

spheres, but spherical uranine crystals. The importance of the microscopical particles generated from the process to determine the health hazard, temperature, chemical factors on the particles. The importance of particle parameters is outlined by the fact that in calibration work, the physical characteristics of the aerosol is essential.

densities of spherically diameter uranine particles, utilizing a 1% aqueous solution of uranine. Particle size and terminal velocity measurements were made for a horizontal elutriator. The particles were sized and located in order to derive the distribution of the particles. The data were analyzed statistically and a ratio of 1.32 for the ratio of the terminal velocity limits between the two size ranges was found. The ratio d_p/d_v parameter did not vary with the size range studied. The ratio $d_p/d_v = 1.32$ corresponds to a density of 0.58 gm/cm³. The density of uranine powder was determined by the ratio d_p/d_v to be 1.53 gm/cm³.

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Measurement of Dust Exposures in the Asbestos Textile Industry

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Data obtained from environmental surveys of nine asbestos textile mills, which represent the baseline for the textile segment of the Public Health Service epidemiological study of asbestos processing industries, are presented. From these data concentration ranges are derived which yield significant differences between typical sample groups. Variance ratio tests of different methods of counting and analysis were made and count weight ratios based on magnesium analyses for asbestos were calculated.

Introduction

THE DIVISION of Occupational Health of the U. S. Public Health Service has been conducting an epidemiological study of the asbestos products industry since January of 1964. This study was prompted by the need to refine and update earlier work done in these industries in relation to asbestosis^{1,2} and to appraise the association of asbestos with other health hazards suggested by a number of investigators.³⁻⁶ The procedures and objectives of this study have been discussed in earlier papers^{7,8} and the relationships between impinger counts and fiber concentrations on membrane filters have been presented.⁹

The environmental field study phase commenced with an asbestos textile plant in January, 1964, and the last of the textile plants to be included in the study was surveyed in June, 1965, thus completing the asbestos textile baseline. The nine plants surveyed account for over 80% of the workers in the industry and provided a cohort of over 2500 employees exposed to asbestos dust in varying degrees.

The conduct of this study was somewhat more complex than previous studies of dusty trades by the Public Health Service in that both the exposure itself and methods of

characterizing the exposure had to be studied simultaneously. In order to accomplish this, a large number of samples were required (Table I).

The analysis of these data by manual methods would have involved an excessive burden and, consequently, the major portion of the data were transcribed onto punch cards for computer processing. In addition to facilitating routine calculations of dust concentrations, computer processing made possible detailed statistical analyses which would otherwise have been prohibitively time-consuming.

This paper summarizes the baseline asbestos textile dust count data and gives some observations on sampling methods and strategy and count-weight relationships. Other data, resulting from analyses for polynuclear aromatic hydrocarbons, trace metals, etc., will be included in later papers.

TABLE I
Numbers of Samples Collected
in Asbestos Textile Plants

	Membrane Filter	Impinger
Breathing zone	608	605
Personal	810	2
General air	478	508
Total	1,896	1,115

TABLE II

Mean Dust Concentration by Plant and Operation
Impinger, mppcf

Operation	Plant									
	A	B	C	D	E	F	G	H	I	All*
Fiber prep.	5.0	1.5	2.6	2.5	0.5	1.7	2.5	0.6	2.3	
Carding	2.2	1.2	2.7	1.8	0.6	0.7	3.2	0.3	1.2	
Spinning	2.2	0.7	3.4	3.0	0.5	2.0	1.3	1.1	1.2	
Twisting	1.3	2.3	2.5	5.4	0.4	3.9	1.5	0.4	1.9	
Winding	1.2	0.9	2.0	1.7	0.4	3.0	0.4	0.4	1.0	
Weaving	1.3	0.5	0.4	3.7	0.6	0.3	1.1	0.4	0.3	
All*	2.7	1.3	2.2	2.8	0.6	0.5	1.7	1.1	0.5	1.3

* The "All" concentrations are the grand mean for all the samples in a plant or operation.

Dust Concentrations

Tables II and III present the mean dust concentrations by plant and principal operation in all the plants surveyed. In all cases, the median was also calculated, and was usually in close agreement with the mean. The impinger concentrations include both grains and fibers, and the counts were made in accordance with the American Conference of Governmental Industrial Hygienists (ACGIH) procedure. Thus, these values may be compared to the existing Threshold Limit Value of 5 million particles per cubic foot (mppcf). The membrane filter (MF) samples were counted using a procedure described in detail by Edwards.¹⁰

Early workers in the study of asbestos exposure elected to count grains as well as fibers since too few fibers were seen in im-

pinger samples. That fibers were not seen was not because they were absent, but because the 100X light field counting method used with the impinger did not reveal them. The ratios of fiber counts by different methods are shown in Table IV.

The ratios given in Table IV were obtained by dividing the concentration of fibers determined by the method given in the heading, by the fiber concentration as determined by the method listed at the side for a large number of the same or comparable samples. For example, the total fiber concentration as determined by optical membrane filter counts at 430X phase contrast was eight times that found on comparable impinger samples counted at 100X light field. These ratios are not necessarily meant to indicate any degree of equivalence, but only to show the relative magnitude of the numbers of

TABLE III

Mean Dust Concentration by Plant and Operation
Membrane Filter - fibers/cc

Operation		Plant									
		A	B	C	D	E	F	G	H	I	All
Fiber Prep.	(A)	38.1	12.3	23.3	34.0	8.1	7.6	35.5	11.8	21.2	
	(B)	15.0	10.0	13.3	18.3	3.0	4.5	17.0	2.6	7.6	
	(C)	7.1	3.4	5.8	8.2	1.1	2.0	9.3	1.2	4.2	
Carding	(A)	18.1	13.6	20.6	32.9	6.0	17.2	28.2	8.3	14.9	
	(B)	10.2	9.2	13.3	15.2	3.5	8.1	13.4	2.0	7.0	
	(C)	4.3	4.1	5.9	8.4	1.6	3.2	7.1	0.9	3.7	
Spinning	(A)	9.6	4.1	20.2	29.8	5.1	24.8	20.8	7.4	12.3	
	(B)	6.6	3.2	18.9	15.7	3.5	10.8	10.5	1.8	6.2	
	(C)	3.2	1.9	6.4	10.3	1.8	6.3	6.1	1.1	3.6	
Twisting	(A)	9.3	6.9	15.8	51.4	4.8	25.9	16.7	3.1	14.0	
	(B)	6.4	5.2	7.5	22.4	3.3	12.9	7.2	1.1	6.2	
	(C)	3.7	3.3	4.7	18.8	1.9	7.8	4.1	0.7	4.7	
Winding	(A)	11.7	4.4	9.6	28.6	4.5	25.7	7.0	3.6	9.9	
	(B)	7.5	3.9	8.9	17.5	3.2	11.7	2.7	1.3	4.6	
	(C)	4.7	1.7	3.4	11.9	2.0	7.3	1.6	0.9	3.4	
Weaving	(A)	7.7	7.0	2.9	33.8	4.5	2.9	9.5	8.1	2.9	
	(B)	4.8	3.1	2.3	17.8	3.9	2.2	5.7	3.0	1.5	
	(C)	2.9	2.8	1.1	9.8	1.4	1.2	3.3	1.8	0.7	
All	(A)	17.3	10.2	15.7	34.7	4.5	4.6	16.2	14.4	5.9	
	(B)	8.5	7.5	9.4	12.1	3.9	3.0	8.1	6.3	1.7	
	(C)	4.4	3.4	4.7	10.5	1.4	1.5	4.4	3.6	0.9	

Note: A = total fibers; B = $> 5 \mu$ fibers; C = $> 10 \mu$ fibers

TABLE IV

Ratios of Fiber Counts by Method

Impinger	Membrane Filter		
	Optical	Electron	Microscope
Total Fibers	Total Fibers	Total Fibers	Total Fibers
Impinger	1	8	(32)
MF Total Fibers	1	1	(100)
Electron			4
Microscope $> 3 \mu$			13
Electron Microscope Total			3
			1

TABLE
Significantly Different Concentration

Group	Impinger mppcf Grains & Fibers	Total Fibers
1	1-5	1-5
2	5-20	5-20
3	20-80	20-80

fibers detected by the dil ratios enclosed in paren by indirect comparisons graphs of impinger sam ble.

It is evident that mo those longer than 3μ , either the impinger or the filter procedure, probab too thin to be detected. However, enough fibers, brane filters at 430X ph statistically useful index fibers present. Since it significant biological p is its morphology, only f brane filters are present.

Regarding the interpre some caution must be u ing excessive significance. Some method of catego ness is needed for even health data to arrive a posure. Given the inher environment and the counting, broad ranges concentrations will be standard deviations calc and operation group of termed that a four fo centration was required fificance level of $p=0.0$ sets. Based on this, t conveniently into three that the probability of not being significantly middle value of an adj exceed $p=0.05$ (see T between corresponding count methods are base between impinger and

IV

ounts by Method

	Membrane Filter	Optical Electron Microscope
	> 3 μ	Total
8	(32)	(100)
1	4	13
	1	3
		1

fibers were not seen
were absent, but be-
eld counting method
did not reveal them.
ts by different meth-
IV.

Table IV were ob-
concentration of fibers
d given in the head-
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fiber concentration
filter membrane filter
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1	All
1.8	21.2
2.6	7.6
1.2	4.2
3.3	14.9
2.0	7.0
0.9	3.7
7.4	12.3
1.8	6.2
1.1	3.6
1.1	14.0
1.1	6.7
7.7	4.7
6.6	9.9
3.3	4.6
9.9	3.4
9.9	8.0
9.9	3.6
9.9	2.5
9.9	12.5
9.9	5.6
9.9	5.5

TABLE V
Significantly Different Dust
Concentration Groups

Group	Impinger Grains & Fibers	Membrane Filter Fibers/cc		
		Total Fibers	> 5 μ Fibers	> 10 μ Fibers
1	1-5	1-5	7-3	3-1.5
2	3-13	5-20	3.0-12	1.5-6.0
3	20-83	20-80	12.0-48	6.0-24.0

fibers detected by the different methods. The ratios enclosed in parentheses were obtained by indirect comparisons since electron micrographs of impinger samples were not possible.

It is evident that most of the fibers, even those longer than 3 μ, are not counted by either the impinger or the optical membrane filter procedure, probably because they are too thin to be detected by light microscopy. However, enough fibers are found on membrane filters at 430X phase contrast to be a statistically useful index of the number of fibers present. Since it is probable that the significant biological property of asbestos is its morphology, only fiber counts on membrane filters are presented.

Regarding the interpretation of these data, some caution must be used to avoid assigning excessive significance to small differences. Some method of categorizing relative dustiness is needed for eventual correlation with health data to arrive at safe levels of exposure. Given the inherent variability of the environment and the variability in dust counting, broad ranges or classes of dust concentrations will be required. From the standard deviations calculated for each plant and operation group of samples, it was determined that a four fold difference in concentration was required to obtain a significance level of p=0.05 on typical sample sets. Based on this, the data fell rather conveniently into three arbitrary groups such that the probability of any value in a group not being significantly different from the middle value of an adjacent group does not exceed p=0.05 (see Table V). The ratios between corresponding groups by different count methods are based on the equivalence between impinger and filter count.

The groups are designated by number rather than low, medium and high, to avoid the implication that they can be compared with any existing standard. Using the concentration ranges given in Table V, a chart of the group numbers by plant and operation was prepared (Figure 1). The upper left triangle contains the group number as determined by impinger and the lower right by membrane filter total fiber counts. In 75% of the cases, the two methods lead to the same estimate of relative dustiness, and in cases where the groups are different, the differences never exceed one group and show no consistent trend.

Since our concern is with exposure, or body burden rather than with dust concentrations, a different grouping may be derived by the method of Roach.¹² It can be shown that:

$$\frac{\text{Coef. of Var. of Body Burden}}{\text{Coef. of Var. of Concentration}} \leq 0.59 \left(\frac{t}{T} \right)^{1/2}$$

where *t* is the duration of the samples used in determining the concentration and *T* is the biological half-time of the contaminant. Since *t* never exceeded two hours and *T* is greater than six months, the ratio of coefficients of variation cannot be greater than 0.026. If the Coefficient of Variation of Body Burden obtained in this manner is used to estimate the standard error of the difference, ranges of concentration can be calculated such that the body burdens caused by sample means falling within one range are significantly different (p<0.01) from those caused by concentrations at the midpoint of an adjacent range (Table VI).

The same procedure illustrated by Figure 1 was applied using the body burden groups. As would be expected from the narrower limits of the classes, the agreement was not as good, with only 50% of the sets of samples yielding the same group by both methods. However, in less than 10% of the sets did the appraisal of dustiness differ by more than one group, in no case by more than two groups, and again these differences showed no consistent trend.

The general agreement between the groups gives one confidence that both methods are

	PLANT								
	A	B	C	D	F	G	H	I	
FIBER PREPARATION	3 3	2 2	3 3	3 3	2 2	2 2	3 3	2 2	
CARDING	3 2	2 2	3 3	2 3	2 2	2 2	3 3	1 2	
SPINNING	3 2	2 1	3 3	3 3	2 2	3 3	2 3	2 2	
TWISTING	2 2	3 2	3 2	3 3	1 1	3 3	2 2	1 1	
WINDING	2 2	2 1	2 2	2 3	1 1	3 3	1 2	1 1	
WEAVING	2 2	2 2	1 1	3 3	1 1	2 2	1 2	1 1	

FIGURE 1. Comparison of results by concentration groups.

measuring approximately the same thing in asbestos textile plants. However, if in the case of either the body burden or concentration method of grouping, the membrane filter total fiber count arrived at exactly the same decision as to relative dustiness as the impinger count, there would be no basis for distinguishing between these dust measurements by their relevance to disease parameters. Both would correlate, or not correlate, equally well with medical findings. Thus, the larger range of disagreement between methods in the body burden groups may be useful in establishing the relevance of the methods.

By either the concentration or body burden method, the results appear to be more uniform for different operations within a

plant than for the same operation in different plants indicating that the engineering effort made toward good dust control within a plant is more of a dominating factor than the difference between operations.

Sampling Methods and Strategy

All of the usual and some of the less frequently used methods of sampling for mineral dusts in industrial environments were used in this study, and the large numbers of samples of each kind permitted comparison of these methods.

One question which could be answered from these data is the relative variability of different count methods of analysis. To examine this factor, the variance ratio test¹² was applied to the sample groups by different count methods in each plant and operation. These methods included impinger grains and fibers versus membrane filter total fibers, total fibers versus $>5 \mu$ fibers and total fibers versus $>10 \mu$ fibers. In all cases, the variance ratio test indicated that the difference between the standard deviations by the different methods was not significant ($p > 0.05$) and that none of the methods could be considered less variable than the others. This finding is interesting in that it had been

assumed that membrane filter phase contrast might be a light field impinger count ($>10 \mu$) fiber counts might be more visible than total fiber counts since they should be more visible.

To investigate this matter, samples on which magnifying asbestos were performed later in this paper) were compared with dust counts made on the same samples. Since the precision of analyses ($<5\%$ error) is compared with dust counts, the variance ratio test was applied. The ability in the asbestos count was not the case, and as between standard deviation was not significant. From this outcome, it was assumed that the sample dependent estimates of the variance. Thus, the variance actually the variability of that is, the variability of group of workers doing job at different times and ability in dust counting. not be significant when actual variability of the

Count-Weight Relations

Chrysotile asbestos, over 90% of the asbestos, is a hydrated magnesium silicate. It has a relatively constant weight of about 25%. With the developed atomic absorption method, it is possible to analyze for sensitivity in the order of $1 \mu\text{g}/\text{m}^3$. Consequently, a direct count-weight relation may be performed on samples which are light and this magnesium weight of asbestos present in the count and weight a direct count-weight relation.

Several potential sources of error are immediately apparent. fibrous parent mineral asbestos developed

TABLE VI
Significantly Different Dust
Concentration Groups
Body Burden Method

Group	Impinger mpcf Grains & Fibers	Membrane Filter fibers/cc		
		Total Fibers	$>5 \mu$ Fibers	$>10 \mu$ Fibers
1	0.1-0.2	1-2	.6-1.2	.3-.6
2	0.2-0.4	2-4	1.2-2.5	.6-1.2
3	0.4-0.8	4-8	2.5-5.0	1.2-2.5
4	0.8-1.6	8-16	5.0-10.0	2.5-5.0
5	1.6-3.2	16-32	10.0-20.0	5.0-10.0
6	3.2-6.4	32-64	20.0-40.0	10.0-20.0

H	1
3	2
3	2
3	2
2	1
2	1
2	1
1	1
1	1

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Category

Some of the less fre-
quency sampling for min-
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assumed that membrane filter counts under phase contrast might be less variable than light field impinger counts, and that long ($>10 \mu$) fiber counts might be less variable than total fiber counts since the long fibers should be more visible.

To investigate this matter further, groups of samples on which magnesium analysis for asbestos were performed (to be discussed later in this paper) were compared with total fiber counts made on the same samples. Since the precision of the magnesium analyses ($<5\%$ error) is very good, compared with dust counts, it was assumed that the variance ratio test would show less variability in the asbestos concentrations determined by magnesium analysis. However, this was not the case, and again the differences between standard deviations were not significant. From this outcome, it may be assumed that the sample variances are independent estimates of the same environmental variance. Thus, the variability observed is actually the variability of the environment; that is, the variability of the exposures of a group of workers doing nominally the same job at different times and places. The variability in dust counting, large as it is, may not be significant when compared to the actual variability of the workers' exposure.

Count-Weight Relationships

Chrysotile asbestos, which accounts for over 90% of the asbestos used in this country, is a hydrated magnesium silicate and has a relatively constant magnesium content of about 25%. With the aid of recently developed atomic absorption techniques, it is possible to analyze for magnesium with a sensitivity in the order of 0.1 micrograms (μgm). Consequently, magnesium analyses may be performed on membrane filter samples which are light enough to count, and this magnesium may be related to the weight of asbestos present on the filter. From the count and weight on the same sample, a direct count-weight ratio may be made.

Several potential sources of error are immediately apparent. Serpentine, the non-fibrous parent mineral from which chrysotile asbestos developed, is usually present in

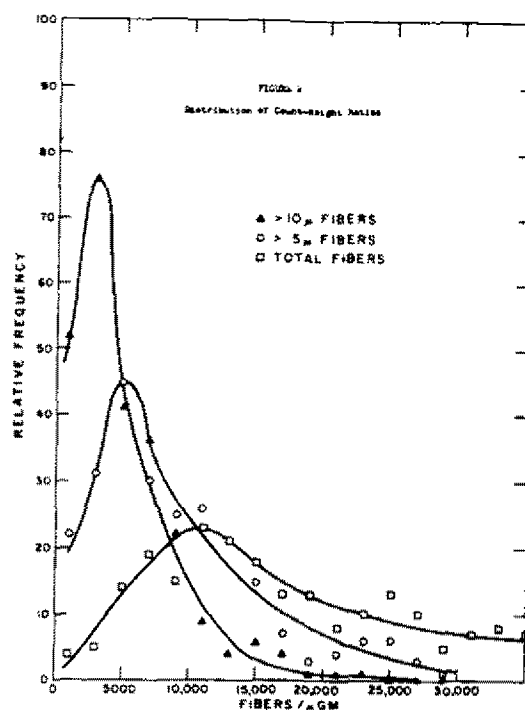


FIGURE 2. Distribution of count-weight ratios.

varying amounts with the fibrous asbestos and will contribute some magnesium but will not contribute to the fiber count. A second source of error is the ubiquitousness of magnesium and magnesium-bearing minerals. Magnesium is found in general air pollution, and significant amounts could be present in industrial dust from other magnesium-rich process materials.

Little can be done to eliminate the first source of error, and a tendency to overestimate the mass of fibrous asbestos is unavoidable. Regarding the second source of error, air pollution survey data¹³ revealed that the usual atmospheric concentrations of magnesium are several orders of magnitude lower than in-plant concentrations. Other magnesium-bearing process materials can be eliminated as a source in textile plants since the other materials do not contain significant amounts of magnesium.

Membrane filters from which a small wedge had been removed for counting were sliced in half with a sharp blade against a

TABLE VII
Count-Weight Ratios

Type Count	Fibers per μgm
Total fibers	11,000
> 5 μ fibers	5,000
> 10 μ fibers	3,000

brass die. From analyses of magnesium on these filter halves, the count-weight ratios in terms of weight of asbestos, for each type count, were calculated for each of the 250 samples analyzed. The frequency distributions of these sets of ratios are given in Figure 2.

Given the sources of error discussed above, and the natural variability of dust counts, a considerable spread in the count-weight ratios would be expected. This spread did occur, in fact, but a central tendency in each of the groups of data is apparent, and yield the approximate values shown in Table VII.

It would appear from Figure 2 that the count-weight ratios of the longer fibers exhibited less spread. However, the ratios were found to follow a log normal distribution with the same standard geometric deviation of 2.3 for all three type counts. Thus, each of the groups of ratios is equally disperse, and no one type of count is to be preferred as an estimate of mass.

An independent estimate of the count-weight ratio was obtained from size distributions on electron micrographs. Since the number of large fibers visible on these slides is small, though their contribution to the weight is very large, it was necessary to pool a number of electron micrographs of different samples, to obtain a statistically useful size distribution. From these data a typical mass median fiber volume of 50 cubic microns (μ^3) was obtained which yields a count-weight ratio of 2000 fibers/ μgm based on a density of 2.5 for chrysotile asbestos. This result is of the same order of magnitude as fiber ratios obtained from the magnesium analyses.

By applying the impinger-membrane filter equivalents obtained earlier to the weight count ratios given in Table VII, it was found that 1 mg/ m^3 of asbestos by magnesi-

um analysis as approximately equivalent to 1 mppcf by impinger. It should be emphasized that this relationship was developed by a very indirect method. However, it does indicate that asbestos mass concentrations may be higher than previously assumed.

A number of sets of simultaneous samples were taken with and without size selective presamplers. Thirty-minute samples on a pair of membrane filters, one of which was preceded by a horizontal elutriator with a 7.1 μ unit density sphere cut-off, were taken in each operation in each plant. While not all of the magnesium analyses are completed, preliminary results indicate that the respirable fraction of asbestos as determined by this elutriation is approximately 50 to 60%. Additional samples were taken in each plant using two pairs of membrane filters run for five to eight hours, with cyclones conforming to the Atomic Energy Commission criteria attached to one pair of filters. From these samples an estimate of respirable fraction of from 30 to 40% was obtained. In both cases the figures given are approximate; however, they do follow the usual performance of these presamplers, in that the cyclone passed a smaller fraction. If these respirable percentages are applied to the gross airborne asbestos by magnesium results, 1 mg/ m^3 of the total dust would probably contain 0.5-0.6 mg/ m^3 of dust passing an elutriator and 0.3-0.4 mg/ m^3 passing a cyclone. Additional magnesium analyses are being performed so that mean mass concentrations by plant and operation can be compared with the groups established for impinger and membrane filter counts, to determine if mass concentrations yield the same relative hazard estimates.

Conclusions

The results of environmental surveys of nine asbestos textile plants reveal that dust concentrations as measured by impinger are generally below the Threshold Limit Value. Due to the natural variability of the environment, categories of significantly different dust measurements must be broad. Three significant groups were obtained from concentration data and six significant groups were derived from body burden considerations. Es-

timates of relative dust filter samples were in those made from imp concentration or body grouping.

Variance ratio tests of measurement indicate variance seen is due to population and that counting exhibit any in terms of a lessened

Count-weight ratios analyses of membrane fibers > 10 μ / μgm or 11,000 total fibers of ratios exhibited a the others. A mass of 50 μ^3 , obtained from yielded a count-weight μgm which was of the tude as the ratio of analysis. Based on the borne mass concentration to one mppcf of 1 mg/ m^3 , and res tions, as determined clone, would be in th m^3 and 0.3-0.4 mg/

Hygienic criteria for disease-producing measure accurate assessment of convenient to use. T venient as any other the large variance for no less accurate the. However, it is diffic ing of the hygienic inated by grains whi to be the causes of the counting of fiber appears to have an industries where asbe tion of the airborne magnesium analysis and the method invo

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of relative dustiness from membrane
samples were in good agreement with
made from impinger samples by either
concentration or body burden methods of
impinger.

Variance ratio tests of different systems
of measurement indicate that most of the
variance seen is due to the variance of the
population and that none of the methods of
sampling exhibit any significant superiority
in terms of a lessened variance.

Count-weight ratios obtained by magnesium
analyses of membrane filters were 3000
fibers > 10 μ /ugm or 5000 fibers > μ /ugm
or 11,000 total fibers ugm. None of the sets
of ratios exhibited any less dispersion than
the others. A mass median fiber volume of
80 μ^3 , obtained from electron micrographs,
yielded a count-weight ratio of 8000 fibers/
ugm which was of the same order of magni-
tude as the ratio obtained by magnesium
analysis. Based on these ratios, a gross air-
borne mass concentration of asbestos equiva-
lent to one mppcf would be on the order
of 1 mg/m³, and respirable mass concentra-
tions, as determined by elutriator and cy-
clone, would be in the order of 0.5-0.6 mg/
m³ and 0.3-0.4 mg/m³, respectively.

Hygienic criteria should be relevant to the
disease-producing mechanisms, capable of ac-
curate assessment of the environment, and
convenient to use. The impinger is as con-
venient as any other method and in view of
the large variance found in the environment,
no less accurate than other measurements.
However, it is difficult to reconcile the bas-
ing of the hygienic criteria on counts domi-
nated by grains while the fibers are thought
to be the causes of disease. In this respect
the counting of fibers on membrane filters
appears to have an advantage, especially in
industries where asbestos is only a small frac-
tion of the airborne dust. The relevance of
magnesium analysis for asbestos is unknown
and the method involves the use of sophisti-

cated and expensive laboratory equipment
not generally available in state, local and
plant hygiene laboratories. However, it is
hoped that the intensive study of total and
respirable mass concentrations, made pos-
sible by this method, will lead to the develop-
ment of a relevant and convenient mass
sampling method.

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