

Review Article

Measurement of Airborne Fibers: A Review

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Abstract: Current fiber measurement techniques arose primarily due to health concerns over asbestos exposure. Fiber toxicity appears to be primarily a function of fiber concentration, dimensions and durability in the lungs. There are two basic approaches to fiber measurement. Fibers can be collected on filters and counted or analyzed by light or electron microscopy; alternatively, fibers can be detected directly using a combination of fiber alignment and light scattering techniques. All of these measurement approaches work best when the fibers are simple rod-shaped particles. However, most fibers can exist as curved rods, complex bundles of fibrils, and agglomerates of fibers and compact particles. These non-ideal shapes contribute to measurement bias and variability.

Key words: Asbestos, Chrysotile, Glass fibers, Fiber measurement, Fiber classification, Microscopy, Direct-reading instrument

Introduction

Historically, fiber-related research primarily grew out of health and manufacturing issues regarding asbestos. A variety of mineral fiber types, especially asbestos, have been used as commercial products for thermal or acoustic insulation, and for reinforcement, especially in high temperature materials such as friction products (e.g., brake linings, clutch linings). In addition, fibers have been found as contaminants of other minerals.

An interesting history of asbestos production is given by Selikoff and Lee¹, with indications of asbestos use in the first century AD and perhaps earlier. Commercial production of asbestos began in the mid-1850s in Europe and peaked in the US in the early 1970s when health concerns over asbestos exposure caused a large-scale shift to alternative materials. Commercial production in several countries still continues at high levels, with Russia, Canada, and China being the highest producers. Total production in 1999 was 1.79 million metric tons².

Asbestos-associated disease was noted as far back as Roman times, but the first careful documentation of lung

disease due to asbestos exposure reported in the literature was credited to Cooke³. Reports of asbestos-related disease continued up to the 1960s and 1970s, when larger scale studies documented the extent and seriousness of the health effects. Some of these include reports by Selikoff *et al.*⁴, Nakamura⁵, and McDonald⁶.

The three primary diseases associated with asbestos exposure are asbestosis, the result of inflammation and collagen formation in lung tissue; lung cancer; and mesothelioma, an otherwise rare form of cancer associated with the lining around the lungs. A current theory describing the toxicity of fibers indicates that fiber dose, fiber dimension, and fiber durability in lung fluid are the three primary factors determining fiber toxicity⁷. The dose, or number of fibers deposited in the lungs, is clearly an important factor in determining the likelihood of disease. Both fiber diameter and length are important in the deposition of fibers in the lungs and how long they are likely to remain in the lungs. Figure 1 indicates some of the factors that determine fiber deposition and removal in the lungs. Fiber length is thought to be important because the macrophages that normally remove particles from the lungs cannot engulf fibers having

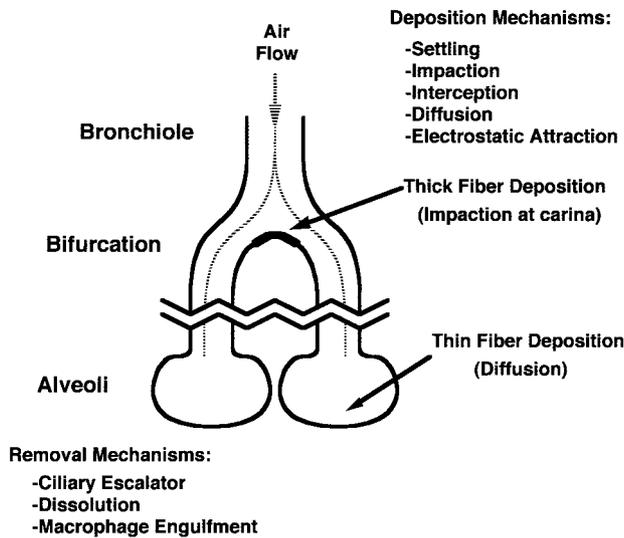


Fig. 1. Schematic of mechanisms that determine fiber deposition and retention in the lungs.

lengths greater than the macrophage diameter. Thus, longer fibers are more likely to remain in the lungs for an extended period of time. The macrophages die in the process of trying to engulf the fibers and release inflammatory cytokines into the lungs⁸). Fiber diameter is also important because fiber aerodynamic behavior indicates that only small diameter fibers are likely to reach into and deposit in the airways of the lungs. The smaller the fiber diameter, the greater its likelihood of reaching the gas exchange regions. Finally, fibers that dissolve in lung fluid in a matter of weeks or months, such as certain glass fibers, appear to be somewhat less toxic than more insoluble fibers. The surface properties of fibers are also thought to have an effect on toxicity.

Asbestos is one of the most widely studied toxic materials and there are many symposia dedicated to and reviews of its behavior in humans and animals^{1, 9-12}).

A variety of techniques were used for asbestos measurement up until the late 1960s¹²). Earlier than this, it was not widely recognized that the fibrous nature of asbestos was intimately related to its toxicity, so many techniques involved collection of airborne particles and counting all large particles at low magnification by optical microscopy. Thermal precipitators, impactors (konimeters), impingers, and electrostatic precipitators were all used to sample asbestos. Perhaps the primary technique in the US and UK during this early period was the liquid impinger, in which particles of dust larger than about 1 μm aerodynamic diameter were sampled at 2.7 l/min and impacted into a liquid reservoir. After sampling, an aliquot of the liquid was placed on a slide in a special cell, particles larger than 5 μm size were

counted, and the results were reported in millions of particles per cubic foot. Dissatisfaction with this approach stemmed from lack of correlation with fiber concentration and disease in the workplace. Various indices of exposure have been developed that attempt to relate a portion of the fiber size distribution to the toxic effects. Some suggestions regarding the appropriate indices for each of the asbestos related diseases were suggested by Lippmann¹³).

Fiber Dimensions

Fibers are particles that have one dimension significantly larger than the other two. Fibers are often characterized or selected according to their aspect ratio, the ratio of the large dimension to one of the short dimensions. If no other criteria are used, then materials that might not normally be considered fibrous may contain a fraction of particles that meet the criteria for fibers. The distribution of fiber dimensions can usually be characterized by assuming a cylindrical geometry, i.e., the two small dimensions are identical, and measuring the length and diameter of individual fibers. The distribution of fiber sizes generated by grinding bulk material or by mechanically releasing particles into the air often results in a two-dimensional (bivariate) lognormal distribution. Such a distribution is characterized by five parameters: the geometric mean length, the geometric mean diameter, the length and diameter geometric standard deviations, and a correlation term that relates length to diameter¹⁴). In addition, various other parameters that are a function of length and diameter, such as aerodynamic diameter, can also be characterized by a lognormal distribution¹⁵).

Most of the discussion here assumes that fibers are straight objects that can be well defined by several parameters. However, many real-world particles are not so simple to describe. In fact, the detailed features of many fibers can aid in their identification. Fibers are often curved or otherwise misshapen. Compact particles are frequently attached to fibers, affecting their aerodynamic behavior. Asbestos mineral is composed of fibrils (about 0.03 μm diameter) that are packed together. When the mineral is broken apart mechanically, the material separates primarily between fibrils and the resulting fibers are usually bundles of fibrils. The ends of the fibers can be broken apart, with smaller bundles or individual fibrils spread apart, yet still part of the fiber. In addition, multiple fibers and compact particles can be held together as complex structures. The complexity of fiber shapes affects all of the measurement and separation techniques described below and frequently makes it difficult to compare one method to another.

In addition to asbestos fibers, there is a wide range of fibrous materials being produced for commercial purposes. These include fibrous glass, mineral wool, refractory ceramic fibers, wood and other plant fibers, and synthetic organic fibers. Most of these fibers tend to have larger diameters than asbestos fibers. Carbon nanotubes (<5 nm diameter) have recently been produced in small-scale commercial quantities and because of their high tensile strength, high conductivity, and other special properties, show great promise as a commercial material¹⁶. Measurement techniques must be tailored to the size distribution and physicochemical properties of the fibers.

This review is limited to measurement of fibers in air. There are a variety of techniques that address concentration of asbestos and other fibers in bulk material and measurement of mass concentration of fibers.

Light Microscope Counting

As asbestos-induced disease became widely studied in the 1960s, cellulose-based membrane filter sampling was applied to asbestos sampling in combination with high magnification phase contrast light microscopy (PCM) for counting fibers. This technique involved collection of fibers uniformly over the surface of a cellulose ester filter, placing the filter on a microscope slide and making it transparent, and observing the fibers in the sample with a high magnification (~450X) phase contrast light microscope. Over the years since then a great deal of research has been carried out to improve and standardize the method. Walton discussed many aspects of this technique in a journal review issue¹⁷. The high variability of the analysis results and the method's dependence on operator technique made this research difficult. The method does not detect all fibers because of the limitations of light microscopy, so that the method is only an index of exposure, with the assumption that what is detected is correlated with the fibers actually causing disease. This should be remembered when considering some of the parameters discussed below. The aim of evaluating changes to the PCM technique may depend on whether consistency with other laboratories within a country or throughout the world is more important than making measurements that are more closely related to health effects. A number of method factors have been investigated, including:

Microscope-related parameters

Microscope magnification: The exact level of microscope magnification depends on microscope design, but most current methods use 450× (± 10%) total magnification. Pang

and coworkers investigated 1250× magnification to improve fiber detectability, but this has not been adopted in any established methods¹⁸. Pang also investigated the effect of using lower magnification (400×) and found that counts were lower for chrysotile asbestos by 25%, but that amosite fiber counts were unaffected¹⁹.

Phase contrast optics: This contrast enhancement technique allows detection of asbestos fibers down in the range of about 0.25 μm diameter, depending on fiber type. Other techniques such as dark field microscopy may offer improved detectability, but also increase the background due to non-fibrous particles.

Test slide to check optics: A test slide was developed to allow a check of proper alignment and magnification in the microscope²⁰. This ensures a reasonable level of uniformity in microscope setup and operation. Improper setup can reduce detectability of fibers. There have also been cases where the optics were "too good," and higher than acceptable counts resulted.

Counting area in microscope field: Some early measurements with the phase contrast microscope were made using a rectangular graticule for defining the counting area, while others were made using the entire microscope viewing area. It was found that larger viewing areas resulted in lower counts, so a graticule was developed that gave a 100 μm diameter counting area in each microscope. This has been standardized in all current methods. Figure 2 contains the Walton-Beckett graticule²¹ with examples of how fibers are counted.

Sample preparation techniques

Filter type: Virtually all measurements are made using 0.8 μm pore size mixed cellulose ester (MCE) filters. Some measurements are made using 1.2 μm pore size filters when sampling low concentrations to allow higher flow rate through the filter. Smaller pore size filters are used to ensure that fibers are deposited as near the surface of the filters as possible. This results in fibers ending up in the same plane so that they can be readily viewed with a minimum change of focus during fiber counting.

Selection of the liquid for making filter transparent: A liquid is placed on the filter that closely matches the filter refractive index, yet has an index that is as far as possible from that of the fibers being detected. Rooker *et al.* showed that refractive index difference between cleared filter and fibers translated directly into detectability of small diameter fibers²². A viscous solution of dimethyl phthalate and diethyl oxalate mixed with cellulose filter material was commonly used in the 1970s and early 1980s. However, it did not result

programs provide feedback, often tied to laboratory accreditation, that provides incentive for laboratories to ensure that their performance is similar to that of other laboratories.

Several methods using optical microscopy have been published by national^[31–33] and international^[34, 35] organizations. Most countries have methods very similar to the ones referenced here.

In addition to simply counting the fibers, there are techniques available for providing at least tentative identification of fiber type. Fiber shape can be used to limit the type of fiber present. For instance, glass fibers tend to be straighter, with smoother sides than chrysotile fibers. Polarizing light techniques can also be used to identify larger diameter ($> 1 \mu\text{m}$) fibers. These are based on the optical properties of the materials, including refractive index and crystallinity. These techniques can provide quite positive identification for the presence of certain types of fibers, but are limited for airborne fibers because they only work for the larger diameter fibers. These techniques are often used in analysis of bulk materials^[36].

Image Analysis

Since fiber counting by human analysts produces relatively high biases and variability, several researchers have attempted to develop automated counting systems. With the increases in computer power over the last 25 years, it has been tempting to assume that fiber counting is a solvable problem and significant efforts have been made to develop such a system. The most intensive effort to produce a fiber counting system was carried out by Manchester University in collaboration with the Health and Safety Executive in the UK^[37]. The Manchester Asbestos Program (MAP) was able to give reasonably good agreement with human counters for certain types of samples. It was used as a reference analyst for the US and UK reference sample programs for several years. Eventually, the MAP was dropped as the reference because it was not sufficiently consistent for all types of samples.

The principle problems with image analysis of asbestos fibers include: the complexity of many fiber shapes, including bundles, agglomerates, and split fibers; the fibers often go in and out of the plane of focus; the background includes many particles and other non-fibrous shapes; the phase contrast optics produces haloes around particles in the sample that can be detected as fibers; and finally, and perhaps most importantly, the contrast between the fibers and background is poor and many fibers are near the detection threshold. An evaluation of the MAP program indicated that a significant

fraction of the fibers were misidentified as multiple fibers, not detected at all and groups of compact particles or edges of large particles were detected as fibers^[38].

Inoue and coworkers have developed image analysis software using a microprocessor-based PC^[39]. Initial tests indicate that it works approximately as well as human counters. Inoue also evaluated how well human counters and the image analyzer did in detecting the same fibers in a sample and found that only about 50% of the fibers were consistently counted by all counters, so the image analysis system did approximately as well as the human counters^[40]. Further testing of the image analysis system is needed.

In addition to image analysis, optical microscopy can be enhanced using a personal computer to more easily observe the image and to mark and measure fiber dimensions, with automatic recording of the fibers counted^[41]. This does not appear to affect the counting accuracy since the analyst still decides which fibers are to be counted.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) has not been the focus of as much method development as either light microscopy or transmission electron microscopy (TEM). PCM found favor because of the low equipment cost and lower training level required for analysis. TEM is preferred for environmental and research studies because it offers the highest resolution and the most positive identification capabilities, allowing visibility of all asbestos fibers, and electron diffraction for crystal structure identification and energy dispersive x-ray analysis for elemental measurement. SEM has intermediate resolution, with many instruments of this type not able to see all asbestos fibers. However, many modern SEMs have the capability of detecting asbestos fibrils. Energy dispersive x-ray analysis is also available for many SEMs, providing some qualitative information of fiber type. However, since electron diffraction cannot be performed by SEM, this often leaves open the question of positive identification of fibers.

Particles are observed in the SEM when a beam of electrons is focussed onto the sample surface and scanned over an area. The electrons are scattered from the surface and detected above the surface synchronously with the beam scan rate and an image of the scanned surface is created. Thus, the SEM measures the surface of particles on a substrate. The best image can be obtained on conducting objects deposited on a smooth, conducting substrate. Particles are often deposited on aluminum or carbon planchets that fit directly into the SEM or onto polycarbonate membrane (track-etched,

Nuclepore) filters. The samples are usually coated with gold or carbon to increase conductivity.

There have been some SEM methods developed for fiber counting⁴²⁻⁴⁴. These methods are primarily used for inorganic man-made fibers that have larger diameter fibers than can occur with asbestos. Thus, all the fibers are potentially visible using the SEM.

Transmission Electron Microscopy

The transmission electron microscope (TEM) is considered the most powerful technique for counting and analyzing fibers. It is capable of detecting the smallest fibers (carbon nanotubes and asbestos fibrils) and can be used to determine crystal structure from electron diffraction as well as determining elemental composition from energy dispersive x-ray analysis. Although TEM analysis is potentially very powerful and accurate, the process of sample collection and preparation and details involved in sample analysis can degrade the quantitative accuracy of the technique. Several other, more specialized techniques have been used for analyzing particles and can also be applied to fibers⁴⁵.

Airborne fiber samples for TEM analysis are typically collected onto a filter, usually a polycarbonate membrane or MCE membrane filter. For the latter filter type, the filter is chemically collapsed to form a smooth upper surface on which collected fibers are trapped. Sometimes the surface is etched using a low temperature asher to expose the fibers collected on or near the surface of the original filter. The filter is coated with a carbon film that entraps fibers exposed on the filter surface and the filter material is then dissolved away. The carbon film is transferred to a TEM grid (usually 3 mm diameter) and the sample can be placed in the TEM for analysis.

The above approach to preparing MCE filters for TEM analysis is called the direct-transfer approach, since fibers are transferred to the carbon film with minimum disturbance to the way they were collected. An alternative technique is to dissolve the entire filter in liquid, ultrasonicate the suspension to disperse the particles, and deposit an aliquot of the particle suspension onto a polycarbonate filter for final transfer to the carbon film. This is called the indirect transfer technique. With the indirect technique, the optimum particle loading of the TEM sample can be obtained and soluble particles can be removed from the sample. However, the suspension process can change the apparent size distribution of the particles and fibers by breaking apart agglomerates or even breaking apart asbestos fibers into smaller fibers or fibrils⁴⁶. The breakup problem can be

especially severe for chrysotile.

The process of sample collection and preparation is a complex one that can introduce biases into the final measurement. Since only small portions of the filter are measured when analyzing by TEM, sampled fibers that deposit non-uniformly onto the filter due to inertial, gravitational and electrostatic effects, will be measured inaccurately⁴⁷. Fibers that penetrate the filter surface and are not transferred to the carbon film will be lost. If the filter is incompletely dissolved away from the carbon film, the sample will be difficult to analyze.

Many of the sources of bias and variability noted in sampling and counting by PCM also apply to TEM analysis. Fiber counting in a TEM can also introduce biases and variability in the final result. There is a tendency to use the high magnification of the TEM to look for the smallest fibers, while ignoring some of the larger ones. Even so, fibers shorter than 0.5 μm tend to be missed because they are difficult to see in the background clutter of the sample⁴⁸. Carter *et al.* found that TEM counting gave poorer precision than counting the same sample by PCM⁴⁹.

There are several established methods for analyzing fibers, especially asbestos fibers, by TEM⁵⁰⁻⁵⁴.

Optical Detection

Two types of light scattering detectors are commonly used for measuring airborne dust concentrations: the optical particle counter (OPC), which detects and counts individual particles and the photometer (sometimes called a nephelometer) that detects the scattering from all particles in a defined detection volume. A standard OPC was used to detect asbestos concentrations in a workplace where the aerosol was primarily fibrous and good correlation with fiber counts was obtained⁵⁵. A nephelometer may also be used, but is less likely to indicate fiber concentration, especially when non-fibrous dusts are present.

Light scattering from single, well-defined fibers has formed the basis of several fiber detection techniques. If a fiber is perpendicular to the axis of illumination, the scattered light is concentrated into a plane containing the illuminating light axis and perpendicular to the long axis of the fiber.

The width of the scattered light plane has been shown to be related to fiber length⁵⁶. A number of instruments have been developed that use the unique light scattering pattern from fibers. In order to take advantage of this property of fibers, the fibers must be aligned perpendicular to the illumination axis.

Several alignment techniques have been applied to fibers.

Timbrell investigated the magnetic alignment properties of fibers and found that many asbestos fibers aligned either parallel or perpendicular to the magnetic field⁵⁷). He applied the field to fibers collected on a filter and suspended from the surface of the filter in a liquid⁵⁸). When the liquid dried, the fibers remained aligned on the cleared filter surface. The scattering intensity and pattern from the filter surface could then be related to fiber type and concentration. A commercial instrument was developed using this approach, but was not successful because the scattering intensity depended too much on fiber type and could not be readily correlated with fiber counts for a variety of samples⁵⁹).

When a sufficiently conductive fiber is placed in an electric field, the fiber will polarize and align parallel to the electric field. The conductivity of the fiber does not have to be very high since the alignment only requires moving a few electrons several micrometers along the length of the fiber. Thus, asbestos is quite conductive on this basis, even though it is normally considered an insulator. Glass fibers are intrinsically non-conductive, though at high enough humidity levels (about 50% RH), the water adsorbed on the surface provides enough conductivity to allow electrostatic alignment. The fibrous aerosol monitor (Model FM-7400, MIE, Inc. Bedford MA) was developed using the electrostatic alignment technique and applies a field that aligns and rotates individual fibers in a laser beam. This allows specific detection of fibers⁶⁰) and may even be used to measure fiber length⁶¹).

Fibers will align parallel to the flow direction in a gradient flow field. Thus, laminar flow through a tube can be used to establish a parabolic flow profile (Poiseuille flow). Fibers will align with their long axis very nearly parallel to the tube axis⁶²), though the fibers will periodically flip 180°⁶³). An instrument was developed using flow alignment of fibers and electrostatic deposition, with optical scattering detection of the deposited particles⁶⁴). Although promising, the instrument was not commercialized. Hirst and coworkers developed an instrument coupled with a neural network algorithm to identify light scattering patterns from flow-aligned fibers, but this instrument also was not commercialized⁶⁵). Figure 3 shows scattering patterns from 12 μm long SiO_2 micromachined fibers. Sachweh and coworkers used a similar instrument with multiple angle scattering detection for laboratory studies⁶⁶). Another device that uses flow alignment and multiangle scattering detection is commercially available (FibreCheck, Casella, Bedford UK). A field comparison of the FibreCheck and the FM-7400 measuring man-made mineral and chrysotile fibers indicated that both instruments tended to underestimate fiber

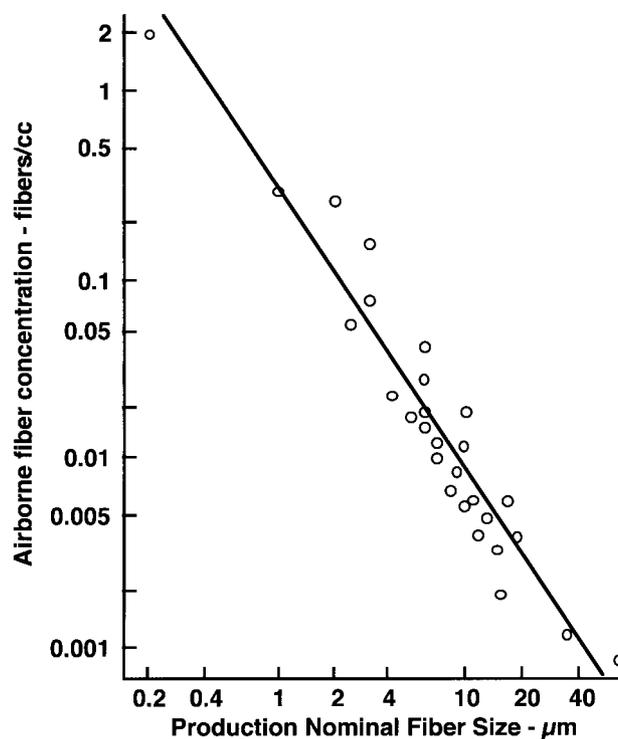


Fig. 3. Relationship between measured average exposures, expressed as fibers/cc (determined by phase contrast microscopy), and nominal diameter of fiber manufactured (Copyright American Industrial Hygiene Association).

concentration compared to phase contrast microscope counting⁶⁷). Although the correlation between all these methods was good for man-made mineral fibers, the FibreCheck had especially poor detection capability for small diameter chrysotile fibers.

Optical techniques can easily detect well-formed $>1 \mu\text{m}$ diameter fibers. When curved or more complex fibers are detected, these methods may become less efficient. Since fiber detection instruments are usually compared with the filter collection/PCM counting method, it can be difficult to calibrate such an instrument for all types and sizes of fibers.

Fiber Separation by Diameter

The aerodynamic diameter of fibers is dependent primarily on fiber physical diameter and fiber density, with a minor dependence on fiber length⁶⁸). Several devices have been used to measure or separate fibers by diameter. A spiral centrifuge was used to separate fibers and reference spherical particles to estimate fiber aerodynamic diameter⁶⁹). It was found that the aerodynamic diameter was directly

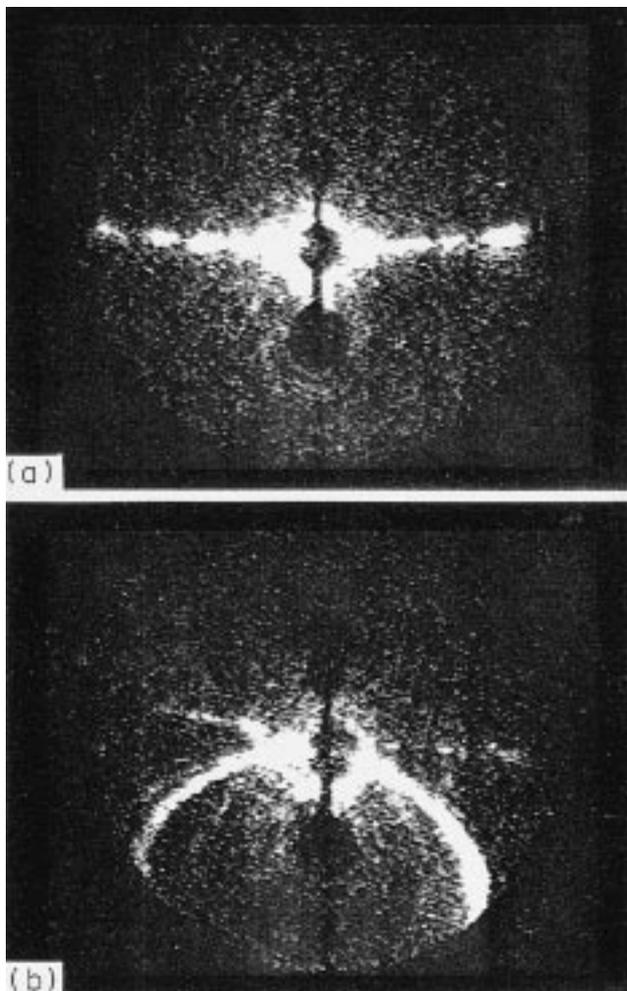


Fig. 4.

(a) Experimental scattering profile recorded from a signal 12 μm silicon dioxide fire (image capture in 2 μs).

The horizontal scattering implies close alignment of the particle with the vertical sample airflow.

(b) Experimental scattering profile recorded from a single 12 μm silicon dioxide fiber (image capture in 2 μs).

In this case the conic section form of the scattering implies a particle orientation approximately 10° clockwise to the vertical in the plane orthogonal to the laser beam axis, and 15° tilted forward (towards the laser) in the plane of the beam axis (Reprinted from *J Aerosol Sci* 23, Kaye, PH, Hirst E, Clark, J, and Micheli, F. Airborne particle shape and size classification from spatial light scattering profiles. 597-611 Copyright (1992) with permission of Elsevier Science).

proportional to physical diameter, proportional to the square root of the fiber density, and proportional to fiber length to the $1/6^{\text{th}}$ power. For mineral fibers having a density of about 3 g/cm^3 , the aerodynamic diameter was approximately three to five times the physical diameter of the fiber. Behavior of glass fibers in a cascade impactor was investigated by Burke and Esmen⁷⁰. A small correction to the aerodynamic diameter

was developed to take into account interception of longer fibers with the impaction surface. An inertial spectrometer was used to measure fiber aerodynamic diameter and good diameter separation was achieved⁷¹.

As with most airborne dusts, fiber settling will reduce the number of larger diameter fibers in a distribution as the distance from the source of the dust increases. Esmen showed that average fiber concentration in workplaces decreased exponentially with an increase of fiber diameter, indicating that the larger diameter fibers settled out more quickly than smaller diameter fibers (Fig. 4)⁷². Cyclones, impactors and porous foam classifiers were evaluated for efficiency of removing airborne fibers not likely to deposit in the lungs⁷³.

Fiber Separation by Length

Since the health effects of fibers are strongly correlated with fiber length, there have been many efforts to separate fibers by length. These efforts included bulk separation techniques and aerosol separation techniques. Spurny used a liquid sedimentation technique that provided some length classification and also suggested that sonic generation could provide size-classified aerosol⁷⁴. A proprietary liquid suspension separation technique was used for an inhalation toxicity study⁷⁵. Hanton *et al.* found that by compressing glass fibers at high pressure, the fibers could be broken to give a length mode in the $10\text{--}20 \mu\text{m}$ range⁷⁶.

Myojo described a technique for classification of airborne fibers by passing them through sieves⁷⁷. This allowed measurement of the fiber length distribution. However, the technique did not provide high resolution and was limited in output because of particle loading on the sieves.

Chen *et al.* electrically charged monodisperse-diameter carbon fibers and separated them by length in a mobility analyzer⁷⁸. Chen indicated that the separation was achieved by a combination of the charging and electrophoresis process. Lipowicz suggested that this separation technique was effective because the fibers were being separated by dielectrophoresis⁷⁹ and provided the theory for a dielectrophoresis-based classifier⁸⁰. Baron and coworkers developed such a classifier (schematic in Fig. 5) and were able to obtain length distributions with standard deviations of about $10\text{--}20\%$ ^{81, 82}. This classifier separated fibers by placing them in a gradient electric field, which polarized the fibers, aligned them parallel to the electric field, and caused them to drift toward the higher field electrode. The drift velocity was proportional to the fiber length squared. This classifier was used to provide small quantities (up to 1 mg per day) of monodisperse-length material for toxicity

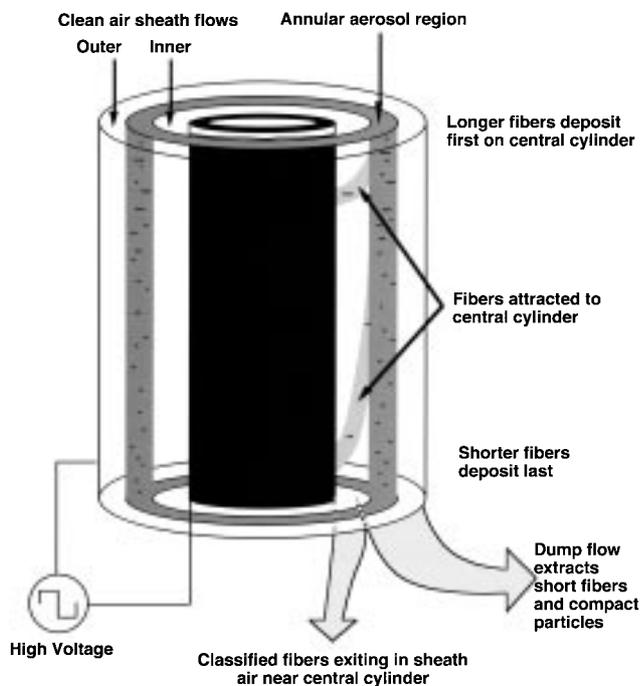


Fig. 5. Schematic of dielectrophoresis classifier showing the sheath and input and output aerosol flows.

Fiber motion toward the inner electrode is caused by induced polarization of the fibers and the higher field closer to the inner electrode. The inner electrode is coated with oil to prevent resuspension. An ac electric field is used to reduce deposition of particles with a net charge.

assays^{8,83}). It was also demonstrated that the dielectrophoresis classifier could be used to measure bivariate fiber distributions when combined with an aerodynamic sizing instrument such as the Aerosizer (TSI, Inc. Minneapolis)⁸⁴. The instrument is not commercially available and is difficult to scale up for production of larger quantities of fibers.

Conclusions

The capability for measurement of fiber size distributions is available through microscopy and to a much lesser extent, through direct-reading instrumentation. The traditional methods of microscopy are relatively inaccurate when compared to many chemical analysis methods because of the many sources of error in the sampling and analysis procedure. Further work is needed in automating fiber counting through improved image analysis of microscope images and through improved direct-reading instrumentation.

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