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Characterizing and Discriminating Airborne Amphibole Cleavage Fragments and Amosite Fibers: Implications for the NIOSH Method

ANN G. WYLIE,[A,B] ROBERT L. VIRTA[A] and ESTELLE RUSSEK[C]

[A]Bureau of Mines, Avondale Research Center, Avondale, MD 20782; [B]Department of Geology, University of Maryland, College Park, MD 20742; [C]Department of Animal Science, University of Maryland, College Park, MD 20742

The NIOSH method for determining asbestos exposure in the mining environment involves using phase contrast microscopy to examine mineral particulates collected on air monitor filters. Particles are classified as asbestiform or non-asbestiform based on their size and length-to-width (aspect) ratio. The procedure works well when only fibers are present. In most non-asbestos mining operations, however, cleavage fragments are the most abundant airborne particulates. In this research, discriminate function analysis was applied to morphological data for airborne amphibole particulates to show that dimensional criteria could distinguish between amphibole asbestos and amphibole cleavage fragments. The particulates for this research were collected from industrial sites where amosite alone was in use and from mining sites where amphiboles are major rock-forming minerals. The results suggest that cleavage fragments can be differentiated from asbestos fibers based on dimensional criteria alone, but only if the current working definition of a fiber is modified. The data suggest that an appropriate definition of a regulatory fiber would be a particle longer than 5μm with a width less than 3μm and an aspect ratio of 20:1 or greater. Adoption of the 20:1 aspect ratio would greatly increase the precision of the NIOSH method. However, a new aspect ratio criterion must be coupled with a lower exposure index in order to prevent an increase in worker exposure to asbestos.

Introduction

The membrane filter method is specified as the method of test by the Occupational Safety and Health Administration (OSHA) Federal Standard for asbestos in industrial air (29 CFR Part 1910.1001) and in the Mine Safety and Health Administration (MSHA) regulations (30 CFR 55.5-1(b), 56.5-1(b), 57.5-1(b) and 71.202) governing mining air. The federal standards define asbestos as chrysotile, amosite, crocidolite, tremolite, anthophyllite and actinolite. The membrane filter method (NIOSH analytical method #P&CAM 239) defines an asbestos fiber as "a particulate which has a physical dimension longer than five micrometers and with a length to diameter ratio of three to one or greater."[1] Futhermore, it specifies that "in an atmosphere known to contain asbestos, all particulates with a length to diameter ratio of three to one or greater, and a length greater than five micrometers should, in the absence of other information, be considered to be asbestos fibers."[1] The five micrometer length is the most practical minimum fiber length measurable by phase contrast microscopy for fiber counting.[2-4] The choice of an elongated aspect ratio was made to eliminate most confounding mineral particles such as dirt and rock fragments, but the lower bound of three was arbitrary.[5] As long as the asbestos fiber definition is applied to an industrial environment in which only asbestos is being used, it provides a useful basis for exposure monitoring. However, in the mining environment, where many nonfibrous particles may fit the definition of a fiber, it may not be appropriate. The problem is especially acute when amphibole minerals are abundant.

Of the six minerals regulated as asbestos in the United States, all but chrysotile belong to a group of silicate minerals known as the amphiboles. Amphiboles are extremely common in the earth's crust. Approximately 30% of the rocks found in the continental United States contain amphiboles as major constituents.[6] Amphiboles are characterized structurally by a double chain of silicon-oxygen tetrahedra and they form prismatic crystals. When crushed, they form prismatic cleavage fragments which frequently have aspect ratios in excess of 3:1. Only rarely do the amphiboles grow with the extreme elongation and narrow widths typical of asbestos. This rare habit is characterized by flexibility and high tensile strength. A more extensive discussion of the asbestiform habit is presented elsewhere.[7,8] Because of the unique physical properties of asbestos, the distinction between asbestiform and other amphibole habits is readily apparent in hand specimens, but these macroscopic properties often cannot be observed on small discrete particles such as those collected on air monitoring filters. In many mining operations amphiboles are a common constituent of the rock while amphibole asbestos is present in trace amounts or absent entirely. In these environments, elongated cleavage fragments are classified as amphibole asbestos fibers according to the existing regulatory criteria and the membrane filter method.

The Bureau of Mines undertook this study in an attempt to provide criteria for discriminating between airborne amphibole cleavage fragments and amphibole asbestos fibers. Specific questions addressed were:

1. What are the dimensional characteristics of both populations?
2. What particle dimensions are common to both populations and how abundant are these particles?
3. How can the populations be best distinguished?

This type of study is necessary because amphibole cleavage fragments are often abundant in the mining environment and because, where comprehensive epidemiological studies have been made, no association between amphibole cleavage fragments and cancer has been demonstrated.[9-11]

Samples

Sixteen air-monitoring filters from two industrial sites where amosite (grunerite-asbestos) alone was being used were provided by OSHA, and eleven air-monitoring filters collected from three mine sites where amphiboles are major constituents of the country rock were provided by MSHA. These are: the Homestake Gold Mine, South Dakota; Peter Mitchell Iron Mine, Minnesota; and the Charlottesville Stone Quarry, Virginia.

For this study, we have assumed that the particles collected from the industrial sites are fibers of amosite, not cleavage fragments of grunerite. While the mining of amosite may produce cleavage fragments in the raw ore, during processing the fibers are separated from the gangue. This separation results in a commercial product which is essentially free of cleaved fragments of country rock. We have also assumed that the particles collected at the three mines are cleavage fragments. This assumption is based on the fact that the geology of the deposits has been described in detail in the literature and significant amounts of asbestos have not been noted.[12-14] On the other hand, the country rocks are known to contain large quantities of nonasbestiform amphibole: cummingtonite at the Homestake Gold Mine; grunerite, hornblende and actinolite at the Peter Mitchell Iron Mine; and actinolite at the Charlottesville Stone Quarry.[12-14] At all three mines, the country rock is crushed during mining and processing, producing large quantities of amphibole cleavage fragments. Futhermore, in preliminary studies of the mine particles collected in the same air filters, Virta *et al.*[15] have shown that the regression coefficients F and b, derived from a least-squares linear regression analysis of the form: log width = F log length + b, are similar to those derived from the same analysis of bulk samples of amphibole cleavage fragments and are markedly different from those of bulk asbestos.[15,16] While we recognize that, because we are dealing with real-world samples, we can not rule out the possibility that there could be an asbestos fiber among the cleavage fragments and cleavage fragments among the asbestos fibers. However, the approach that we have used is one that evaluates population characteristics, and the presence of a few anomalous particles would not affect the results and conclusions of this study.

Approximately 1000 particles were measured from each environment on the scanning electron microscope. All particles have aspect ratios of 3:1 or greater. Energy dispersive x-ray analysis was used to confirm the identity of every particle measured. Details of sample preparation and measurement have been presented elsewhere.[15]

Discriminant Function Analysis

In discriminant function analysis, the objective is to find the linear function of the variables — in this case, log width and log length — that most efficiently discriminates between two previously defined groups. The data were transformed into log values so that their distributions would more closely approximate normality. The analysis defines a linear function which, when computed for each particle in the two sample types, maximizes the variance between the groups relative to the variance within the groups.[17] Discriminant function analysis depends upon a prior knowledge that there are, in fact, two distinct populations. In this study the two populations from which the discriminant function was derived are the amosite asbestos fibers collected from the industrial sites and the amphibole cleavage fragments collected from the mine sites. The discriminant function that divides the two populations is of the form

$$Y = 5.9 \log \text{length} - 9.2 \log \text{width} - 6.63 \quad (1)$$

A particle is classified as a "Group A" particle if its value of Y is greater than 0 and as a "Group B" particle if Y is less than 0. By using equation (1), 81% of the asbestos fibers were assigned to Group A and 91% of the cleavage fragments were assigned to Group B. We will call the particles in Group A "fiber-like" and those in Group B "cleavage-like."

The frequency distributions of width, aspect ratio, and length for the cleavage fragments and asbestos fiber populations are shown in Figure 1. Also shown are the frequency distributions of the cleavage fragments that were classified by equation (1) as "fiber-like" and the asbestos fibers that were classified as "cleavage-like." Several characteristics of the populations are evident from the distributions shown in Figure 1. First, the distribution of length of the cleavage fragments is similar to that of the asbestos fibers while the distributions of width and aspect ratio are different. Second, while the cleavage-like asbestos fibers are wider and shorter (60% are less than 5μm) than the asbestos population as a whole, their most notable characteristics are that they have low aspect ratios (93% have aspect ratios less than 10:1) and large widths (80% are wider than 0.6μm). The distributions of aspect ratio and width of the cleavage-like asbestos fibers are very similar to that of the cleavage fragments. Third, the particles from the mine which were classified as fiber-like are distinguished from the other cleavage fragments by their narrower widths and higher aspect ratios. Seventy-six percent have aspect ratios in excess of 10:1 and 71% have widths less than 0.6μm. However, their lengths are only slightly less than those of the cleavage fragment population as a whole; approximately half are less than 5μm long.

Discussion

We do not consider it practical to use the specific discriminant function we have derived as a basis for the regulation of asbestos fiber exposure. The magnitudes of the coeffecients are too sensitive to slight changes in the populations. However, it is possible to make some general observations from the analysis which might form the basis for formulating alternative dimensional criteria. First, there are dimensions that are common to populations of airborne amphibole cleavage fragments and amosite asbestos fibers. Amosite fibers which are wide and have low aspect ratios look like

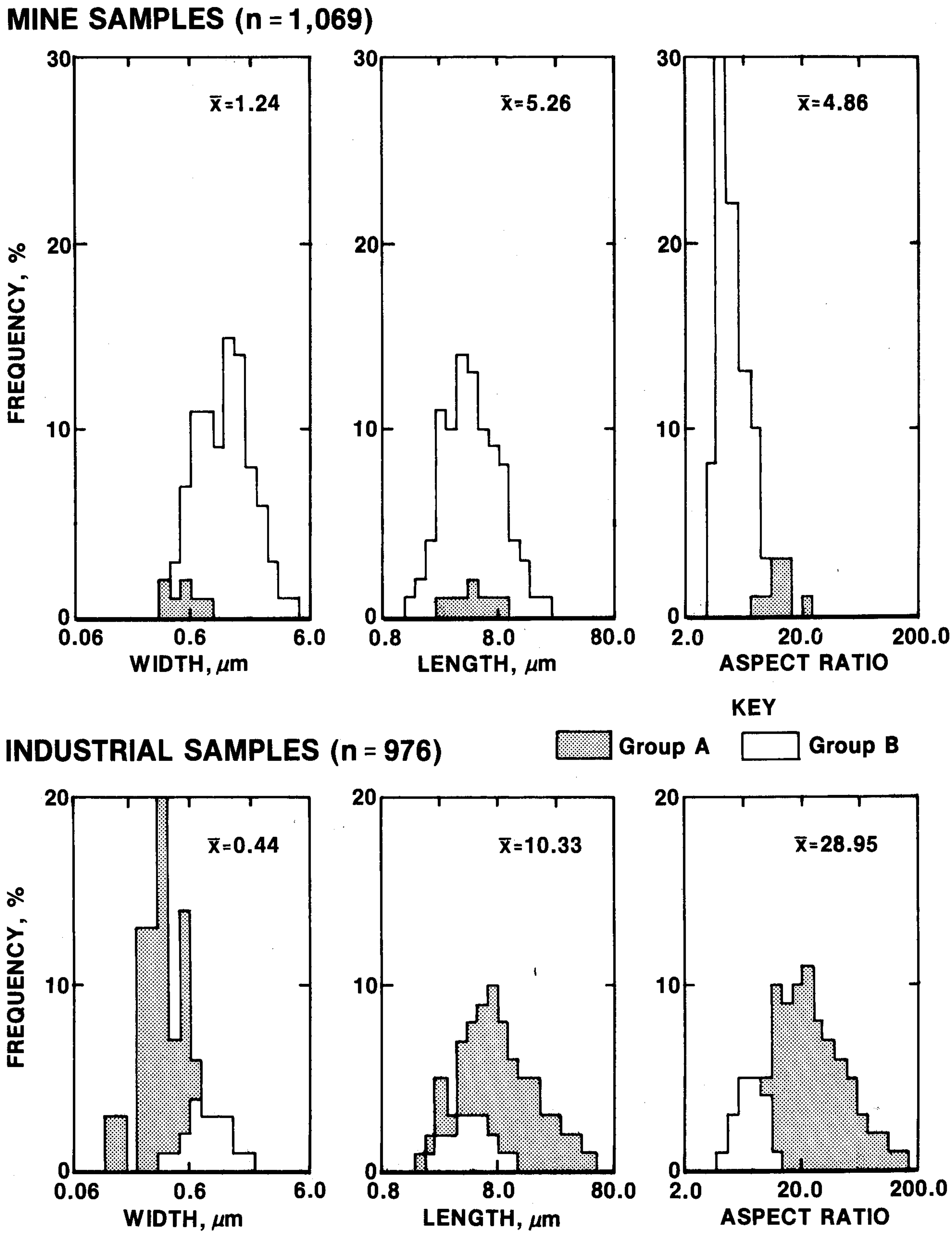

Figure 1 — Frequency distributions of width, length and aspect ratio of the amphibole cleavage fragments (Mine Samples) and amosite asbestos (Industrial Samples). Group A and Group B are the two populations defined by the discriminant function analysis.

cleavage fragments and cleavage fragments which have narrow widths and high aspect ratios look like amosite fibers. Second, particles which cannot be differentiated based on dimensions comprise a fairly small percentage of the total airborne particle population. Futhermore, amosite fibers are generally wider and have lower aspect ratios than other forms of commercial asbestos, crocidolite and chrysotile. Yet only 19% of the airborne amosite fibers could not be differentiated from cleavage fragments. These results imply that the definition of a fiber could be based on dimensions, and, if carefully chosen, could include enough asbestos fibers to provide a reasonable basis for an exposure standard while it would exclude most cleavage fragments and alleviate the problem the mineral industries face under current definitions. Third, if dimensional criteria are to be used to define a fiber, they should be chosen to describe and include long, thin particles of high aspect ratio. These are the dimensions which are most characteristic of asbestos fibers and least common in a population of cleavage fragments.

In Table I we have examined the effectiveness of six dimensional criteria for differentiating the two populations. Three of the criteria have been cited in the literature as having biological relevance. Two were chosen because they were generally consistent with our findings from the discriminant function analysis. The sixth is the criteria employed in the membrane filter method (NIOSH criteria). It is evident from the data that both the industrial and the mine populations are composed of significant amounts of "fibers" if the NIOSH criteria are applied. According to these criteria, the two populations appear similar; in both populations close to half of the elongated particles meet the regulatory criteria for fibers. It is evident that the NIOSH criteria do not dicriminate between cleavage fragments and fibers. The dimensions suggested by Stanton *et al.*[18] and Pott[19] include a very small number of the airborne amosite fibers, and it would appear that it would be impractical to base an exposure standard for amosite on them. On the other hand, if other dimensional criteria are applied, the populations can be distinguished fairly well. For example, an aspect ratio of 20 and length greater than or equal to 5μm would include 41% of the amosite fibers while it would eliminate almost all of the cleavage fragments. Similar results are obtained by using the dimensional criteria suggested by Spurney *et al.*[20]

TABLE I
Percentage of Amphibole Cleavage Fragments and Amosite Asbestos Fibers that Conform to Several Dimensional Criteria

Dimensional Criteria		Percent of Total Particles	
Length and Aspect Ratio	Width (w)	Cleavage Fragments	Amosite Asbestos Fibers
Length $\geq 5\mu m^A$	all widths	41	64
Aspect ratio ≥ 3	$w \geq 0.25\mu m$	41	50
	$3\mu m \geq w \geq 0.25\mu$	39	50
Length $\geq 5\mu m$	all widths	6	57
Aspect ratio ≥ 10	$w \geq 0.25\mu m$	6	43
	$3\mu m \geq w \geq 0.25\mu m$	6	43
Length $\geq 5\mu m$	all widths	1	41
Aspect ratio ≥ 20	$w \geq 0.25\mu m$	1	27
	$3\mu m \geq w \geq 0.25\mu m$	1	27
Length $\geq 10\mu m$	$w \leq 0.25\mu m^B$	0	5
Length $\geq 5\mu m$	$w \leq 0.5\mu m^C$	2	42
Length $\geq 8\mu m$	$w \leq 0.25\mu m^D$	0	7

^A^NIOSH membrane filter method criteria for a "fiber."

^B^Suggested by Pott (1978)[19] as having a high probability of being carcinogenic.

^C^Suggested by Spurney *et al.* (1979)[20] as having a high probability of being carcinogenic.

^D^Suggested by Stanton *et al.* (1981)[18] as having a high probability of being carcinogenic.

The NIOSH method uses phase contrast microscopy for monitoring asbestos exposure. By examining only particles with widths greater than or equal to 0.25μm, it is possible to evaluate the effects of the use of the optical microscope in conjunction with various dimensional criteria for fiber counting. A value of 0.25μm was chosen as the lower limit of visibility of fibers in the optical microscope. This is somewhat lower than the theoretical resolution of the optical conditions normally employed in air filter analysis but probably is a good approximation of the width of a visible fiber.[21] The effects of an upper width limit of 3μm, the maximum width of a respirable particle, are also given in Table I.

From Table I it is evident that the optical microscope and the SEM provide essentially identical data from the mine samples. This agreement is a result of the large widths of amphibole cleavage fragments. On the other hand, for the airborne amosite population the use of the optical microscope results in a reduction in the number of particles in all dimensional categories, especially in those of higher aspect ratio. For example, while 41% of all the amosite fibers are longer than or equal to 5μm and have aspect ratios greater than or equal to 20:1, only 27% of the visible fibers fall in this category. These data reflect the mineralogical reality that asbestos fibers have narrow widths and that many airborne fibers are not visible by optical microscopy. If the same analyses were made for crocidolite or chrysotile, the effect would be much more striking. These minerals have significantly smaller widths than amosite and considerably fewer would be visible by optical microscopy. For example, in one study it was shown that only 15% of the crocidolite fibers longer than 5μm can be seen by optical microscopy.[22] Under the present regulatory procedures and definitions, the difference in the widths of cleavage fragments and asbestos fibers has the effect of allowing higher total exposures to asbestos fibers, a designated carcinogen, than to cleavage fragments for which no carcinogenic potential has been established.

Recommendation

The existing regulatory criteria for counting asbestos "fibers" are useful for industrial monitoring during the processing and utilization of asbestos. These criteria have been in place for many years and are used worldwide to evaluate exposure in such an industrial environment. In contrast, there are many mining operations in the United States and elsewhere where employees are exposed to airborne amphibole cleavage fragments for which there are no biological or epidemiological data to support the exposure limitations required for asbestos. The critical problem is that the existing regulatory definition does not distinguish between amphibole cleavage fragments and asbestos fibers.

This research indicates that the two classes of particulates can be distinguished statistically using the following criteria for an amphibole fiber: length greater than or equal to 5μm and aspect ratio greater than or equal to 20:1 This definition includes approximately 50% of airborne amosite amphibole fibers and eliminates most amphibole cleavage fragments. For airborne particulates, these dimensions would include only fibers with widths less than 3μm, the upper limit of the size of respirable dust.

If this definition were adopted, other changes would have to follow. The 20:1 aspect ratio would include approximately 50% of the amosite particles presently counted using the 3:1 aspect ratio criterion and the optical microscope. This suggests that the occupational exposure index must be lowered so that no change in total occupational exposure would occur. If the exposure index was reduced from two fibers/mL to one fiber/mL and the 20:1 criterion was used, then those working with amosite would have a slightly reduced total exposure limit. For the other types of amphibole asbestos, especially crocidolite, these numbers would be somewhat different. Crocidolite fibers in general are much narrower than amosite fibers, and a higher percentage of the fibers longer than 5μm have aspect ratios in excess of 20:1. Approximately 75% of the optically visible airborne crocidolite fibers longer than 5μm have aspect ratios in excess of 20:1.[22] These data suggest that an exposure standard for crocidolite of two fibers/mL based on a 3:1 aspect ratio would be equivalent to 1.5 fibers/mL based on a 20:1 aspect ratio if only optically visible fibers were considered.

The adoption of new fiber criteria would bring with it other changes. The allowable levels of occupational exposure would have to be revised to insure that there were no increases in the exposure to total fiber (*i.e.*, all lengths and widths). If such a change were forthcoming, the instrumentation used for fiber counting might also be re-evaluated. The data show that the ratio of optically visible to total fiber varies dramatically among the asbestos minerals.[22] In view of this fact, electron microscopy might be more appropriate. The undertaking would be complicated. However, the alternative of ignoring the facts and leaving the existing regulations in place puts an unnecessary burden on our domestic mining industry without any obvious benefits for their employees, customers, or the general public.

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