The Interrelationships of Selected Asbestos Exposure Indices

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Based on the assumption that the biological effect of asbestos is related to the concentration of respirable fibers, an index was developed which yields the concentration in numbers of asbestos fibers visible under 430× phase-contrast illumination. Data are presented relating this index to overall dustiness as measured by impinger counts and to absolute fiber concentration and distribution as measured by electron microscopy. The relation between count estimates and gravimetric measures of total dust and chrysotile asbestos deduced from magnesium analyses are given for gross and respirable samples. These relations are developed for use in operations in the manufacture of asbestos textile, friction, cement, and insulation products. The most convenient, practical, and direct index of asbestos fiber exposure proved to be the concentration of fibers longer than 5 microns counted on membrane filters at 430× phase-contrast illumination.

Introduction

AT THE NEW YORK ACADEMY OF SCIENCES Conference on the Biological Effects of Asbestos in 1965, Gilson[1] noted the proliferation of dust sampling methods and appealed for international comparability of dust measurement data to be related to biological data. He also observed that, as dust levels are lowered, it becomes more important to use the index that is biologically most appropriate.

At the present time the goal of international comparability has been partly achieved by the adoption of the concentration in numbers of fibers longer than 5 microns counted on membrane filter samples at 430× magnification with phase-contrast (PC) illumination as the standard method in both Britain and the United States.[2,3] However, information that would permit evaluation of the biological appropriateness of this index is still not complete.

It is rarely possible to make an absolute measurement of that characteristic of an airborne dust which is directly responsible for its biological effect. To be practical, measurement for the purpose of assessing hazard and evaluating control must not only be convenient and relevant but also permit the use of statistically adequate sampling strategies. To evaluate indices obtained from varying exposure situations, an examination of the consistency of their relation to other and absolute measures was undertaken.

The large number of methods which might be used to measure exposure to airborne dust containing fibers results from what might be called the "degrees of freedom" of the dust cloud. In measuring the concentration of a gas in air, there is only one attribute to be measured, and one accurate method gives the same result as another. With *granular* dust, however, the attribute could be either number or weight, and with *fibrous* dust, length gives another degree of freedom; furthermore,

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a dust of *mixed* fibers and grains gives yet another.

Because of this variety of attributes, there could be as many as 100 indices of exposure to the asbestos in a dust cloud. In this United States Public Health Service epidemiological study of the asbestos products industry, the choice was narrowed down to the count and weight methods shown in Table I. Based on the results of analysis of almost 10,000 samples, this paper presents summaries of the relationships between these methods in order to (1) exhibit the effect of product and operation, (2) reveal the bias of the methods, and (3) evaluate the usefulness of the indices derived.

Impinger Relationships

The early epidemiologic data on asbestos were based on the impinger method and, until the beginning of the present study, most sampling in the United States was done by this method, since only in this way could the exposure be evaluated against the threshold limit value (TLV) of 5 million particles per cubic foot (mppcf).[4,5] Consequently, it is necessary to develop ratios between present methods of measurement and impinger counts performed in the traditional manner so that the results that would have been obtained years ago had present methods been used might be predicted.

The ratios shown in Table II were developed from simultaneous pairs of impinger–membrane filter samples and are expressed as the fiber counts equivalent to 1 mppcf by impinger. Equivalence means the fiber concentration that would be found, on the average, when the impinger samples were giving, on the average, a concentration of 1 mppcf in the same product area. The product areas are *textile* for asbestos spun and woven products, *friction* for brake linings and clutch facings, and asbestos cement pipe.

In all cases the correlation coefficients from the large numbers of pairs of simultaneous samples are not over 0.6, as would be expected from pairs of measurements of a real environment, each having its own intrinsic error and not necessarily measuring the same thing. The impinger results are counts of all visible particles, mostly grains with generally less than 20% fiber. These few fibers seen in the impinger sample are a small fraction of the fibers counted on the membrane filters, since the membrane filter is a more efficient collector of fibers and the magnification/illumination used results in improved visibility. In the case of the impinger versus total and >5-micron fiber ratios in the pipe plants, the correlation coefficient was not significantly different from zero at the 95% confidence level, and the hypothesis that the measures of exposure are unrelated cannot be rejected. In this case a usable prediction ratio will probably need to be based on ratios calculated for subsets within pipe manufacturing operations.

TABLE I
Selected Measures of Fiber Exposure

Count	Weight
Total dust in impinger at 100×	Total dust
Total fiber on MF at 430× PC	Respirable dust
Fibers >5 microns on MF at 430× PC	Chrysotile by magnesium
Total fiber on MF by electron microscope	Respirable chrysotile by magnesium

TABLE II
Impinger/Membrane Filter Count Ratios (fibers/ml for 1 mppcf)

Product	Fibers Total	Fibers >5 μ	Fibers >10 μ	Number of Pairs
Textile	10.3	5.9	2.7	500
Friction	3.7	2.2	1.0	200
Pipe	4.8*	1.9*	0.7	100

*Correlation coefficient not significant at 95%.

Size and Visibility

To appraise the value of an exposure index based on measurement of only a part of the things which may have biological significance, it is necessary to examine how that part relates to the whole. A count of fibers longer than a stated length as seen through a precisely defined optical system may be chosen as an index in order to eliminate as a variable the microscopic system's resolving power. It follows, however, that some fibers that are seen will be below the stated length and others will be below the limit of visibility and will not be seen at all.

Table III
Fiber Size Distribution

Operation	430× Phase Contrast, % of Total Fibers	
	Longer than 5 µ	Longer than 10µ
Textile		
Fiber preparation and carding	50	25
Spinning, twisting, and weaving	61	38
Friction		
Mixing	68	30
Grinding, cutting, and drilling	63	31
Pipe		
Mixing	57	28
Finishing	58	27
Insulation		
Mixing	55	27
Finishing	50	29

Table IV
Ratio of 970× to 430× Fiber Concentrations (phase contrast)

Operation	Fibers	
	Total	>5 µ
Textile		
Fiber preparation and carding	2.0	2.1
Spinning, twisting, and weaving	1.8	1.9
Friction		
Mixing	1.1	1.1
Grinding, cutting, and drilling	1.0	1.1
Pipe		
Mixing	1.2	1.2
Finishing	1.6	1.8
Insulation		
Mixing	1.0	1.1
Finishing	1.8	2.0

The proportions of >5-micron and >10-micron fibers of all the fibers visible at 430× PC on membrane filters are shown in Table III, broken down by operation within product area. Despite the fact that the textile operations and the three mixing operations are all cases of secondary dust dispersion (that is, the small dust particles already exist in the bulk material and are being shaken loose) whereas grinding and finishing are primary dispersion (that is, the dust is being produced and dispersed *simultaneously* by mechanical abrasion), the proportions are quite consistent. *Although* mode of dispersion undoubtedly has an effect on the proportion of large particles, this effect apparently has a negligible influence on the number distribution of particles in the size range of biological significance. Similarly, the variation in bulk asbestos quality, from the long fiber used in textile to the short fiber used in pipe, has no apparent effect on the count proportions of fibers by length.

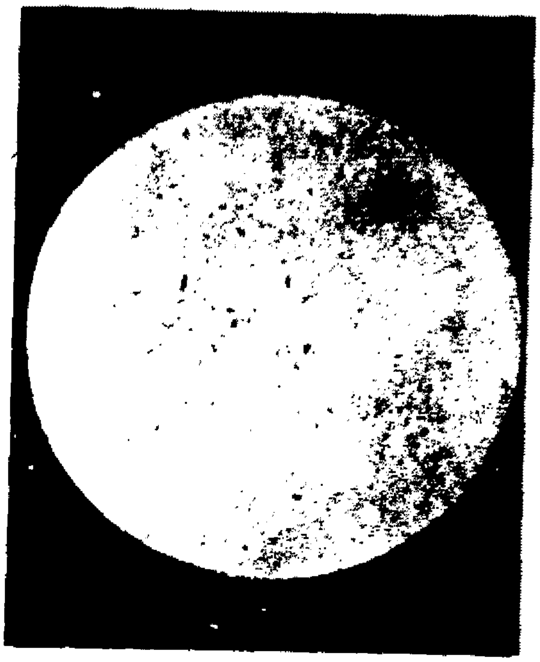

Figure 1. Chrysotile asbestos dust viewed at 430×, phase contrast.

Figure 2. Chrysotile asbestos dust viewed at 970×, phase contrast.

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Vorwald,[6] in his early animal studies of the toxicity of asbestos, suggested that the long fibers are more toxic than the short, and this possibility has been raised again by the results of recent investigations.[7] While this possibility undoubtedly influenced researchers in England and in the United States to count fibers longer than 5 microns, the present continued use of this index is based on the reduction of visibility variability, referred to above as well as on the biological implications.

The ratio of the number of fibers seen at 970× PC to those seen at 430× PC on the same filter is shown in Table IV. These results are based on a relatively small number of samples, and the confidence limits may be quite wide. They do, however, indicate that the increase in visibility is roughly the same for fibers longer than 5 microns as for total fibers. Thus, the critical factor in fiber resolution at this level of magnification is fiber diameter. A typical 430× PC field is shown in Figure 1 and a 970× PC in Figure 2.

The electron microscope, which has sufficient resolving power to reveal the elementary chrysotile fibril, permits measurement of all dust particles of interest. Fraser[8] has developed a method for the direct transfer of dust particles from membrane filters to electron microscope grids. A large number of electron micrographs of samples from the different operations were sized with a Zeiss particle size analyzer. Size distributions, such as that shown in Figure 3, were used to obtain the statistical parameters in Table V. It is important to note that only a small proportion of the fibers were over 5-microns in length. Even if it is assumed that all these are being counted at 430× PC, only 1/25 to 1/100 of the true number of fibers would be counted. Further, as was shown in Table IV, 430 × PC may count as few as half of the fibers > 5-microns visible at 970 × PC. Even total fiber counts at 430 × PC, which are about twice as high as over—5-micron 430 × PC counts (Table III), still include less than 10% of the true number of fibers in the air.

Since all light microscope methods can measure only a small part of the whole airborne fiber cloud, it is important to consider the use of electron microscope counts as an exposure index. Certain disadvantages, such as preparation time, equipment cost, and lack of general availability, are obvious. Several other problems should also be considered. Samples of a particle density appropriate for light microscope counting are too sparse for electron microscopy unless a very large number of fields are counted. Special techniques are required for random field selection to avoid counter bias. Most important is the occasional presence of large numbers of very small fibers (about 0.1-micron thick by 1.0-micron long) as seen in Figure 4. Since these small fibers often occur in groups, it is possible that they are airborne as clumps (of respirable size) rather than as single fibers.

A number of electron microscope preparations of samples previously counted by optical microscopy were made. The counts of longer fibers on electron micrographs did not ap-

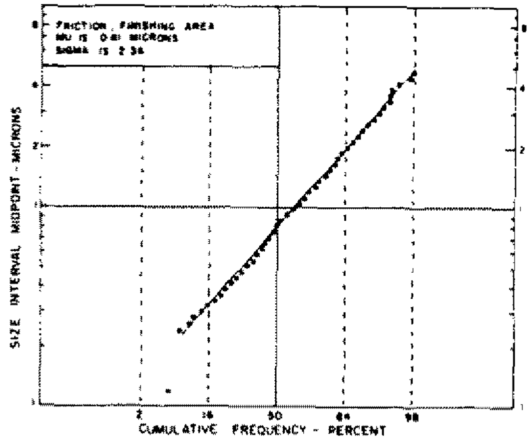

FIGURE 3. Fiber length distribution.

TABLE V
Fiber Size Distribution
(5000× electron microscope)

Operation	Count Median Length (μ)	σg	% >5 μ
Textile			
Fiber preparation and carding	1.4	2.0	4
Spinning, twisting, and weaving	1.0	2.0	2
Friction			
Mixing	0.9	2.2	2
Grinding, cutting, and drilling	0.8	2.4	2
Pipe			
Mixing	0.9	2.3	2
Finishing	0.7	2.2	1

FIGURE 4. Electro[illegible]rograph of chrysotile asbestos dust.

T[illegible] VI
Coun[illegible] W[illegible]ght Ratios

Product	Type of Fiber Count	Geometric Mean ([illegible] per μg)	Geometric Standard Deviation
Textile	Total	14,500	2.5
	$>5\ \mu$	6,700	3.3
	$>10\ \mu$	3,400	3.5
Friction	Total	26,300	3.4
	$>5\ \mu$	13,900	3.6
	$>10\ \mu$	5,300	4.4
Pipe	Total	46,500	2.8
	$>5\ \mu$	22,500	2.9
	$>10\ \mu$	6,300	3.4

pear to be greater t[illegible] those obtained by optical microscopy. Th[illegible] technical difficulties involved in the prepa[illegible]on and counting of asbestos samples mak[illegible] quantitative conclusions impossible from th[illegible] data obtained, but it appeared that the [illegible] difference between electron microscope [illegible]nts and optical counts was in those fibe[illegible] shorter than 1-micron. These small fibers, w[illegible]n they are present, dominate the electro[illegible] microscope count. Even if the other technic[illegible] difficulties mentioned could be overcome, [illegible] would result, from an electron microsco[illegible] count method, would be fiber concentra[illegible] strongly biased by these very small fibe[illegible] Present evidence does not indicate that th[illegible] should be given such a dominant role.

Weight Relationships

Differences betw[illegible] counters and certain statistical considerations make it difficult to obtain close agreement between counts even within a laboratory, and the differences are even greater between laboratories. These factors, plus the tediousness of counting, led industrial hygienists to seek weight methods of analysis wherever they are appropriate. Recent examples of this trend are the new weight TLV's for quartz and bituminous coal. This reasoning applied to asbestos led to the collection of many gross and respirable mass samples, analysis of which yielded some relationships between count-and-weight and among-weight methods.

Chrysotile asbestos and its parent rock, serpentine, are hydrated magnesium silicates containing a relatively constant 25% magnesium. Owing to the extremely high sensitivity of the atomic absorption spectrometer for magnesium (0.01 $\mu g/ml$ for 1% absorption), it is possible to count asbestos fibers on one-half of a membrane filter at 430× PC and to analyze the other half for magnesium. In this way, the direct count/weight ratios shown in Table VI were obtained. Several difficulties with this method are readily apparent. Only chrysotile asbestos is determined; thus, the crocidolite used in some types of asbestos cement pressure pipes is not included in the weight of asbestos. Further, all other sources of magnesium, especially the nonfibrous parent rock associated with the chrysotile asbestos, interfere directly.

Although count data did not exhibit any consistent shift in fiber length distribution with product, operation, or mode of dispersion, the weight of asbestos, calculated from the magnesium content, gave decreasing fiber weight in this order: textile, friction, pipe (Table VI). When the count/weight ratios were used to convert the tentative TLV of 12 fibers (5 μ length) per milliliter to the equivalent gross weight concentrations of asbestos (based on magnesium determinations), the gross weight concentrations were 2 mg/m^3 for textile, 1 mg/m^3 for friction, and 0.5 mg/m^3 for pipe. A single value for the weight TLV for all product areas would be equivalent to a fourfold difference in fiber threshold between textile and pipe plants.

Since only the dust capable of penetrating into the pulmonary air spaces is biologically significant in pneumoconiosis-producing diseases, a number of samples were collected by means of respirable-mass size-selective sampling devices. A horizontal elutriator having characteristics similar to those proposed by the British Medical Research Council[9] for respirable dust sampling was used ahead of membrane filters on which fibers were counted at 430× PC. A membrane filter sample without the elutriator was taken simultaneously, and the counts from the pair of samples were used to calculate the data in Table VII. The finding that 60% of the fibers over 10 microns were able to penetrate the elutriator reveals that many of the longer fibers are thin enough to have falling speeds in the respirable range. Other simultaneous sample pairs, using a Hexhlet and a gross dust filter side by side, were analyzed for asbestos by magnesium, giving the results shown in Table VIII. The 95% confidence intervals of the mean percent passing are typical of the range of most of this data. Use of the gross weight of dust found on these same samples, together with the asbestos by magnesium analyses, resulted in Table IX. The percent asbestos in the product, total dust, and respirable dust does not vary greatly for the same product. However, the percent of asbestos to be expected in either the total or the respirable dust will vary from 5% to 65% from product to product.

Summary

The impinger measures all types of dust, and as the TLV for asbestos decreases, the non-asbestos dust present becomes a major source of error in the estimation of exposure to asbestos. Other count methods, however, are available to count asbestos fibers, with varying degrees of convenience. Weight methods that cannot differentiate asbestos from other dust suffer from the same disadvantage as the impinger in that the asbestos fiber concentration could differ by a factor of 10 for the same total or respirable dust concentration, depending on the product area. The method for chrysotile weight by magnesium analysis is not specific or general enough to form the basis for a threshold for asbestos.

TABLE VII
Respirability of Textile Fibers by Count

Type Fiber Count	% Passing Elutriator
Total	84
>5 μ	80
>10 μ	60

TABLE VIII
Asbestos Dust Passing an Elutriator

Product	Mean Weight % Passing	95% Confidence Interval
Textile	31	24–38
Friction	29	21–37
Pipe	44	39–49
Insulation	22	19–25

TABLE IX
Asbestos in Product and Dust

Product	% Asbestos Content		
	Product	Total Dust	Respirable Dust
Textile	75–85	68	64
Friction	30–60	22	36
Pipe[a]	10–30	12	18
Shingle	10–30	25	28
Insulation[b]	5–15	4	6

[a] Not including crocidolite.
[b] Not including amosite.

Conclusions

Certain general statements are possible, based on the data presented:

1. There is, at present, no practical absolute method for the routine measurement of exposure to airborne asbestos fibers. The technical difficulties of the electron microscope for dust counting make its routine use unfeasible: when it is used, the results are heavily biased in favor of very small fibers.

2. Each of the methods considered measures something different and, therefore, they do not correlate well. Ratios between results by different methods should be used for qualitative prediction only.

3. Each method is strongly influenced by one attribute of the dust cloud. The biologically optimum method cannot be selected un-

less it is known which attribute is biologically most appropriate.

4. The preferred index of asbestos exposure is fibers longer than 5 microns counted on membrane filters at 430× phase contrast. The method of counting is convenient and practical, and fibers >5 microns constitute a direct index of asbestos fiber exposure.

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Radiation Publications

The International Commission on Radiation Units and Measurements has recently issued two new reports which are of interest to industrial hygienists dealing with radiation problems. These reports are:

ICRU Report 16: *Linear Energy Transfer.* This report defines the concepts of linear energy transfer and the methods of calculations of distribution of absorbed dose. The applications and limitations of the linear energy transfer concept are also covered. In a series of nine appendices, measurement, range, distribution, dosimetry, and symbols are presented. An extensive bibliography is included. The publication may be purchased for $3.00 per copy.

ICRU Report 17: *Radiation Dosimetry: X-Rays Generated at Potentials of 5 to 150 kv.* In this report there are discussions of measurement of energy fluence, spectral distribution, measurements and absorbed dose. This publication may be obtained for $2.50 per copy.

Address orders or inquiries to ICRU Publications, P.O. Box 4869, Washington, D. C. 20008.

Proposed Revision

The American National Standards Institute is proposing to revise the following standard:

Z9.1-1951 *Safety Standard for Ventilation and Operation of Open-Surface Tanks.* This standard covers the protection of operators from contact with gases, vapors, mists, or liquids used in, created, related, released or disseminated by open-surface tank operations and the design of ventilating systems for controlling and removing said gas, vapors, or mist. This guide does not cover protection from fire.

Comments relative to the proposed revision of this guide will be welcomed by the Board of Standards Review and the comments should be received by November 24, 1970. Copies of the standard may be purchased from the American National Standards Institute, Department BSR, 1430 Broadway, New York, New York 10018.