minerals crystallized in the asbestiform habit be considered in relevant studies. The known health hazards of the commercial asbestos fibers may or may not apply to all the untested asbestiform fibers of other minerals, although there is a school of investigators which considers morphology as the major determinent in carcinogenicity. Therefore, additional studies concerning the biological effects of fibrous rock-forming silicates, especially those nonasbestiform amphiboles which have asbestiform analogues, which occur as gangue minerals in many ore deposits, should be started immediately. Control of such substances should be the same as imposed on asbestos until "safety" is demonstrated.

(5) In addition to experimental studies, it is urgent that more data be collected concerning the varieties and characteristics of inorganic fibers as they occur in human tissues.

The papers that follow represent a number of the formal presentations.

PLAINTIFF'S EXHIBIT

SA-518

FIBER LENGTH AND ASPECT RATIO OF SOME SELECTED ASBESTOS SAMPLES*

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The primary diagnostic characteristics of asbestos used by most microscopists studying environmental air and water samples are mineral identity and aspect ratio (length/width). These indices are used primarily because other asbestos characteristics, such as tensile strength, surface charge, and flexibility, are not practically demonstrable under the microscope for such samples. Therefore, microscopists rely heavily, and sometimes exclusively, on morphologic features. However, the choice of a 3:1 aspect ratio as the definition of a fiber[1] is an unfortunate one. Many minerals, including the amphiboles, pyroxenes, and alumino silicates, such as sillimanite, readily cleave into fragments with this aspect ratio. It is especially inappropriate for distinguishing between fibrous and nonfibrous amphibole fibers.

Yet, the constraints of phase-contrast microscopy for particle counting require a reasonable aspect ratio criterion for asbestos. To help establish such an aspect ratio, we have characterized four samples of commercial asbestos by size distribution analysis and mineralogy. These data suggest that the choice of an aspect ratio on the order of 20:1 would ensure that most asbestos particles are counted. This aspect ratio would probably preclude the misidentification of nonfibrous silicates. However, aspect ratio cannot be used as the only criterion for the identification of asbestos.

SAMPLES

Four samples of asbestos were characterized in this study: a short-fiber chrysotile from the New Idria Serpentinite Body, Diablo Range, California (COF-25); a long-fiber chrysotile from the Jeffrey Mine, Asbestos, Quebec, Canada (Plastibest 20); an amosite sample that consists of about 95% grunerite asbestos and 5% actinolite asbestos from Africa (S-33); and a crocidolite sample (blue asbestos), also from Africa (ML 6). The two chrysotile samples had not been milled but had been processed to remove impurities. The amosite and crocidolite samples were both air-jet milled to reduce the average particles length.

ANALYSIS

Sample Preparation

All samples were prepared for observation in the scanning electron microscope (SEM) in the following manner. A few milligrams of the mineral were agitated in distilled water with a small amount of detergent added to aid in dispersion. This suspension was filtered onto a 0.1 μm Nucleopore® filter and washed several times with distilled water to remove the soap. Segments of the filter were then mounted

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directly on aluminum specimen tabs, and a drop of a suspension that contained 1.1 μm latex spheres was added and allowed to dry. These spheres served as the internal standard for size calibration for all measurements. The tabs were then coated with either copper or carbon before being placed in the SEM.

Data Collection

To obtain data that would describe the samples in terms of number of particles, only the length and width of particles whose center fell closest to the center of the field of view as the specimen tab was moved in increments were recorded. This technique essentially reduces all particles to points and ensures that the data are not skewed to favor the longer-sized fractions. Length and widths were measured directly on the cathode ray tube by a ruler calibrated to the 1.1 μm latex spheres. It should be noticed that in most cases, the width measured was the intermediate dimension, because most particles will settle out of suspension with their minimum dimension perpendicular to the surface on which they settle. Generally, morphologic features alone were sufficient to ensure that only asbestos particles were being counted. However, when the aspect ratio of a particle was small, energy-dispersive x-ray analysis was performed to confirm the mineral's identity. This procedure was necessary since all of the bulk samples contained small but significant mineral impurities. The data for each mineral represent between 1200 and 2000 individual particle measurements taken from 12–20 separate sample preparations. All data were collected with a Cambridge Mark IIa SEM located at the Institute for Physical Sciences and Technology, University of Maryland, or an AMR 1400 SEM located at the Bureau of Mines, College Park.

RESULTS

FIGURES 1–4 summarize the results of these experiments. The raw data are presented as the percentage of particles in each length class that have a given aspect ratio. Also shown for each sample are the frequencies of each aspect ratio class.

It is clear from these Figures that there is a linear relationship between aspect ratio and length. The linear equations derived from a regression analysis of the mean aspect ratio of each length class and the mean length in each length class are as follows (see FIGURE 5):

1) long-fiber chrysotile

$$\log_{10} \text{aspect ratio} = 1.01 (\log_{10} \text{length}) + 0.77 \quad (1)$$

2) short-fiber chrysotile (SEM)

$$\log_{10} \text{aspect ratio} = 0.99 (\log_{10} \text{length}) + 0.83 \quad (2)$$

3) crocidolite

$$\log_{10} \text{aspect ratio} = 0.88 (\log_{10} \text{length}) + 0.62 \quad (3)$$

4) amosite

$$\log_{10} \text{aspect ratio} = 0.77 (\log_{10} \text{length}) + 0.59 \quad (4)$$

The data fit linear models exceptionally well. The R^2 values, or "percent explained,"[2] by the four linear models given above are: long-fiber chrysotile, 97.1%; short-fiber chrysotile, 98.2%; crocidolite, 99.2%; and amosite, 98.9%.

Equations 1–4 can be written in a general form as follows:

$$\log l/w = M \log l + B, \quad (5)$$

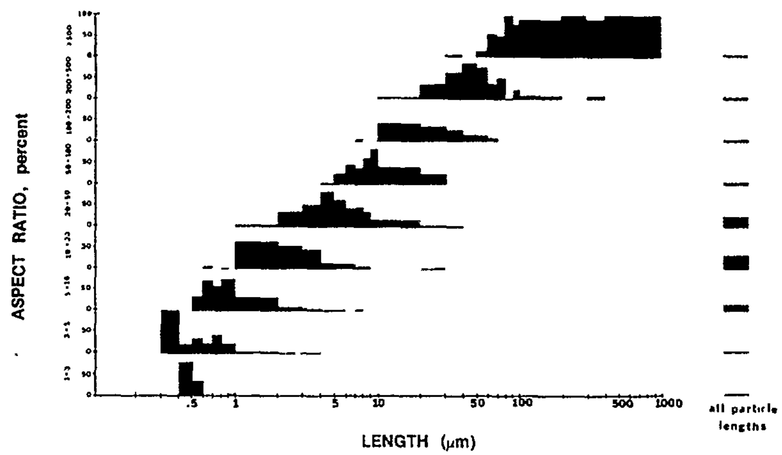

FIGURE 1. Frequency of aspect ratios in each length class of long-fiber chrysotile. Aspect ratio frequencies are expressed as percentages; lengths are given in micrometers. The frequencies of aspect ratios found in the sample as a whole (all particle lengths) are also indicated.

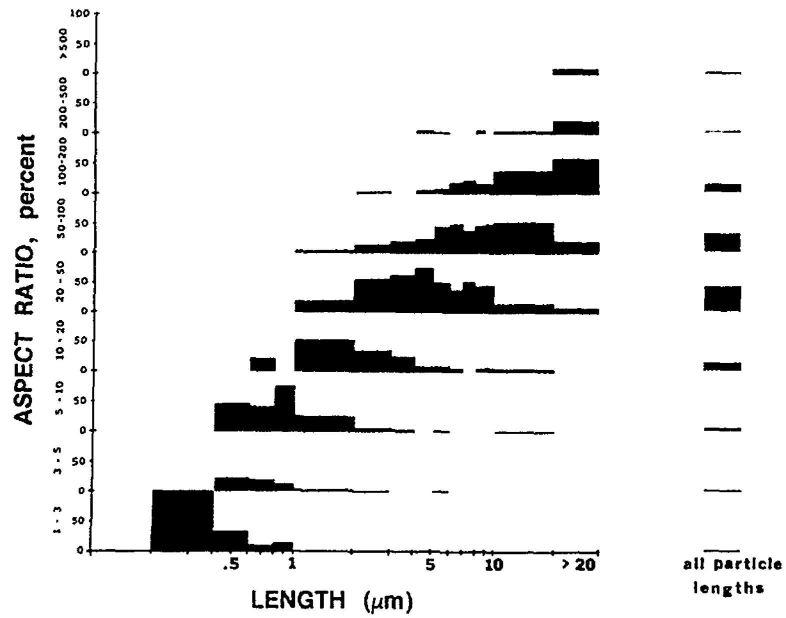

FIGURE 2. Frequency of aspect ratios in each length class of short-fiber chrysotile. Aspect ratio frequencies are expressed as percentages; lengths are given in micrometers. The frequencies of aspect ratios found in the sample as a whole (all particle lengths) are also indicated.

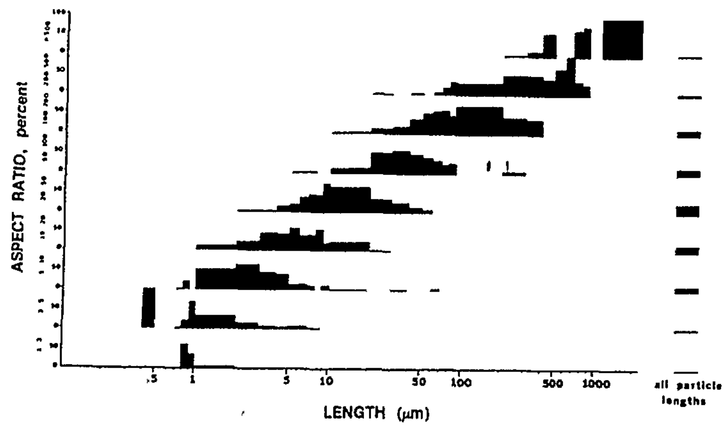

FIGURE 3. Frequency of aspect ratios in each length class of amosite. Aspect ratio frequencies are expressed as percentages; lengths are given in micrometers. The frequencies of aspect ratios found in the sample as a whole (all particle lengths) are also indicated.

where l is the length, w is the width, and M and B are constants.

Rearranging Equation 5, we have:

$$-\log w = \log l\,(M-1) + B. \tag{6}$$

From this equation, it is evident that when $M = 1$, width remains constant throughout all length classes. This relation holds for both samples of chrysotile. There is a slight

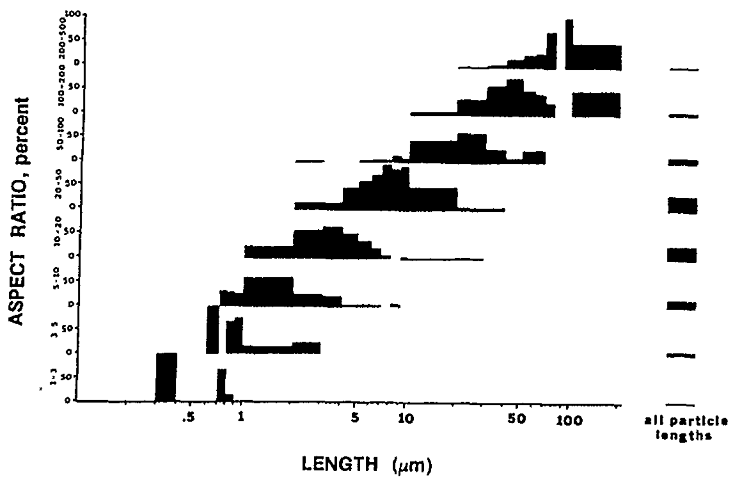

FIGURE 4. Frequency of aspect ratios in each length class of crocidolite. Aspect ratio frequencies are expressed as percentages; lengths are given in micrometers. The frequencies of aspect ratios found in the sample as a whole (all particle lengths) are also indicated.

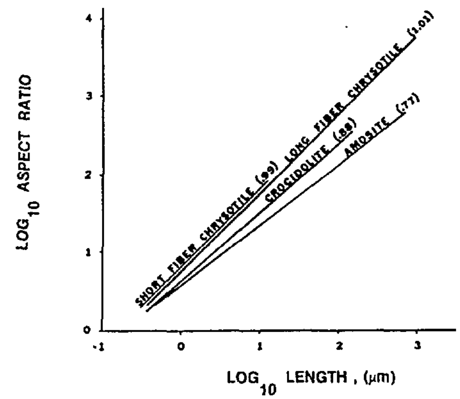

FIGURE 5. Linear models show aspect ratio dependency on length. The equations for the straight lines were derived from regression analyses of the mean aspect ratio in each length class.

increase in width as length increases for crocidolite ($M = 0.88$); the effect is more pronounced for amosite ($M = 0.77$).

CONCLUSIONS

The widths of asbestos fibers show very little variation with length, probably because asbestos is composed of fibrils, unit single or twinned crystals.[3-5] Individual fibers may be composed of one or more fibrils. The chrysotile fibril has a distinct tubular structure, with a diameter of 250–500 Å.[5] Amphibole fibril widths exhibit more inter- and intrasample variations. Franco *et al.*[4] have reported finding crocidolite fibrils ranging from 500 to about 1500 Å in diameter. The crocidolite described here has fibril widths less than 3500 Å; the amosite fibril widths are less than about 5000 Å. More work is needed to describe more accurately the shape and size of these fibrils.

The value of M (Equation 5) may be a good "fibrosity index." It is essentially a measure of the dependency of width on length. Asbestos with well-developed uniform fibrils, such as chrysotile, will have M values close to unity. The values of M for asbestos types that exhibit more variation in fibril shape, such as crocidolite or amosite, will be slightly less. Preliminary results from a study of massive tremolite suggest that M values characteristic of nonfibrous amphiboles are less than 0.5.

TABLE 1

ASPECT RATIO FREQUENCY FOR ASBESTOS PARTICLES LONGER THAN 5 μm

	Particles with Aspect Ratios Greater Than or Equal to 10:1 (%)	Particles with Aspect Ratios Greater Than or Equal to 20:1 (%)	Particles with Aspect Ratios Greater Than or Equal to 50:1 (%)
Long-fiber chrysotile	99.5	96.2	76.6
Short-fiber chrysotile	99.2	95.7	59.0
Amosite	96.8	83.9	59.6
Crocidolite	99.0	89.0	37.8

Further testing of this model is required before its validity as a reliable measure of fibrosity can be established.

The aspect ratios predicted by Equations 1–4 are very large for long particles, but for particles less than 1 μm, they approach ratios typical of many nonfibrous silicates (less than 5:1). But 5 μm is usually given as the practical working microscopic limit for asbestos particle measurement.[6] TABLE 1 shows that more than 96% of all measured particles longer than 5 μm have aspect ratios in excess of 10:1; many have aspect ratios in excess of 50:1. Aspect ratios of this magnitude and frequency are uncharacteristic of most rock-forming mineral fragments and are probably unique to asbestos. This observation does not mean, however, that a single mineral particle with an aspect ratio of this magnitude is necessarily an asbestos fiber. Only the prevalence of high aspect ratios in a population of particles of a mineral known from hand samples to occur in an asbestiform habit should be used as a criterion for asbestos identification.

Since the preferred index of asbestos exposure is the presence of fibers longer than 5 μm counted on membrane filters at 430× by phase-contrast microscopy,[7] the data suggest that once the presence of asbestos has been established, if only particles with aspect ratios in excess of 20:1 are counted, most asbestos particles would be included; most nonfibrous mineral fragments probably would not be counted.

The choice of 10:1 as the aspect ratio used would increase the probability of including *all* asbestos fibers, but, in this case, some nonfibrous acicular cleavage fragments might also be counted as asbestos. The exact aspect ratio criterion might be designed to fit the particular circumstances of each individual case. In any event, the use of 3:1 is not justified on mineralogic grounds and should be abandoned.

SUMMARY

Four samples of asbestos: short fiber chrysotile, long fiber chrysotile, amosite and crocidolite, have been characterized by particle length and aspect ratio on the scanning electron microscope. A linear model expressed by $\log l/w = M \log l + B$ (or, $-\log w = \log l(M-1) + B$) approximates the data very well. It is proposed that M be considered as a "fibrosity index." The data indicate that most asbestos fibers longer than 5 μm in length are characterized by aspect ratios in excess of 20:1.

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OPTICAL PROPERTIES OF THE FIBROUS AMPHIBOLES*

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FIBERS AND FIBRILS

Dana[1] gives the definition of asbestos as follows:

> Tremolite, actinolite, and other varieties of amphibole pass into fibrous varieties, the fibers of which are *sometimes*† very long, fine, flexible and easily separable by the fingers and look like flax. These kinds are called asbestos. . . . Byssolite is a stiff fibrous variety.

This definition clearly states that there may be several types of fibrous amphiboles. Therefore, according to Dana, "fibrous" and "asbestos" or "asbestiform" are not synonymous. Asbestos is a particular fibrous variety; there are others.

FIGURE 1 shows actinolite variety (var.) byssolite; FIGURE 2 shows grunerite, var. asbestos. Although the byssolite may appear "stiffer," the differences between these two types of fibers are not obvious from the Figures. Probably, there is a continuum of properties, from the extreme development of fine fibers called asbestos, to the thicker, stiffer fibers of byssolite. However, there are easily identifiable distinctions between the samples pictured in FIGURES 1 and 2.

FIGURE 3 is a zero-level Weissenberg‡ x-ray diffraction photograph of a single actinolite (var. byssolite) fiber, 0.08 mm in width. The regular pattern of spots indicates that the crystal diffracts as a single lattice. Doubling of some spots may indicate that the fiber is composed of several individual fibrils, probably related by twinning, but there remains structural continuity throughout. By contrast, FIGURE 4 is a zero-level Weissenberg x-ray diffraction photograph of a similarly sized fiber from actinolite (var. asbestos) taken under the same conditions as the byssolite photograph shown in FIGURE 3. The regular order of spots has given way to a pattern of lines, producing what is known as a "fiber photograph."[4] This pattern develops when, rather than having a single lattice orientation (or two if twinning is present), the "single fiber" is actually composed of hundreds of fibrils, or smaller single crystals. All fibrils have a common crystallographic axis parallel to the length of the fiber, but their other two crystallographic axes are in some state of disorder. Sometimes, the disorder is not complete. Unequal intensities along the diffraction lines are a common, but not necessary, characteristic of the asbestos we have investigated.

Franco *et al.*[5] have confirmed the fibrillar structure of crocidolite by direct lattice imaging by use of a transmission electron microscope (TEM). The fibrils they describe are irregular in shape and range from about 500 to 1500 Å in median diameter. A study of asbestos fiber sizes (also reported here)[6] shows that the three major kinds of

*Supported in part by the Bureau of Mines, Department of the Interior.
†Italics are the author's.
‡Weissenberg techniques are discussed in most x-ray techniques books; see, for example, Reference 2 or 3.

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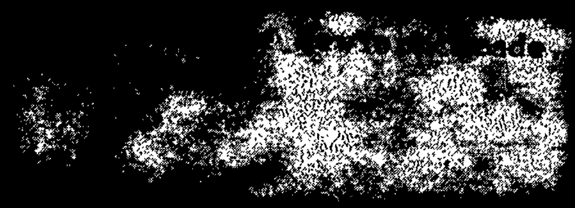

HEALTH HAZARDS OF ASBESTOS EXPOSURE

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