distinct early fibrosis produced by anthophyllite and fibrous pyrophyllite, with subsequent regression; crystalline pyrophyllite inert throughout [illegible] about long thick splinters; at 1 months, definite fibrosis surrounding giant cells of anthophyllite and fibrous pyrophyllite reaction; at 6 months, fibrosis which started at 4 months had decreased, especially with fibrous pyrophyllite. At 12 months, reaction to all three dusts consisted of foreign body giant cells with lymphocytes but without necrosis or fibrosis. No anhectosic bodies.
Pyrophyllite (fibrous)				
Pyrophyllite (crystalline)				

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Table 24

ANALYSIS OF FIBROUS MINERALS

	Anorite	Amphibole	Antigorite-phyllite	Granite	Chrysotile	Grunerite	Tremolite
	per cent	per cent	per cent	per cent	per cent	per cent	per cent
	46.2[illegible]	53.04	59.30	0.80	38.36	51.09	55.20
	4.05	3.0[illegible]	0.37	0.73	2.55	23.27	7.23
	33.05	-	-	0.36	-	0.29	-
	1.00	1.09	0.52	0.46	0.01	1.01	0.56
	2.01	12.22	0.14	0.04	0.03	0.30	0.44
	6.20	23.50	35.67	33.39	38.35	12.25	20.52
	0.25	0.43	0.32	0.01	0.20	0.02	0.70
	0.10	0.12	0.15	0.10	0.03	0.37	0.39
ation Al_2O_3	0.05	0.02	0.07	0.53	4.00	0.02	0.03
(P_2O_5)	5.00	5.00	4.00	25.05	14.00	2.55	2.78
	99.97	99.77	99.32	99.75	99.03	99.05	99.02

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