Prod. Info. Asbestos

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FROM (NAME—LOCATION—PHONE) Dept. of Medicine & Environmental Health N. C. Stout - G2WB

DATE May 28, 1986 cc G. Roush, Jr., M.D.

SUBJECT Asbestos Literature Search

REFERENCE

TO : J. L. Henshaw
R. S. Nair

When we met about a month ago to discuss phosphate fibers, one of the assignments given to me was to do a literature search on the characteristics of airborne fibers, particularly asbestos fibers. It was felt that this literature search would provide background information with which to compare data we collect for airborne phosphate fibers.

I have enclosed a draft of this literature search for your review. Please look it over and let me know any criticism you may have. I do consider this a draft, so please feel free to submit comments. Basically, I want to know if you feel I am covering the right material and if I address issues that will help us evaluate the potential hazards of phosphate fibers.

Please send comments to me by June 4.

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HEALTH SIGNIFICANCE OF FIBER DIMENSIONS AND CHARACTERISTICS OF AIRBORNE ASBESTOS FIBERS

EXECUTIVE SUMMARY

Epidemiological and animal studies indicate that the important determinants for the biological activity of fibers are the dimensions of fibers, the exposure dose, and the durability of fibers in biological systems.

The disease-producing potential of airborne fibers depends upon fiber dimensions for two major reasons: 1) fiber dimensions determine the aerodynamics of the fiber, and therefore affects penetration and deposition in the respiratory system, and 2) diameter and length of a fiber may both be important in the ability of a fiber to induce mesothelial tumors.

The deposition characteristics of a fiber depend primarily on the diameter of the fiber. Though "compact" (i.e., non-fibrous, roughly spherical) particles of 10 μm diameter or more are generally not able to penetrate to the alveoli space, fibers as long as 200 μm have been detected in human lung samples. Fibers with actual diameters of 3 μm or less can be considered respirable, even with fiber lengths exceeding 100 μm.

Experiments using techniques to implant fibers of various types and differing dimensions into the pleural or the peritoneal cavities of animals predominantly support the "long, thin" hypothesis for the pathogenesis of malignant fibrous neoplasms. For example, one study concluded that fibers with diameters less than 1.5 μm and lengths greater than 8 μm had the highest potential to elicit pleural sarcomas. The mechanism for pathogenesis of malignant fibrous neoplasms is believed to involve incomplete or "frustrated" phagocytesis. This process results in leakage of tissue-damaging enzymes from the cell without being specifically toxic to the phagocyte. The resultant tissue damage is presumed to be the ultimate inciter of fibrosis.

Airborne asbestos fibers in the workplace have been studied qualitatively and quantitatively. It has been found that the diameters of individual fibers in air seldom exceed 5 μm, and fibers lengths range from 0.2 to 1000 μm. The amount of asbestos fibers in workplace air varies considerably. Risk estimations used today are based on estimates of past exposures which were by today's standards massive. For example, some jobs in an asbestos textile factory were estimated to have exposures of up to 78 fibers/cc.

HEALTH SIGNIFICANCE OF FIBER DIMENSIONS

Epidemiological and animal studies indicate that the important determinants for the biological activity of fibers are the dimensions of the fibers, the exposure dose, and the durability of the fibers in biological systems.[1] The purpose of this review is to summarize the evidence that the hazard potential of exposure to airborne fibers depends upon fiber dimensions. Major focus is on asbestos fibers.

The disease-producing potential of airborne fibers depends upon fiber dimensions for two major reasons: 1) fiber dimensions determine the aerodynamics of the fiber, and therefore affects penetration and deposition in the respiratory system, and 2) diameter and length of a fiber may both be important in the ability of a fiber to induce mesothelial tumors.[2]

Behavior of fibers in the respiratory system

The aerodynamic behavior of particles in the respiratory tract is very complex. Inspired air containing particles is first filtered in the nasal passages, then passes along the respiratory tree with over 20 generations of branching. The diameter of these branches and the velocity of airflow progressively decrease. The flow is reversed with each respiratory cycle, leading to considerable mixing in the air sacs. Five physical processes may affect the probability of deposition of particles in the respiratory tract: 1) inertial impaction, which is the major process by which larger particles are arrested in the airways; 2) sedimentation, which is the major mechanism for deposition of a broad range of particles up to diameters of 50 μm, but has less influence than diffusion for particles with effective diameters less than 0.5 μm; 3) diffusion, which is the main mechanism for deposition for particles with effective diameters less than 0.5 μm; 4) interception, which is a significant mechanism of deposition for long, fibrous particles, particularly at bifurcations and in narrow airways; and 5) electrostatic precipitation, which is a minor contribution to total deposition.[3]

A respectable body of literature describes the details of particle behavior, including fibrous particles, in the respiratory tree. In 1965, Timbrell[4] studied the relationship among falling speeds, diameters, and lengths of fibrous particles. He conducted this study because he recognized that "compact" (i.e., non-fibrous) particles found in significant numbers in alveoli are 10 μm or smaller in diameter. In contrast, asbestos fibers 50 μm and even 200 μm long have been found in alveoli.[5] He found that the "equivalent diameter" (i.e., the diameter of the unit density sphere of the same falling speed) of a fiber is determined predominantly by the actual diameter, and secondarily by the length, especially for fibers with high aspect ratios.

Timbrell summaried his findings on particle aerodynamics are follows:

> "The largest compact particles normally found in lungs are about 10 microns in diameter. The presence of asbestos fibers 50 microns and even 200 microns long can be explained by the fact that the parameter of the two main deposition mechanisms

> is particle free-falling speed, and for a fiber, this is predominantly determined by the diameter and not the length. If the diameter of an asbestos fiber is less than about 3.5 microns, the fiber stands a chance of escaping deposition by these two mechanisms and of penetrating deeply into the lung. The more symmetrical a fiber is, the greater its chance of penetrating. The limitation on the lengths of the fibers which reach the pulmonary air spaces is imposed by the nasal hairs and by the small diameters of the respiratory bronchioles. Pathologists can expect to find that places where respiratory bronchioles branch are preferred deposition sites for long fibers."

Thus, fibers with actual diameters of approximately 3 μm or less can be regarded as respirable, even with a fiber length in excess of 100 μm.

Based for the most part on Timbrell's work, Harris and Fraser[6] in 1976 developed a mathematical model for estimating lung deposition of fibers. They calculated that there would be maximum deposition in the pulmonary spaces of fibers with actual diameters of 0.12-0.5 μm, followed by a minimum between 0.05-0.12, and, using the International Commission on Radiation Protection model, a rapid rise in deposition of fibers with still smaller diameters. They pointed out that the nasopharyngeal compartment is very effective for removing long, thin fibers for inhaled air. They calculated that 90% of fibers 200 μm long are deposited in the nose by interception. The authors concluded by saying: "The model offered here is analytical in character. The calculated results are consistent with reported observations of fibers in human lungs. The results have not been validated by comparison with data representing actual observations of rods or fibers deposited (as district from retained) at specific sites in human lungs."

In summary, based on what is known about fiber behaviors in the respiratory system, we would expect the largest particles to be deposited by impaction and the longest particles by interception in the nasal passages and large airways, particularly at the bifurcations. Of the remainder, particles with actual diameters down to about 0.25 μm would tend to be deposited by sedimentation, and long particles by interception, in the smaller airways. The small particles with actual diameters less than 0.25 μm would tend to pass through and be deposited in the respiratory bronchioles and the alveolar sacs by sedimentation and diffusion. A proportion of these small particles would escape deposition and be washed out again in expiration.

There appears to be fairly good correlation between what is expected of fibrous particle behavior in the airways based upon the Harris and Fraser model and what is actually found in post-mortem studies of lung tissue. The physical characteristics of asbestos fibers that penetrate to lung were studied by Sebastien et. al.[7] They looked at the diameter and length of 5000 asbestos fibers from the lungs of 10 deceased persons who had occupational exposure to asbestos. All fibers found in lung tissue had actual diameters less than 0.5 μm. The proportion of fibers shorter than 5 μm ranged from 70% to 90%.

Pooley and Clark[8] characterized the fibrous materials from post-mortem lung tissue obtained from cases of mesothelioma and asbestosis. The majority of fibers of three minerals (chrysotile, crocidolite, and amosite) detected in lung tissue samples were less that 6 μm in length: the percentages of fibers greater than 6 μm were 5, 10.5 and 23% for chrysotile, crocidolite, and amosite, respectively. Only 4.2% of the chrysotile fibers from lung tissue specimen had actual diameters greater than 0.125 μm. The crocidolite fibers were somewhat thicker, with 29% of the fibers having diameters greater than 0.125 μm. Less than 1% of crocidolite fibers had diameters exceeding 0.375 μm. The mean diameter for crocidolite fibers was 0.14 μm, compared with 0.07 μm for chrysotile. Amosite fibers were larger still, with 76% of fibers having diameters greater than 0.125 μm, and 15% with diameter greater than 0.375 μm. The mean diameter for amosite fibers was 0.28 μm. The size distributions of amosite and crocidolite fibers were similar in airborne dust samples and in the lung, though the fibers of both minerals found in the lung appeared to be longer, perhaps indicating a selective clearance of smaller fibers. (This observation will be discussed in more detail in the next section.)

Fondimare et. al.[9] (1974) studied the dimensions of 5000 asbestos fibers from the lungs of 10 deceased persons who had been occupationally exposed. All fibers had actual diameters less than 0.5 μm in diameter.

Fiber dimension and tissue response

The foregoing discussion shows that fiber dimensions are extremely important in determining respirability and deposition characteristics of fibers and the ability to penetrate to the lungs. Fiber dimensions, it is now believed, is also crucial from the standpoint of tissue response and the development of disease.

Discussion of the influence of fiber dimension on pathogenesis probably started in 1951 with the publication of a study by Vorwald et. al.[5] They conducted intratracheal injection and inhalation experiments on guinea pigs. The initial conclusions were that "apparently only long fibers have any specific effect...when the injected dust consisted of fibers 20-50 μm long, all the fibrous minerals tested except the anthophyllite produced fibrosis." However, in 1964, Holt et. al.[10] demonstrated production of parenchymal fibrosis in rats with inhalation of dust in which 84% of the particles were 5 μm or less in length. Since that time, other studies have been reported, some supporting and some refuting the fibrogenicity of fibers shorter than 5 μm in lung tissue.

A clearer picture seems to emerge when fibers are implanted into the pleural or the periotoneal cavities of animals by various techniques. Stanton et. al.[11] implanted 17 diverse types of fibrous glasses in the pleurae of rats. "Neoplastic response correlated well with the dimensional distribution of fibers. Fibers less than or equal to 1.5 μ in diameter and greater than 8 μ in length yielded the highest probability of pleural sarcomas, and probability trends suggested that pleural sarcoma incidence increased with increasing lengths of fibers with diameters of less than 1.5 μ. Morphological observations indicated that fibers less than or equal to 8 μ in length were inactivated by phagocytosis." The researchers also concluded that "since neoplastic

response to a variety of types of durable fibers, particularly asbestos fibers, was similar, our experiments reinforce the idea that the carcinogenicity of fibers depends on dimension and durability rather than physicochemical properties and emphasize that all respirable fibers be viewed with caution."

Wagner, Berry, and Timbrell[12] inoculated rats intrapleurally with asbestos samples and other materials. They designed four experiments to study the effects of varying dose and varying the types of dust. The authors defined "significant" fibers as those that were less than 0.5 μm in diameter and also greater than 10 μm in length. For samples of UICC (1'Union Internationale Cantre le Cancer) crocidolite, UICC anthophyllite, ceramic fiber, glass fiber, and chrysotile, they were able to classify the carcinogenicity of each type based on the number of "significant" fibers present -- i.e., "...the number of 'significant' fibers decreases with decreasing carcinogenicity of the materials." The authors concluded: "If the finer fibres are the more carcinogenic when applied to the pleura then, since the finer fibres are also able to penetrate to the pleura more easily after inhalation, these 2 factors would combine together to give the finer fibres more relative importance than even the aerodynamic differences would suggest."

There are numerous other studies using various techniques to implant fibers of various types and dimensions into the pleural or the peritoneal cavities of animals. Essentially all of these experiments support the "long, thin" hypothesis for the pathogenesis of malignant fibrous neoplasms. The mechanism which Kuschner and Wright[13] believed best explains the commonality of response to a variety of fiber types is one that has been demonstrated for granulocytes and has been extended to macrophages. Cells attempting to engulf long fibers are involved in incomplete or "frustrated" phagocytosis. The process, known as "exocytosis," results in leakage of tissue-damaging enzymes from the cell without being specifically toxic to the phagocyte. The resultant tissue damage is presumed to be the ultimate inciter of fibrosis.

In 1974, Kuschner and Wright[13] studied the effects of intratracheal instillation of glass fibers of different dimensions in guinea pigs. This study substantially supports the "long, thin" hypothesis so clearly demonstrated in the pleural and intraperotineal implant studies described above. Six categories of glass fibers based on fiber dimensions were defined as shown in Table I below.

Table I
Types of Glass Fibers Used in Intratracheal
Administration to Guinea Pigs

Fiber Description	Fiber Dimensions Diameter, μm	Length, μm
Very thin and short	<0.3	<5
Very thin and long	<0.3	>10
Thin and short	<1	7% > 10
Thin and long	<1	7% > 10
Thick and short	2	88% < 10
Thick and long	2	75% > 10

The first two categories studied consisted of thin fibers, most with diameters less than 1 μm. Short thin fibers, of which only 7% were longer than 10 μm, and long thin fibers, of which only 7% were shorter than 10 μm, caused different tissue reactions. No fibrosis was found after exposure to short fibers but alveoli filled with macrophages and fibers within macrophages in the lymph nodes were observed. Exposure to long fibers resulted in interstitial reaction at areas around respiratory bronchi and proximal alveoli six months after exposure. At one year after exposure, peribronchiolar interstitial fibrosis was observed.

Thinner fibers, most with diameters less than 0.3 μm and lengths less than 5 μm or grater than 10 μm, produced reactions similar to those induced by the previous set of long and short thin fibers. The very thin long fibers caused a fibrotic reaction whereas the very thin, short fibers did not.

Thick fibers, with diameters averaging 2 μm, with 88% shorter than 10 μm or 75% longer than 10 μm, were compared. The short, thick fibers resulted in some interstitial fibrosis after 2 years. This may have been due to the presence of the 12% of fibers in that group longer than 10 μm. The long, thick fibers caused focal areas of interstitial fibrosis at six months after exposure.

The investigators also studied various sizes of asbestos fibers by the method described and found a markedly greater degree of fibrosis with the longer fibers. They theorized that the marked quantitative difference between fibrous glass and asbestos was a consequence of the less durability of a long glass fiber as compared with the durability of asbestos.

Summary

Fiber dimensions determine the aerodynamics of fibers and therefore influence the ability of fibers to penetrate and deposit in the respiratory system. The deposition characteristics of a fiber depend primarily on the diameter of the fiber. Though "compact" particles of 10 μm diameter or more are generally not able to penetrate to the alveoli space, fibers as long as 200 μm have been detected in human lung samples.

Fibers with actual diameters of 3 μm or less can be considered respirable, even with fiber lengths exceeding 100 μm.

Experiments using techniques to implant fibers of various types and differing dimensions into the pleural or the peritoneal cavities of animals predominantly support the "long, thin" hypothesis for the pathogenesis of malignant fibrous neoplasms. There is only scant data on the influence of fiber dimensions on fibrogenesis; and no data relating to branchogenic cancer.

CHARACTERISTICS OF AIRBORNE ASBESTOS FIBERS

Commercial asbestos consists predominantly of long fibers, suitable for weaving or molding into matrices, with a variable quantity of short or fine fibers interspersed. It is dust of this nature to which asbestos workers are generally exposed. As the material is handled or treated, asbestos tends to fragment longitudinally and transversely, giving shorter and finer fibers. Chrysotile in particular can continue longitudinal fragmentation into quite fine (0.5 μm and less) diameter fibers. The amphiboles (amosite, crocidolite, tremolite, etc.) tend to maintain larger diameters. The fibers in asbestos products may continue to fragment with use, thereby exposing the user to smaller and finer fibers[3].

This section reviews the available data on the characteristics of airborne asbestos fibers in occupational environments, and relates this data to the foregoing discussion to help determine the physiological significance of exposure to these fibers.

Qualitative Characteristics of Airborne Asbestos Fibers

G. W. Gibbs and C. Y. Hwang[2] studied the physical characteristics of airborne asbestos fibers in various work environments. Samples were collected using nucleopore membrane filters (G. E. 40, 37 mm diameter, pore size 0.4 μm), and examined by scanning electron microscopy. Samples were collected at the following locations:

(1) at the carding machine in an asbestos textile plant which used chrysotile only.
(2) at an asbestos products plant during the emptying of bags of amosite and crocidolite into hoppers "dumping".
(3) at a local oil refinery during the application of insulation materials containing mainly amosite.
(4) in the dryer and bagging areas of a chrysotile mill.

Two samples were collected at each location.

Results of this study are summarized in Table II. As can be seen in Table II, all fibers measured had actual diameters less than 3 μm. Thus, based on actual diameter alone, all fibers were in the respirable range as defined by Timbrell. The authors also concluded that "on diameter criteria only...chrysotile encountered during carding was potentially the more respirable of the fibers examined." The authors compared their results with epidemiological studies of asbestos disease and reached the following conclusion:

Table II
Physical Parameters of Asbestos Fibres

		d_t [1] (μm)	l_t [2] (μm)	d_c [3] (μm)	l_c [4] (μm)	Mass [5] (x 10^{-12} gm)	Aspect ratio
Amosite Dumping	median	0.415	3.90	0.510	3.60	2.200	8.00
	range	0.072-2.922	0.57-38.04	0.072-3.00	0.57-38.04	0.011-251.278	3.06-50.16
Amosite Application	median	0.370	2.50	0.428	2.93	1.000	7.20
	range	0.071-2.482	0.47-30.94	0.075-3.36	0.47-33.39	0.006-126.033	3.10-50.81
Crocidolite Dumping	median	0.248	2.50	0.292	2.49	0.538	9.65
	range	0.011-1.347	0.17-16.18	0.051-1.347	0.17-16.18	0.0001-38.714	3.22-56.18
Chrysotile Drying	median	0.173	1.25	0.317	1.18	0.126	6.30
	range	0.011-1.446	0.22-14.88	0.052-2.265	0.22-16.12	0.0012-25.866	3.07-64.41
Chrysotile Bagging	median	0.158	1.35	0.264	1.24	0.128	7.25
	range	0.013-1.135	0.34-9.81	0.013-1.551	0.27-15.01	0.0017-23.011	3.07-36.76
Chrysotile Carding	median	0.150	1.00	0.233	0.93	0.068	6.60
	range	0.011-1.251	0.26-12.24	0.011-1.829	0.23-12.16	0.0001-15.432	3.04-81.95

(1) true diameter (d_t)--(the width of central portion of a fibre excluding particles attached to the fibre)

(2) true length (l_t)--(the length of a fibre after straightening)

(3) coil diameter (d_c)--the maximum fibre diameter including attached particles or widest diameter of coil)

(4) coil length (l_c)--(the length of the fibre as it appeared on the filter)

(5) mass (m)--calculated from the true fibre diameter and stretched fibre length by assuming that all fibres have a circular cross-section. This assumption was not strictly valid for amosite in which it is eliptical or circular and for chrysotile which in cross-section has a swiss roll appearance.

> "The lower prevalence of radiological change among chrysotile asbestos workers than among insulation workers would suggest that asbestosis is related to mass rather than fibre concentrations. Experimental evidence supports this for amphibole fibres. For the same concentration, amosite workers would potentially inhale up to 31 times more asbestos in mass than chrysotile workers. Other factors such as solubility, translocation and fibre length are also likely to play a role, once the fibre has entered the lung or penetrated to the pleura."

And:

> "Our results so far support the experimental work on animals suggesting that asbestosis is related to the mass of airborne dust inhaled and that primary malignant mesothelial tumours are related to exposure to fibres in a specific range of fibre diameters and lengths."

Unfortunately, the authors did not report quantitative results of sampling -- i.e., fibers/cc or mppcf measured at the various sampling points.

C. Y. Hwang[14] studied the characteristics of airborne asbestos fibers in mines and mills. Samples were collected using millipore membrane filters (type AA; 0.8 μm pore size, 37 mm diameter). The samples were collected at an underground mine and two mills producing crocidolite in Cape Province, South Africa; an underground mine and three mills producing amosite in Transvaal, South Africa; and an open pit mine and a mill producing chrysotile in Quebec, Canada. Samples were examined using light optical microscopy and transmission electron microscopy (TEM).

Results of this study are summarized in Table III. No airborne fibers measured had true diameters greater than 3 μm. So again, all fibers measured were in the respirable range based on true diameter alone.

TABLE III
Median true diameter, median true length, and median aspect ratio by stage of processing

Stage of asbestos processing	Crocidolite	Amosite	Chrysotile
Initial			
Median true diameter	0.07	0.20	0.05
Median true length	0.95	1.83	0.34
Median aspect ratio	11.70	8.40	6.30
Final			
Median true diameter	0.09	0.26	0.06
Median true length	1.16	2.53	0.55
Median aspect ratio	13.20	8.80	8.00

Noting that a study by Pooley and Clark[8] showed that fibers detected in lung tissue are longer than airborne fibers, the authors speculated:

> "One of the most likely explanations might be that the clearance mechanisms of the lung operate more efficiently with shorter fibres. Evidence from animal experiments supports such an explanation. The size and shape of fibres may reduce the diffusion coefficient and affect the total lung deposition, thus the difference between the size distributions measured in the lung and those in the air may reflect the size selection of the fibre deposition mechanisms as well as that of the clearance mechanisms."

The authors also summarized the status of current knowledge of the relationship between mesothelioma production and fiber dimension:

> "If the dimension of asbestos fibres are important in the production of mesothelioma the aspect ratios and the percentages of such long but thin fibres could be the most significant properties. The possible existence of a specific fibre dimension likely to be more hazardous to health, in particular, to the production of mesothelioma, than other dimensions has been reported by Stanton and Wrench, Stanton et. al., and later, by Pott. Stanton et. al. have related higher tumour rates in animals to implanted fibres with a diameter less than 0.25 μm and with a length greater than 8 μm. According to Pott, the carcinogenic potency of a fibre is related to its length, diameter, and possibly, by its aspect ratio and there might be a dimensional category in which fibres have a higher carcinogenic potency (with a carcinogenic factor of 100) relative to the carcinogenic potency of fibres in the other dimensional categories (with carcinogenic factors less than 100)."

The authors concluded that the results of this study support the "long, thin" hypothesis in that "crocidolite fibers, in particular, have been related to the production of mesothelioma. The physical properties were best differentiated crocidolite fibres from other asbestos types and which had higher values determined from crocidolite fibres than these obtained from other types, were median aspect ratio of fibres and the proportion of long, thin fibers...."

Unfortunately, again the authors did not report quantitative measurements of airborne fibers in these industries.

C. Y. Hwang and G. W. Gibbs[15] studied the characteristics of airborne fibers collected at an underground mine and two mills producing crocidolite, and at a plant manufacturing pipes using crocidolite and chrysolite. Samples of dust were collected using both millipore membrane filters (type AA; 0.8 μm pore size, 37 mm diameter) and Nucleopore (0.4 μm pore size, 25 mm diameter). Nucleopore filter samples were examined using scanning electron microscopy. Membrane filter samples were examined by light optical microscopy and transmission electron microscopy.

Results are summarized in Table IV. Again, no airborne fiber measured had a true diameter greater than 3 μm, and no quantitative data were given on the concentration of airborne asbestos fibers.

The Joint ACGH-AIHA Aerosol Hazards Evaluation Committee wrote a review document in 1975 which presented background information for the "Recommended Procedures for Sampling and Counting Asbestos Fibers: Procedures for the Evaluation of Occupational Exposure to Airborne Asbestos."[16] They provided the following summary of the characterization of airborne asbestos in industry:

> "The size distribution measurements that have been carried out on asbestos dust clouds are not strictly comparable because of variations in optical and electron microscope techniques; however, clear indications of large variations in size distribution have been given for difference types of asbestos and different manufacturing processes and application methods.
>
> These studies have shown that:
>
> (a) many fibers are smaller than the resolution limit of optical microscopes;
> (b) the diameter of chrysotile fibers which occurs in bundles of fibrilos cannot be clearly defined;
> (c) long chrysotile fibers are frequently curly, the others are mainly straight;
> (d) other asbestoses (crocidolite, amosite, and anthophyllite) frequently occur as single fibers;
> (e) the minimum diameters for fibers are: chrysotile 0.25 μm, crocidolite 0.06 μm, amosite 0.15 μm, and anthophyllite 0.25 μm;
> (f) the diameters of individual fibers in the air seldom exceed 5 μm;
> (g) the fiber lengths range from 0.2 μm to 1000 μm; and
> (h) large clumps of fibers have been observed frequently."

Quantitative Studies of Airborne Asbestos Fibers

The amount of asbestos fibers in the workplace air can of course vary considerably, depending upon the processes, engineering controls, work practices, and numerous other variables. Studies have been done to extrapolate from limited industrial hygiene data available before 1964 and work history information to develop life time dose estimates, and from these estimates develop dose-response relationships for lung cancer, mesothelioma, and asbestosis. More recently, data has been reported on the amount of asbestos fibers found in various work environments.

Estimating past exposures and cumulative doses is difficult for many reasons. Methods of measuring dust levels have changed over time with respect to sampling instrument (thermal precipitation vs. midget impinger vs. membrane filter), location of sampling (personal vs. area) and dust counting (particles vs. actual fibers) and/or evaluation techniques

Table IV
Distribution of Fibres by Length and Diameter Observed by Trnasmission Electron Microscopy

True length (µm)	Mining and milling True diameter (µm) ≤0.10	0.11 -0.20	0.21 -0.40	>0.40	Manufacturing (preparation) True diameter (µm) ≤0.10	0.11 -0.20	0.21 -0.40	>0.40	Manufacturing (finishing) True diameter (µm) ≤0.10	0.11 -0.20	0.21 -0.40	>0.40
≤2.50	55.66	22.21	4.25	0.28	55.61	23.97	5.09	0.28	93.05	2.09	0.20	0.00
2.51-5.00	4.87	5.13	2.20	0.58	4.03	4.31	2.94	0.70	3.13	0.50	0.00	0.05
5.05-7.50	0.76	1.43	0.78	0.19	0.59	0.73	0.50	0.06	0.30	0.20	0.20	0.00
7.51-10.00	0.17	0.48	0.21	0.09	0.14	0.14	0.31	0.03	0.15	0.00	0.00	0.00
10.01-20.00	0.11	0.36	0.11	0.09	0.17	0.11	0.14	0.12	0.00	0.00	0.10	0.05
>20.00	0.00	0.01	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overall	61.57	29.62	7.56	1.23	60.57	29.26	8.98	1.19	96.63	2.79	0.50	0.10

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(whole fields vs. eyepiece graticule). As a result, conversion of dust levels obtained by one method to levels comparable to another method is far from simple, and is subject to considerable error. Another factor which may lead to differences of opinion on the exact shape of the dose-response curve is the measure of the dose. The commonly used measures of exposure are the cumulative dose and the duration of employment. Since using cumulative dose as a measure of exposure gives equal weight to the concentrations of dust experienced in each year of exposure, exposure of many years ago is considered as important as recent exposure. This practice unrealistic for the chronic diseases having a long latency period. Duration of employment has also been used as a measure of exposure under the assumption that increasing the work time approximates increasing the dose. This procedure has the same problem as using the cumulative dose. Furthermore, in the absence of reliable past exposure data, the duration of employment may not equal the total dose of asbestos.[17]

Berry et. al.[18] reported that the occurrence of crepitations, possible asbestosis, and certified asbestosis was related to the cumulative dose. Of men first employed after 1950 in an asbestos textile factory, 6.6% had possible asbestosis after an average length of follow-up of 16 years and an average exposure level of 5 fibers/cm^3 (dust levels determined by electrostatic precipitation area samplers). The authors calculated the average exposure level at which possible asbestosis occurs in no more than 1% of people so exposed for 40 years could be as high as 1.1. fibers/cm^2 or as low as 0.3 fibers/cm^3. The authors admit that this calculation is tenuous because it is based on extrapolation from higher exposures, and post exposures were estimated based on more current sampling data. Estimated exposure levels are shown in Table V.

TABLE V
Dust Exposure of Mem Employed in Certain Years

	Mean dust level(f/cm^3)	Percentage of men exposed to <2f/cm^3	2.1-5f/cm^3	<5f/cm^3
1936*	13.3	0	0	100
1941*	14.5	4	0	96
1946*	13.2	2	2	96
1951†	10.8	3	8	89
1956†	5.3	2	40	58
1961	5.2	6	35	59
1966	5.4	23	22	55
1972	2.9	32	65	3

*There were no dust measurements in these years and the dust levels given are considered to be lower limits.
†Fibre counts are not made in these years.

Dement et. al.[19] estimated the dose-response for respiratory cancer and nonmalignant respiratory diseases among chrysotile asbestos textile workers. Cumulative exposures were estimated based on over 1000 samples collected in this plant by the U.S. Public Health Service from 1965 to

1971 using impinger counts, measured in millions to particles per cubic foot of air (MPPCF), and membrane filter counts, measured as fibers cm^{-3}. All impingers results were converted to fibers cm^{-3} based on 120 paired impinger-membrane filter samples. A summary of exposure estimates is shown in Table VI. Notice that out of 76 exposure categories based on plant operations, calendar time intervals, and job categories, only one exposure category had estimated exposures less than 2 fibers cm^{-3}. The highest estimated exposure category was 78 fiber cm^{-3}.

The authors concluded that "A linear relationship appears to adequately describe the form of the dose-response curve for both diseases [lung cancer and nonmalignant lung diseases]. Lung cancer demonstrated a statistically significant excess in even the lowest cumulative exposure category of less than 10,000 fibre cm^{-3} days." Figure I shows the dose-response curves developed by the authors. 100 Fibre/cc x years is highlighted to show the point on the curve where a lifetime exposure at the current OSHA PEL of 2 fibers/cc would fall - i.e., 2.0 fibers cm^{-3} for 50 years).

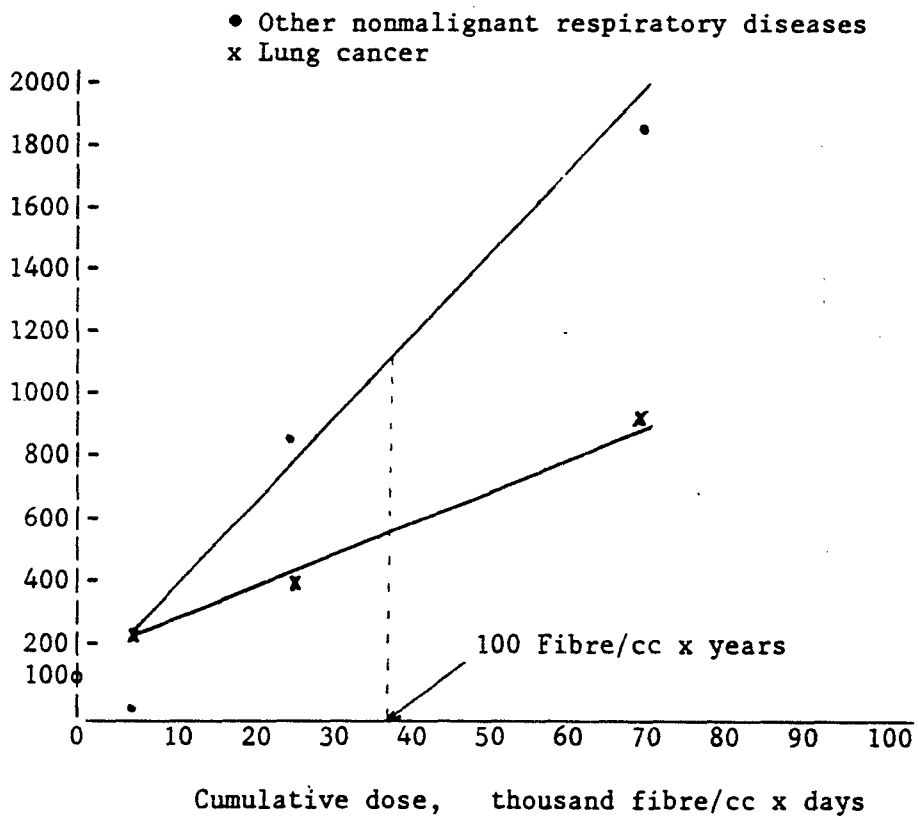

Figure I
Plot of lung cancer and other nonmalignant disease SMRs by cumulative dose, white males

Table VI
Summary of Estimated Mean Fibre Exposures by Operation, Calendar Time and Uniform Job Categories

Plant operation and calendar time period	Estimated mean exposure by UJC (fibres >5 μm cm^{-3}) A General area	B,Machine operators Sub-category 1	Sub-category 2	Sub-category 3	Sub-category 4	C Clean-up	D Raw fibre handling
Preparation/waste recovery							
1930-1944	26.2	78.0	78.0	45.9		54.4	35.0
1945-1964	8.1	23.9	23.9	14.1		16.7	10.8
1965-1975	5.8	17.2		10.1		12.0	7.3
Carding							
1930-1935	10.8	13.3				18.1	22.8
1936-1945	5.3	6.5				8.8	11.0
1946-1965	2.4	2.9				4.0	5.0
1966-1975	4.3	5.3				7.2	9.0
Ring spinning							
1930-1965	8.2	6.6				N	N
1966-1970	8.6	6.9				N	N
1971-1975	6.2	5.0				N	N
Mule spining							
1930-1975	4.6	4.6				6.7	N
Foster winding							
1930-1937	10.4	13.6				20.9	N
1938-1975	4.2	5.5				8.4	N
Twisting							
1930-1938	24.6	36.0				31.9	31.9
1939-1975	5.4	7.9				7.0	7.0
Universal winding							
1930-1975	4.1	4.1				8.4	N
Heavy weaving							
1930-1936	9.2	17.3	9.7	14.3	5.3	30.6	30.6
1937-1975	2.6	4.6	2.6	3.8	1.4	8.2	8.2
Draper weaving							
1930-1975	2.7	2.7				6.9	

N: No jobs within particular UJC.

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The authors also compared their results with the limited dose-response data published. Since the other studies used impinger data reported as MPPCF, the data in this study was converted to MPPCF using the paired impinger-membrane filter samples collected by the U.S. Public Health Service. The comparison is shown in Table VII. Notice that the SMR for lung cancer in this study is significantly higher when compared with the other two studies.

Table VII
Comparison of Dose-Response Relationships for Lung Cancer with Other Published Data

Present study		Enterline and Henderson (1973)		McDonald et. al. (1980)*	
Approximate MPPCF yr	SMR	MPPCF yr	SMR	MPPCF yr	SMR
<9.1	223				
9.1-36.5	357			30	104
36.5-91.3	978			100	114
		<125	168.2		
		125-249	224.5	300	142
		250-499	296.3	500	170
		500-749	500.0		
		<750	555.6		
				1200	268

*Based on cumulative exposures until age 45 yr. SMRs calculated from regression line provided by authors.