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# Human Occupational and Nonoccupational Exposure to Fibers

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**Human exposure to fibers in occupational and nonoccupational environments has been a health concern for nearly a century. In this review, selected results from the literature are presented to highlight the availability, limitations, and interpretive difficulties associated with the past and current human fiber exposure data sets. In the traditionally defined asbestos fibers, large amounts of the data available suffer from the diversity of sample collection and analysis methods. Two simple generalizations suggest that occupational exposures are several orders of magnitude higher than that of environmental exposures; and currently extant data and the current routine measurement practices present significant difficulties in the consistent interpretation of the data with respect to health effects. The data on the human exposures to man-made vitreous fibers are much more complete than the data on asbestos exposure, while exposure data on other man-made fibrous materials are lacking. The human exposure data to many minerals which, at times, exist in fibrous habit, are very scanty, and in view of the biological activity of some of these fibers, this lack may be of significant concern.**

## Introduction

As potentially hazardous entities, fibers are uniquely *ipso facto*, problematic because the unifying concept of being included in this classification, geometry, does not readily pertain to a biological interaction. For this reason, it is perhaps important to consider the definition of a fiber to some extent before human exposure to fibers and fiber characteristics can be discussed. The operational definition of a fiber includes the restriction that the particles have a length-to-width ratio (aspect ratio) of 3:1. In general, it is tacitly assumed that the long side of the particles are more or less parallel. This definition is based on optical microscopic counting of fibers in thermal precipitator samples obtained in an asbestos textile factory (*1*). It is safe to assume that the aspect ratio chosen was based on convenience rather than on empirical or theoretical reasoning. Both the surface area and the aerodynamic properties of a fiber may be related to its aspect ratio. If the ratios of aerodynamic sedimentation and impaction diameters to the fiber diameter (*2*) and the ratio of fiber surface to spherical surface of equal volume is normalized with respect to unit aspect ratio, as shown in Figure 1, then a justification for the choice of 3 for aspect ratio may be sought. The results shown in the Figure 1 suggest that if only the increased surface as compared to an isometric particle is of importance, then the proper aspect ratio is somewhat larger than 3, perhaps between 5 and 8. On the other hand, if a combination of aerodynamic properties and increased surface is of importance, then a slightly lower aspect ratio, perhaps 2, would be more appropriate. Thus, the choice of 3 for aspect ratio for defining a fiber is an entirely reasonable one.

Although a considerable amount of recent measurements of human exposure to fibrous dusts use this concept, a number of recent exposure measurements and almost all exposure measurements taken prior to 1961 deviate from this concept (*3*). Even if this definition for a fiber is accepted, purely physical and biological considerations suggest that various potential hazards associated with fibers must be related to some chemical and/or physical property of the inhaled fiber. There is sufficient evidence to back this claim. A logically ordered summary of this evidence is presented in a recent review by Lippmann (*3*). After review of all recent experimental evidence, Lippmann recommended three asbestos exposure indices as related to the disease-specific risk of exposure (*3*): the surface area of fibers with length > 2 µm and diameter > 0.15 µm for asbestosis; the number of fibers with length > 5 µm, diameter < 0.1 µm for mesothelioma; and the number of fibers with length > 10 µm, diameter > 0.15 µm for lung cancer. If these definitions are extended to the currently available epidemiological data on nonasbestos fibers, such as man-made vitreous fibers, it may be observed that studies to date reported virtually no fibers that fit the size restrictions which pertain to mesothelioma, and correspondingly, there is no excess of mesothelioma observed in the cohorts studied. Conversely, in these studies a fraction of fibers were observed to fit the restrictions which pertain to lung cancer, and the epide-

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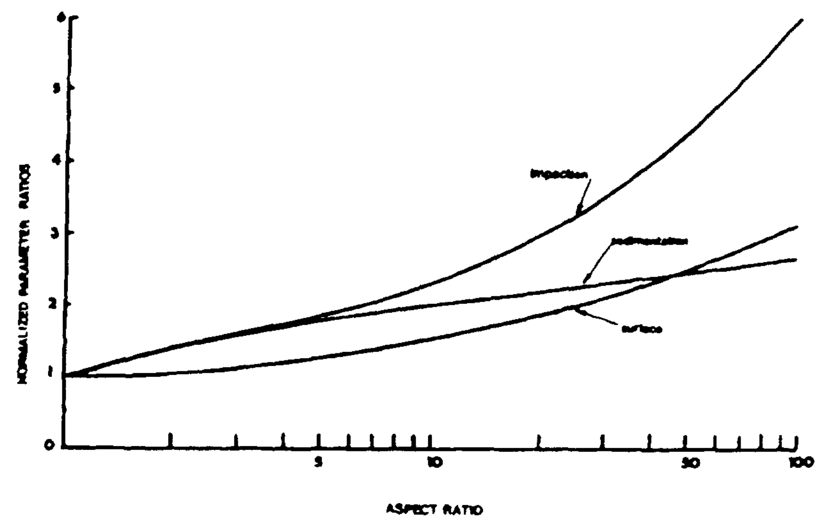


FIGURE 1 The relationship between normalized ratios of aerodynamic sedimentation and impaction diameters to the fiber diameter of the fiber surface to spherical surface of equal volume as a function of aspect ratio.

miologic data seem to indicate a possible lung cancer excess. These observations suggest the importance of the physical dimension above and beyond the reasoning given in the selection of these indices. Similar arguments can also be made with respect to the chemical composition of fibers. The generalization of the indices developed for asbestos to other fibers may or may not be biologically appropriate. Even with this caveat, such a generalization provides a convenient categorization of the available data. Without implication of risk, in this paper the fibers are categorized as shown in Table 1.

This brief review of human exposures to fibers is directed toward the limitations and difficulties associated with the available human exposure data in the frame work of fiber types and gross chemistry.

## Traditional Asbestos

Mineralogically, asbestos or asbestiform habit is the generic term used to describe a macroscopic property-based habit of a group of naturally occurring hydrated mineral silicates of the rock-forming amphibole or serpentine groups. As a macroscopic quality, the identification of asbestos is based on the morphology, crystallography, color, appearance, optical properties, and hardness of a sizable specimen. Such a mineralogical definition for isolated fibers is not possible (4,5). Therefore, for the purposes of this review, any fiber derived from a mineral that exists in asbestos habit will be classified as asbestos whether that specific fiber is a cleavage fragment from the nonfibrous analog or a true fragment of mineralogically classified asbestos. Although such a classification is not rigorous, it is a necessary simplification. Table 2 presents the definitions and the nomenclature of asbestos used in this review. A large number of amphiboles and transformed serpentines can also assume fibrous habit; however, these minerals are discussed under a different heading.

Asbestos has been recognized as a health hazard for over a half century, and consequently, a substantial amount of human exposure data on both in occupational and environmental exposures exist in the literature. The measurements of occupational exposure to asbestos prior to about 1960 involve sample collection and analysis by essentially three techniques: impinger (USA, Canada), thermal precipitator (UK), konimeter (UK, South Africa, and Germany) (6). There are a number of studies reported that obtain conversion factors, be-

**Table 1. Fiber categories as related to fiber dimensions.**

| Category | Length, μm | Diameter, μm | Comments |
|---|---|---|---|
| Type 0 | < 2 | — | Fragments |
| Type 1 | > 2 | < 3.5 | Respirable total |
| Type 2 | > 5 | < 0.1 | Translocatable |
| Type 3 | > 10 | > 0.15 | Tracheobronchial |
| Type 4 | > 100 | > 8 | Extrathoracic |

**Table 2. Nomenclature and definitions for asbestos.**[a]

| Name | Mineral | Ideal formula |
|---|---|---|
| Chrysotile | Antigorite, lizardite (serpentine) | $Mg_6(OH)_8Si_4O_{10}$ |
| Actinolite | Actinolite | $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ |
| Amosite | Cummingtonite, grunerite | $(Mg,Fe)_7Si_8O_{22}(OH)_2$ |
| Anthophyllite | Anthophyllite | $(Mg,Fe)_7Si_8O_{22}(OH,F)_2$ |
| Crocidolite | Riebecktite | $Na_2Fe_3Fe_2^{3+}Si_8O_{22}(OH,F)_2$ |
| Tremolite | Tremolite | $Ca_2Mg_5Si_8O_{22}(OH,F)_2$ |

[a] Adapted from *Handbook of Chemistry and Physics* (11).

tween the various past sampling and analysis methods and the currently used membrane filter/phase contrast optical microscopy method (MFPCOM) (*6–10*). These conversion factors are summarized in Table 3. In the estimation of exposures, such conversion factors would be useful if the correlations of side-by-side samples were better than those shown in the table, and more importantly, if the methods of microscopic analysis of the samples were, by and large, based on a standardized practice. Unfortunately, neither condition is fulfilled *vis-a-vis* the conversion factors hitherto reported. Consequently, the use of such factors must be considered as very general estimates of the fiber exposure levels, with the possibility of errors in the order of a magnitude. In order to provide a sense of the available data, a table of selected exposures is provided without specific annotation for each study (Table 4). The diversity of the measurement methods as well as the results is quite apparent in the table. Estimation of past exposures in terms of the current knowledge of fiber characteristics and consolidation of the available data, albeit a monumental task, would be an important contribution to seeking a reconciliation of differences observed in the epidemiological studies. Of necessity, such a project would have to involve the cooperation of diverse industries and governments who have access to such data. Unless a substantial amount of unreported findings exist, expectations from even such a large undertaking should not be very high.

The nonoccupational asbestos exposure data are rather haphazard. On one hand, a considerable amount of fiber-count data exists on asbestos exposure in schools and public buildings. On the other hand, scattered data on waterborne or foodstuff-borne asbestos levels are reported according to the passing interest of researchers. To consolidate the data, selected nonoccupational exposures (excepting exposures in schools and public buildings) are shown in Table 5. Exposures in schools and public buildings are shown in Table 6. There is very little size distribution information available in all cases. The reported data on weight concentration basis, on the counting basis that considers fibers longer than 0.5 μm, and MFPCOM fiber counts are not easily reconciled. What seems to be apparent is that the nonoccupational asbestos exposures, with a few possible exceptions, range several orders of magnitude lower than occupational exposures.

In the data shown and discussed in Tables 5 and 6, the lack of exposure data on tremolite and actinolite is reflected. The measurements of exposures with specific reference to these forms of asbestos are virtually nonexistent. The most extensive measurements of tremolite are briefly reported in a study of talc containing asbestos (*25*).

The importance of the diameters as well as the lengths of the inhaled asbestos has been reported in the literature since the seminal work performed by Stanton and Wrench in 1972 (*38*). The size distribution data of occupational and/or environmental exposure to asbestos is woefully lacking. The few complete studies reported to date are summarized in Table 7.

In as much as the findings are strongly influenced by the self-selective nature of the sample, the fiber characteristics of fibers obtained from lung specimens provide an important exposure index. Although such an exposure index is *post facto* with respect to the ascertaining risks, nevertheless, in understanding a number of exposure level and fiber characteristic parameters,

**Table 3. Conversion factors for various measurement methods.**

| | Count ratios[a] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Impinger, mppcf[b] | Konimeter[c] | | STP[c] | | | |
| Asbestos type and process | | 1 | 5 | 1 | 5 | $r^d$ | Reference |
| Chrysotile | | | | | | | |
| Textile | 5.9 | — | — | — | — | 0.6 | (*8*) |
| Friction | 2.2 | — | — | — | — | 0.6 | (*8*) |
| A/C pipe | 1.9 | — | — | — | — | 0.0 | (*8*) |
| Mining | — | 8.1 | 2.8 | 9.8 | 3.2 | 0.4 | (*9*) |
| Mining | 6–14 | — | — | — | — | 0.4 | (*6*) |
| Cape crocidolite | | | | | | | |
| Mining | — | 4.3 | 2.0 | 4.5 | 1.5 | 0.4 | (*9*) |
| Transvaal crocidolite | | | | | | | |
| Mining | — | 6.8 | 2.6 | 4.5 | 1.5 | 0.4 | (*9*) |
| Amosite | | | | | | | |
| Mining | — | 7.9 | 3.2 | 8.8 | 4.9 | 0.4 | (*9*) |
| Disintegrator | 109 | — | — | — | 1.2 | ? | (*10*) |

[a] Ratio of the indicated number concentration by the instrument to membrane filter phase contrast microscopy indicated number concentration of > 5-μm long fibers measured at about 430 × magnification.
[b] Midget impinger counts are given in mmpcf, millions of particles per cubic foot.
[c] Konimeter, Witwaterstrand type. STP, Cassella standard thermal precipitator. Konimeter and thermal precipitator concentrations are given in fibers per milliliter. 1 denotes the instrument—indicated concentration of 1 fiber/mL and represents low concentration readings; 5 represents high concentration reading.
[d] Approximate correlation coefficient.

**Table 4. Selected asbestos exposure values.**

| Type | Process | Level[a] | Method[b] | Reference |
|---|---|---|---|---|
| Chrysotile | Mining and milling | | | |
| | 1948 | ~ 33 mppcf | Impinger | *(15)* |
| | 1958 | ~ 1 mppcf | | |
| | 1966 | ~ 2 mppcf | | |
| Chrysotile | Mining and milling screening | 1.7–16.6 fibers/mL | MF | *(16)* |
| Chrysotile | Processing | 3.5–27 fibers/mL | MF | *(1)* |
| Chrysotile | Brake repair | 0.04–0.4 fibers/mL | MFPCOM > 5 μm | *(17)* |
| Chrysotile | Drywall taping | 4–8 fibers/mL | SEM | *(18)* |
| Chrysotile/amosite | Insulation | | | |
| | Prefabrication | 0.8–28.8 mppcf | MFPCOM | *(19)* |
| | Application | 0.8– 8.2 mppcf | | |
| | Finishing | 1.2– 6.2 mppcf | | |
| | Tear out | 2.5– 8.6 mppcf | | |
| | Mixing | 2.8–16.0 mppcf | | |
| | General | 0.6– 1.8 mppcf | | |
| Amosite/hornblend | Gold mine | 0.4 fibers/mL | TEM/SEM > 5 μm | *(20)* |
| | | | total | |
| | | 4.8 fibers/mL | | |
| Chrysotile<br>Tremolite<br>Anthophyllite | Spackling | 1.2–59 fibers/mL | MFPCOM<br>TEM | *(21)* |
| Amosite | Disintegrator | 0.11 mfpcf | Impinger | *(10)* |
| | | 0.37 | MF | |
| | | 0.54 | TP | |
| | | 0.12 | Light scattering | |
| Amosite/<br>Chrysotile/<br>Crocidolite | Shipyard<br>A number of operations | 0.1–2000 fibers/mL | MFPCOM > 5 μm | *(22)* |
| Crocidolite | Shipyard insulation | | | |
| | Application | 8.8 fibers/mL | MFPCOM | *(23)* |
| | Removal | 200–400 fibers/mL | MFPCOM | |
| Crocidolite | Mining and milling | | | |
| | Underground | 650–1500 fibers/mL | Konimeter | *(24)* |
| | Surface, post-1965 | 1000–2700 | | |
| | Underground | 150–370 fibers/mL | TP | |
| | Surface | 270–370 | | |
| Tremolite/<br>Anthophyllite | Mining and milling<br>Various operations | 8–260 fibers/mL | MFPCOM/TEM > 5 μm | *(25)* |

[a] mppcf, millions of particles per cubic foot; mfpcf, millions of fibers per cubic foot.
[b] Method descriptors: impinger, midget impinger; MF, membrane filter; MFPCOM, membrane filter and phase contrast optical microscopy; TEM, transmission electron microscopy; SEM, scanning electron microscopy; TP, thermal precipitator.

the exposure index is important. In fact, size and composition analyses of the fibers recovered from the lung tissue provide the most detailed information on the deposition and long-term retention of fibers in the lung so far available. As each reported result presents a detailed summary of the fiber size parameters, fiber types, and lung loads, an attempt to summarize even a selected set of studies would be beyond the scope of this review (*12,39–44*). One very important observation that seems to be common among these studies is the relative lack of chrysotile fibers in contrast to the relative abundance of the amphibole fibers, although the exposures may be primarily due to chrysotile. The durability of the fibers in the human lung, as observed from the ratios of the fibers recovered, confirms the fiber durability studies in animals. As the biological response mechanisms of the three end points of asbestos exposure, namely neoplasia at deposition site, neoplasia after translocation, and fibrosis, differ significantly, the effect of chemical composition on these three end points is also expected

Table 5. Selected environmental asbestos exposure values.

| Type | Location | Level | Method | Reference |
|---|---|---|---|---|
| Chrysotile | Ambient air | 10–50 ng/m³ | TEM[a] | (26) |
| Chrysotile | Rural background | 3– 5 ng/m³ | TEM | (27) |
| | Urban background | 1– 8 ng/m³ | | |
| | Downwind from waste | 12–800 ng/m³ | | |
| Amosite | Downwind of factory | 500–2000 ng/m³ | TEM | (27) |
| | Downwind from waste | 900–4700 ng/m³ | | |
| Asbestos | Recreational area | 0.3–5.3 fibers/mL | TEM | (28) |
| Asbestos | Water supplies | | — | (29) |
| | 117 cities | Not detectable | | |
| | 216 cities | < 1 million fibers/L | | |
| | 33 cities | 1–10 million fibers/L | | |
| | 40 cities | > 10 million fibers/L | | |
| Chrysotile | Drinking water | | — | (30) |
| | Connecticut | < 0.7 million fibers/L | | |
| | Quebec | 1.1–1300 million fibers/L | | |
| | Bay Area, CA | 0.2–36 million fibers/L | | |
| | Puget Sound, WA | 7 –200 million fibers/L | | |
| Amphiboles | Municipal water | | TEM | (31) |
| | Duluth, MI | 1–30 million fibers/L | | |
| Asbestos | Beverages | | TEM | (32) |
| | Beer | 1–7 million fibers/L | | |
| | Sherry | 2–4 million fibers/L | | |
| | Vermouth | 2–12 million fibers/L | | |
| | Soft drinks | 1–12 million fibers/L | | |
| Chrysotile | Parenteral drugs | 3.3–1100 ng/g | TEM | (33) |

[a]TEM, transmission electron microscopy.

Table 6. Selected airborne asbestos levels in schools and public buildings.

| Location[a] | Type | Level | Method[b] | Reference |
|---|---|---|---|---|
| School (6) | Mixed | Below detection | SEM | (34) |
| Houses (5) | Mixed | Below detection | TEM | (34) |
| Offices (22) | Mixed | 0–0.022 fibers/mL | SEM | (35) |
| Buildings (43) | Mixed | < 0.001–0.04 fibers/mL | TEM | (36) |
| School (71) | Chrysotile | Median 0.0083 fibers/mL<br>Geometric SD 4 | TEM | (37) |
| | Amphibole | Median 0.00065 fibers/mL<br>Geometric SD 4 | | |

[a]Numbers in parentheses indicate locations sampled.
[b]SEM, scanning electron microscopy; TEM, transmission electron microscopy.

to differ. There is sufficient animal model evidence to buttress this point (3). In terms of human evidence, in cohorts exposed to what is normally considered to be all chrysotile (more than 90%), the lung tissue assays show that the chrysotile fibers are generally a small fraction of the asbestos present (44,45). In the cases of mesothelioma due to nonoccupational exposures, the involvement of amphiboles, specifically crocidolite and tremolite, has been suspected (46,47). Unfortunately, neither in occupational nor in nonoccupational exposure measurements is the identification of asbestos types involved sufficiently or frequently reported.

For the most part, due to varied objectives behind the collection of data, the available exposure measurements present a number of difficulties in the interpretation of the exposure levels and fiber characteristics. Some of the problems stem from the varied measurement methods, but the most important problem seems to be the inappropriateness of the accepted MFPCOM methodologies. Collection of samples solely on the basis of that methodology, as pointed out by Lippmann (3), is expected to fall short of both answering the relevant research questions and constructing reasonable risk estimates. Consequently, the large number of legally required asbestos samples collected today are expected to present similar interpretive difficulties to the future

**Table 7. Fiber categories for airborne asbestos.**

| Material and process | Estimated occurrence in fiber category, %ᵃ | | | | | Reference |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | |
| **Amosite** | | | | | | |
| Bagging | 42 | 58 | 0.19 | 6.8 | 0 | (6) |
| **Anthophyllite** | | | | | | |
| Mining | 25 | 75 | 0.15 | 14.4 | 0 | (12) |
| Milling | 16 | 84 | 0.03 | 19 | 0 | (12) |
| Bagging | 7 | 87 | 0.05 | 47.5 | 0 | (12) |
| **Chrysotile** | | | | | | |
| Bagging | 77 | 23 | 0.86 | 0.9 | 0 | (6) |
| Textile | 58 | 42 | 5.4 | 1.0 | 0 | (13) |
| **Crocidolite** | | | | | | |
| Mining | 78 | 22 | 1.2 | 0.8 | 0 | (14) |
| Ore storage | 72 | 28 | — | — | — | (14) |
| Crusher | 76 | 24 | — | — | — | (14) |
| Bagging | 71 | 29 | 1.5 | 0.8 | 0 | (14) |
| Dumping | 81 | 19 | 0.5 | 0.1 | 0 | (14) |
| Mixing | 70 | 30 | — | — | — | (14) |
| Cutting | 93 | 7 | — | — | — | (14) |

ᵃCategories are those given in Table 1

researchers, as was the case with impinger, konimeter, and thermal precipitator samples of the past.

## Natural Nonasbestos Fibers

A substantial number of minerals may occur in fibrous habit (48). With the exception of two such minerals, there are few studies that consider potential toxicity of these minerals. One of the two exceptions is wollastonite, which in one reported study did not show remarkable human health effects, even though the fiber concentrations reported were in the order of 1 to 20 fibers mL (MFPCOM) (49). The other exception, a fibrous zeolite, erionite, in the past decade proved to be the most potent mesothelioma-inducing fiber yet known. While occupational exposure to erionite is not known, the nonoccupational exposure is definitely known. In three villages in central Cappadocia, the mesothelioma rates range from equal to four times the mesothelioma rates reported among various asbestos worker cohorts (50). The general airborne fiber concentration levels were reported to be generally low, in the order of 0.00X fibers/mL in the "mesothelioma villages" (MV) and the "control village" (CV); but the zeolite content of the samples in MVs is three to four times higher than the CV. In the two MVs, fiber concentrations of about 0.2 fibers/mL were observed in children's play areas; also, sweeping wall blocks in two MVs generated concentrations up to 1 fiber/mL. In one of the villages mixed fibers of zeolite, other aluminum silicates, and a small amount of tremolite and chrysotile were found. In the other village, the fibers were virtually all zeolite (51). The size distribution of the fibers in the samples mentioned above are reported to be comparable to IUCC crocidolite fiber size distribution, but specific size distribution of erionite in the air samples is not reported.

It is interesting to note that three other fibrous minerals, long-fibered sepiolite, long-fibered attapulgite, and fibrous diatomaceous earth were reported to have the same class of biological activity as the dust from one the MVs in an *in vitro* assay (52). With the exception of one dramatic case, the investigations that pertain to the fibers classified in this section are lacking.

## Man-Made Vitreous Fibers

In contrast to naturally occurring fibrous minerals, man-made vitreous fibers constitute a class of inorganic fibers that are more or less amorphous, vitrified material manufactured to size specifications ranging from 0.1 μm in diameter to over 100 μm in diameter. These fibers include glass wool, slag wool, rock wool, glass threads, and ceramic fibers. It is interesting and perhaps ironic that epidemiologically and toxicologically the least potentially hazardous of mineral fibers have the most complete recent exposure and size distribution data available.

One of the important facets of the exposure to man-made mineral fibers during its production is the strong relationship between the nominal diameter of fibers produced and the airborne fiber concentration. The slope of the relationship observed for all fiber classes in factory airborne fiber concentration measurements (53) was duplicated in a controlled laboratory study (54). Although the laboratory study refers to respirable fibers (MFPCOM) and the field study refers to total fibers (MFPCOM), if the latter case is converted to respirable fibers, the change in the slope of the relationship would not be altered significantly to lead to a disagreement. The levels shown in the laboratory study are higher than the field study, and intuitively this is in the wrong direction. The reality is most likely counter-intuitive because the experimental investigation is most likely to give the maximum attainable concentration, while the personal exposure of workers are likely to be considerably less than this maximum due to the varied amount of time they spent in the tasks performed. The nominal fiber diameter/airborne fiber concentration relationship is shown in Figure 2.

The occupational exposures in the production of man-made mineral fibers studied in a number of countries and a number of locations show a remarkable consistency (54–60). Based on the extensive fiber size distribution data available, a table of approximate fiber category fraction may be generated (Table 8). Another table which can classify the expected exposure levels under current conditions with respect to the fiber classes (Table 9) can be generated with the aid of Table 8 and more or less the narrow ranges of exposure levels observed.

In mineral wool and ceramic fiber production, when the averages of the exposure measurements to total suspended particulate matter and same sample fiber counts are considered over general work classes, they seem to be fairly well correlated (56,61,62). This correlation provides order-of-magnitude estimates for the

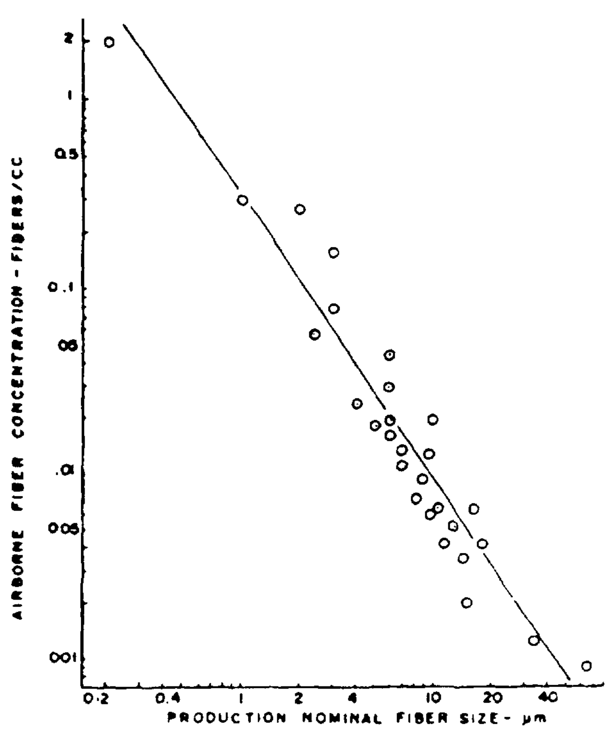


FIGURE 2. Relationship between measured average exposures, expressed as fibers per cubic centimeter and nominal diameter of fiber manufactured. Fibers per cubic centimeter determined by phase contrast microscopy.

**Table 8. Fiber categories for airborne man-made vitreous fibers.**

| Material | Estimated occurrence in fiber category, %[a] | | | | | Reference |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | |
| Fibrous glass | | | | | | |
| Insulation | 8.5 | 18 | 0.03 | 48 | 1 | (27) |
| Specialty | 5 | 86 | 4.0 | 54 | 0.2 | (27) |
| Coarse | 0 | 8 | 0.0 | 68 | 14 | (27) |
| Micro | 12 | 86 | 15 | 67 | 0 | (27) |
| Mineral wool | | | | | | |
| Insulation | 7 | 60 | 3 | 44 | 0.3 | (27) |
| Ceramic fiber | | | | | | |
| Insulation | 2 | 80 | 3.2 | 46 | 0 | (28) |
| Textile | 3 | 78 | 3.6 | 49 | 0 | (28) |

[a]Categories are those given in Table 1.

historically existing conditions in such facilities. In fact, the estimates of early conditions reported by two independent methods agree well (*54,61*). These estimates suggest fiber exposures in the order of 1 fiber/mL in the early phases of mineral wool production and a steady reduction to current levels from about 1945 (*54*). This type of an estimate for ceramic fiber production is not reported. For glass fiber production facilities the suspended particulate matter and fiber count is shown to be uncorrelated (*57,62*). However, it is believed that the historical exposure levels in the fibrous glass production was more or less comparable to the current exposure levels, as designated by the type of fiber produced and type of tasks involved.

Most of the information available pertain to the production of man-made mineral fibers. However, the information hitherto available (*60,63–66*) suggests that if the use and processing is carried out in well-ventilated or open spaces, the airborne fiber concentrations are comparable to those observed in fiber production. Similarly, the fiber exposures in confined or poorly ventilated areas are about one order of magnitude higher than the ones experienced in fiber production. The size distribution of the fibers from user samples are comparable to the same from production worker samples.

The data on environmental exposure to man-made vitreous fibers is sparse. One investigation on the entrainment of fibers from high efficiency filters reported estimated fiber levels in the order of 0.001 fibers/mL during the first day of installation and reduction to background levels in 10 to 20 h (*67*). In atmospheric samples taken in Pittsburgh, approximately up to 1% of the fibers detected were amorphous mineral fibers, suspected to be of man-made origin (Kahn and Esmen, unpublished data). Thus, environmental exposure to manmade mineral fibers is not expected to be a significant portion of the nonoccupational exposure to fibers.

One difficulty associated with man-made vitreous fibers pertains to the composition of the fiber and the fiberized material in a segment of the mineral fiber industry known as slag wool. Historically, and to some extent currently, the feedstock of slag wool has been locally available slag from sundry metal production industries and is generally highly variable in composition. In a number of facilities studied, presence of exposures to highly toxic material such as arsenic at levels as high as 69 mg/m$^3$ through the use of slag is suspected (R. Musselman, personal communication, 1989).

## Man-Made Nonvitreous Fibers

A number of man-made, inorganic fibrous materials exist in use and production. Of these materials, silicon nitride, silicon carbide, and carbon fibers see some commercial applications. Carbon fibers are generally 6 to 8 μm thick, long strands. In sawing, grinding, and milling carbon fibers break mostly transversely, although a small amount of longitudinal splitting occurs, and the fiber sizes generated are more or less in the order of coarse glass fibers (Seibert and Esmen, data submitted for publication). Occupational and nonoccupational exposure levels for carbon fibers are too scarce and spotty to report.

Silicon nitride and silicon carbide fibers are used as fillers for a number of metallic castings (*68*). Both of these materials were shown to be highly cytotoxic in *in vitro* tests (*69,70*). The fibrous silicon nitride used in the experiment was as received from the supplier.

**Table 9. Typically expected concentrations as related to the type of fiber produced.**

| Fiber type | Total | Concentration, fibers (mL × $10^{4}$)* | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 |
| Continuous | 5 | — | — | — | — | — |
| Coarse fiberglass | 1–5 | 0 | 0.1–0.4 | 0 | 0.7–3 | 0.1–5 |
| Ordinary fiberglass insulation | 10–70 | 1–6 | 2–13 | 0.3–2 | 5–30 | 0.1–7 |
| Specialty | 1000–2500 | 50–120 | 900–2100 | 40–100 | 500–1300 | 2–5 |
| Micro fiberglass | 1000–50000 | 120–6000 | 900–43000 | 150–7500 | 700–34000 | 0 |
| Mineral wool | 100–2000 | 7–140 | 60–1200 | 3–60 | 40–900 | 0.3–6 |
| Ceramic fiber | 100–2600 | 2–50 | 80–2000 | 4–100 | 50–1200 | 0 |

*Total fiber concentration as measured by transmission electron microscopy and phase contrast optical microscopy.

Ninety-nine percent of the fibers in this dust were under 1.6 μm and 21% were longer than 12 μm (*70*). Exposure data for these fibers are unavailable.

## Conclusions

After half a century of concern, and some 20 years of intense research and control activity, a large amount of data available with respect to human exposures to fibers unfortunately does not allow many definitive statements to be made with respect to historical exposures and quantitative exposure-effect relationships. Perhaps a good starting point in sorting out what might be salvaged from the available data is to undertake a cooperative effort in the compilation and analysis of the available exposure data. However, in such an endeavor, expectations for fruitful results should not be high. The significant gaps in the knowledge of fiber size distributions and the lack of sufficient information on the consistency of the past and present analysis and classification methods for fiber size distributions and the fiber concentration measurements exist. There is also a relative lack of data on the fiber chemistry with respect to different fiber types and exposure circumstances. In addition, to a large extent, the *in vivo* biological reactivity of many different types of fibers are unknown. *Consequently, a large amount of the human exposure* data available may be impossible to interpret in the light of the biological and physical knowledge gained in the last two decades. Lippmann has noted that while the current occupational exposure index based on phase contrast optical measurements of fibers with an aspect ratio > 3 and a length > 5 μm was a reasonable choice when it was made, it is now apparent that the exposure index cannot provide an adequate index for any of the several fiber (asbestos) hazards (*3*). The studies of the past changes in the exposure assessment methodology of fibers indicate that the correspondence between the prior indices and the newer indices are not necessarily good, and in terms of estimation of the past exposures they provide at best an order-of-magnitude estimate of the general state of affairs *vis-a-vis* exposure experience of the cohort at risk. The likelihood of a better correspondence between the effect-based indices that should be developed and the current measurements required by law is slim.

If a more consistent and rigorous analysis is expected of the future epidemiologic studies, then fiber exposure measurements currently taken or attempted in the near future must consider both chemical and physical analyses much more sophisticated than hitherto carried out.

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