25

PLAINTIFF'S EXHIBIT

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Background Documentation on Evaluation of Occupational Exposure to Airborne Asbestos

Joint ACGIH-AIHA Aerosol Hazards Evaluation Committee

This review presents background information and literature documentation to supplement the "Recommended Procedures for Sampling and Counting Asbestos Fibers: Procedures for the Evaluation of Occupational Exposure to Airborne Asbestos" prepared by the Joint ACGIH-AIHA Aerosol Hazards Evaluation Committee. It reviews the nature of the inhalation hazard associated with asbestos fibers, the sampling and analytic methods which have been used, and a rationale for the selection of the membrane filter sampling-optical phase microscope identification and assay methodology which is recommended.

Introduction

THE INHALATION OF ASBESTOS FIBERS is known to cause asbestosis and mesothelioma in man, and to significantly increase the incidence of lung cancer. Most, if not all of the increased mortality has been associated with occupational exposures. Asbestos is a nearly ubiquitous material in industrialized societies, and has also been found in community air samples and in human lungs in most cases where it has been diligently sought. However, the association between community air pollution exposures and increased lung cancer mortality has not been established. One reason is the general difficulty of establishing a clear causal relationship between low-level exposures and a possible increase in disease incidence in a large population, especially when other known and suspected carcinogens are also present in the atmosphere. This problem is compounded by the lack of a method for the quantitative assay of airborne asbestos fibers when they are present in much lower concentrations than are other airborne particles. The method recommended herein for occupational exposure evaluations depends on visual discrimination of fibers in the presence of a background of non-fibrous particles. It cannot be used for community air evaluations, where background particles would usually obscure too large a fraction of each viewing field.

Diseases Associated with Asbestos

Asbestosis

The inhalation of excessive amounts of airborne asbestos fibers over an extended period of years will cause in some individuals a pneumoconiosis, termed asbestosis. The onset of asbestosis probably depends upon the asbestos dust concentration, fiber morphology, and the length of exposure. Merewether and Price[1] demonstrated in 1930 that asbestosis posed a threat to workers in the asbestos textile trade. It is now known that in any of the trades in which excessive airborne exposures to asbestos fibers occur, it is likely that some employees will develop asbestosis. Major sources of exposure occur during asbestos mining, milling, textile weaving, insulation installation and stripping, and during the manufacture and application of friction products and cement products. Harries[2] in 1968 suggested that a worker engaged in trades in which intense intermittent exposures to asbestos occur, may also develop asbestosis.

Asbestosis is a progressive disease which

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may develop fully in seven to nine years and may cause death as early as thirteen years after the first exposure.[3] Usually, the pneumoconiosis becomes evident 20-40 years after the first exposure to asbestos. Once established, asbestosis progresses even after the exposures have ceased, as shown by Lanza[3] in 1938.

The consistent pathologic change in the lung is interstitial, septal, peribronchiolar or perivascular fibrosis which is eventually visualized by x-ray. It is accompanied by the formation of intra-alveolar ferruginous bodies.

The principal findings in asbestosis include reduction in forced vital capacity and forced expiratory volume in one second, as well as reductions in other measures of pulmonary function. Selikoff *et al.*[4] referred to asbestosis as a monosymptomatic disease with dyspnea being the main complaint. The British Occupational Hygiene Society[5] suggests that basal rales are the first sign of asbestosis. Becklake *et al.*[6] administered a symptom questionnaire to approximately 1,000 employees undergoing pulmonary function tests and found that breathlessness on exertion was probably the most sensitive symptom index related to dust exposure.

Neoplasia

Bronchogenic carcinoma and mesothelioma of the pleura and peritoneum are causally associated with asbestos exposures. Selikoff *et al.*[7] have shown that asbestos insulation workers who smoke had a higher incidence of lung cancer than those who did not. Excesses of cancer of the stomach, colon, and rectum have also been observed.[8]

There is a little likelihood of asbestosis or lung cancer arising from non-occupational exposures but mesotheliomas have been found among families of asbestos workers, and in the neighborhoods of asbestos plants not having environmental controls. According to Selikoff[9] it may be unjustified to give any estimate of the magnitude of the risk associated with indirect occupational or family exposure. According to Cooper[10] the major potential for risk appears to be related to "indirect occupational contact, household contact, or residence in the immediate neighborhood of an asbestos source; and even there, the actual risk is poorly defined. It is not known what range of respirable airborne asbestos fibers will ultimately be found to have no measurable effects on health."

All studies which indicate differences in pathogenicity among various types of asbestos suffer from lack of information about fiber characteristics, lack of quantitative data on cumulative exposure and the influence of trace materials such as nickel, chromium or manganese, and various hydrocarbons.[11] There is evidence that the development of mesothelioma varies between groups exposed to different types of fibers.[12-17]

The association of exposure to asbestos with bronchogenic carcinoma was first reported in 1935 by Lynch and Smith[18] but it was not until 1947 that this was fully recognized. Merewether[19] demonstrated bronchogenic carcinoma in 13% of autopsies of persons who had asbestosis arising from employment in the textile trade. In 1955, Doll[20] found that textile workers exposed for at least 20 years during the period between 1922 and 1953 had a frequency of ten times the expected rate. More recently, Williams[21] in 1965, and Selikoff *et al.*[22] in 1969, reported a frequency of bronchogenic carcinoma among insulation workers much greater than that anticipated. The possibility that asbestos is a co-carcinogen, also, was suggested by Wright[23] in 1969.

Cigarette smoking is strongly implicated as a co-carcinogen among asbestos workers. Selikoff *et al.*[7] reported that the incidence of bronchogenic carcinoma among nonsmoking asbestos workers is not significantly greater than that of non-asbestos workers, while asbestos workers who smoke have a much higher incidence.

In 1959, Wagner[24] reported 33 cases of pleural mesothelioma occurring after ex-

posure to crocidolite in the Northwest Cape region of South Africa. Additional information supporting association between mesothelioma and asbestos exposure has been developed. Selikoff *et al.*[25] reported 22 deaths from mesothelioma among 532 asbestos workers who were exposed to mixed asbestos insulation materials, compared to the expected very low incidence of mesothelioma in the general population. Stumphius and Meyer[26] reported 17 cases of mesothelioma in 1968 among shipyard workers, and concluded that amphibole asbestos minerals, especially crocidolite, may have caused the tumors. McDonald *et al.*[27] reported several cases of mesothelioma among current and former Quebec chrysotile miners and mill operators. They concluded that primary malignant mesothelioma, although rare in Canada, occurred more frequently than expected among workers in manufacturing and industrial applications, but not among workers in mining and milling operations. Wright[23] has noted that employees engaged in dusty chrysotile mining and milling operations have lower incidence of asbestosis, bronchogenic carcinoma and mesothelioma than those working in insulation operations.

In 1971, Stanton and Wrench[28] and Wagner *et al.*[29] postulated that the development of mesothelioma associated with asbestos exposure may not be due to its chemical composition but to its morphology. Mesothelial responses were initiated in animals by intrapleural implants of durable fibers other than asbestos, such as fibrous glass. The carcinogenicity of asbestos and fibrous glass under these experimental conditions appeared to be primarily related to the structural shapes of these materials rather than to physiochemical properties.

Signs and Symptoms of Asbestos Exposure

Pleural Plaques and Pleural Calcifications

Localized pleural thickening, which may become radio-opaque through calcification, has often been observed in persons having occupational exposures to asbestos. Calcified plaques also occur in certain geographic regions such as Northern Finland,[30] Czechoslovakia[31] and Bulgaria.[32] It is interesting to note that even large calcified plaques appear to have little effect on respiratory function. There is no evidence that they result in malignant disease.[33]

Asbestos Bodies

Murray[1] reported the first recorded death resulting from asbestos exposure and made, perhaps, the first reference to asbestos bodies. Similar observations were made by Marchand and Riesel as cited by Gloyne[34] and by Fahr.[35]

Cooke[36] in 1924 described the first conclusive case of asbestosis in which Cooke and Hill[37] demonstrated the presence of "curious bodies".

Gloyne[38,39] described the asbestos body, stating that its formation was the result of a tissue reaction to a foreign body acting as a benign irritant. Merewether,[40] Blount,[41] and Suzuki and Churg[42] have described its biochemical composition.

Pseudoasbestos Bodies—Ferruginous Bodies

Prior to the adoption of the more general term "ferruginous body", there was considerable debate about the origin of atypical asbestos bodies. Thus, they were referred to as "pseudoasbestos bodies" and have been reported forming around rutile needles by Sundius and Bygden,[43] brucite and $MgO.H_2O$ by Vorwald,[44] and ceramic aluminum fibers, cosmetic talc and attapugite by Gross *et al.*[45]

Gross *et al.*[45] proposed that the controversy between the term "asbestos" body and "pseudoasbestos" body be ended by adopting the more general term "ferruginous" body. Thus, the asbestos body is one kind of ferruginous body.

Properties of Asbestos Affecting Lung Retention

Timbrell[46-49] has discussed the properties of fibers in connection with their deposition in the lungs and bronchial passages. He

showed that deposition depends on fiber diameter, fiber length and fiber shape. He also stated that because of aggregation, particularly with chrysotile, it is very difficult to define diameter and length of many fibers. The extreme length of the fibers results in increased bronchial deposition by interception, a mechanism whose effect can usually be neglected for particles of more compact shapes. The fiber shape is important because it affects the orientation which the fibers assume within the airways; the straighter, more needle-like amphiboles tend to align themselves with the axis of the airway, and penetrate deeper into the lung, while the "curly" chrysotile fibers do not.

Characterization of Airborne Asbestos

On the basis of the preceding discussion, it appears that the hazards from inhaled asbestos are more closely related to the fibrous nature of the particles than to their chemical composition or surface properties. Thus, the most appropriate index of hazard is fiber concentration, but whether this should be expressed by number, surface area, or mass is not yet clear. At present, the only practical way to determine fiber concentration is by counting fibers which have been mounted on a suitable substrate so that they can be identified as individual fibers. Such identifications can be made with optical or electron microscopes. Electron microscopy reveals fibers which are too small to be resolved with light microscopy, but is too expensive for most routine evaluations. Furthermore, it is believed that occupationally related asbestos diseases are most closely associated with fibers which are large enough to be resolved optically.[50,51] For air pollution exposures, it is possible that the smaller fibers may also be of concern.

Since the inhalation hazard from airborne asbestos is initimately related to fiber size and shape, it is necessary to consider the crystalline characteristics of the family of minerals known as asbestos.

Asbestos is a generic name for naturally occurring mineral silicates whose crystals are in the form of filaments. Thus, when the bulk material is subdivided, it separates into filaments, some of which are small enough to become airborne. The most widely used asbestos mineral in the U.S. is chrysotile ($3MgO.2SiO_2.2H_2O$) a fibrous form of serpentine. Other types of asbestos are known as amphilboles and include amosite ($5.5FeO.1.5MgO.8SiO_2.H_2O$); crocidolite ($Na_2O.Fe_2O_3.3FeO.8SiO_2.H_2O$); tremolite ($2CaO.5MgO.8SiO_2.H_2O$); anthophyllite ($7MgO.8SiO_2.H_2O$); and actinolite ($2CaO.4MgO.FeO.8SiO_2.H_2O$).

Asbestos Dust in Industry

A number of studies have been carried out on composition and fiber size distribution in dust clouds containing asbestos: The composition of the dust depends on the proportion of the asbestos in the material worked and on other sources of dust.

The size distribution measurements[49,52-55] that have been carried out on asbestos in dust clouds are not strictly comparable because of variations in optical and electron microscope techniques; however, clear indications of large variations in size distribution have been given for different types of asbestos and different manufacturing processes and application methods.

These studies have shown that:

(a) many fibers are smaller than the resolution limit of optical microscopy;
(b) the diameter of chrysotile fibers, which occurs in bundles of fibrils, cannot be clearly defined;
(c) long chrysotile fibers are frequently curly, the others are mainly straight;
(d) other abestoses (crocidolite, amosite, and anthophyllite) frequently occur as single fibers;
(e) the minimum diameters for fibers are: chrysotile 0.25 μm, crocidolite 0.06 μm, amosite 0.15 μm, anthrophyllite 0.25 μm;
(f) the diameters of individual fibers in the air seldom exceed 5 μm;

(g) the fiber lengths range from 0.2 μm to 1000 μm; and
(h) large clumps of fibers have been observed frequently.

Threshold Limit Values (TLV's) and Alternative Hazard Indices

The asbestos TLV of ACGIH[56] for 1974 is 5 fibers longer than 5 μm per cm^3 of air for all types of asbestos, using a 400-450 × phase contrast objective lens. As published in the Federal Register,[57] the interim Occupational Safety and Health Administration (OSHA) standard of 5 fibers/cm^3 will be reduced to 2 fibers per cm^3 on July 1st, 1976. The British standards for chrysotile[5] (1968) and amosite[58] (1973) asbestos recommend 2 fibers/cm^3. The chrysotile standard[5] gives equivalent threshold limit values using a range of other instruments as shown in Table I. It should be noted that this table refers to conditions in textile factories using chrysotile asbestos and the equivalents may not be aplicable in other places.

TABLE I
Table of Alternative Indices Used in Great Britain

Method	Concentration
Membrane filter	2 fibers/cm^3 (current British Standard)
"Respirable" mass	0.03 mg magnesium/m^3 0.04 mg SiO_2/m^3 0.10 mg ash/m^3 0.12 mg asbestos/m^3
Thermal precipitator	25 particles/cm^3 greater than 1 μm after incineration
Impinger	10 particles/cm^3
Royco particle counter	2 particles/m^3 greater than 4 μm

The fact that many airborne fibers may be less than 5 μm long[59] suggests that additional data be obtained to quantitative the relative concentration of less than 5 μm fibers. This might provide a basis for estimating the health significance of fibers which will not be counted using currently recommended standard procedures.[5,56,57,60] It is not practical to extend "high-dry" phase contrast microscopy to counting fibers much less than 5 μm. In all probability this technique would provide unreliable data for fibers much less than 2 to 3 μm in length. The use of electron miscroscopy to provide additional data of this type seems desirable until alternate techniques for sampling small fibers are developed. Various methods of transferring samples from membrane filters to electron microscope grids, have been proposed,[61-65] as have techniques for direct collection on electron microscope grids.[66,67] The scanning electron microscope can, however, be used directly on samples collected on a membrane with a minimum of preparation.[68] It would seem that the main drawbacks to electron microscopy are the costs and the need to examine more fields to determine the concentration of long fibers (greater than 5 μm) sufficiently accurately; however, there are possibilities in instrumental identification and assessment of fibers in the presence of other particles.[69,70] Although electron microscopy samples may not be practical for routine air monitoring, and cannot be directly compared to the current TLV, they may provide an essential additional basis for a retrospective reevaluation of the inhalation hazard.

Review of Sampling and Analysis

Sampling Techniques

Almost every type of dust sampling instrument has been used for sampling asbestos dust clouds: (a) konimeter,[52,70-73] (b) impinger,[5,56,71,74,75] (c) thermal precipitator,[5,71,76] (d) membrane filters,[5,56,71,76,77] (e) open filters,[5,56,71,27,78] (f) electrostatic precipitators,[78] (g) respirable dust samplers,[5] and (h) light scater instruments.[5,71] The first four types are assessed by optical microscopy, and (e) to (g) by weighing or analytical methods (ash or magnesium determination).

Of the techniques which have been used for sampling asbestos to estimate potential health hazards,[5,56,57,72,77] principle attention in the United States has been directed towards the use of impingers or membrane fil-

ters. Air concentrations of asbestos based on impinger sampling are primarily determined by the concentration of nonfibrous particles present in the air. While a reduction in total particle concentration is probably accompanied by a reduction in asbestos fibers, a quantitative relationship between these two components (fibers and other particles) for all processes is not possible.[79,80] Since fibers are the etiological contaminant of concern, the currently recommended safe air concentrations and sampling procedures are defined in terms of fiber concentration.[5,56,57,60]

The determination of fiber concentration involves the collection of essentially all airborne particles on a submicron pore size membrane filter. The filter is rendered transparent by the application of immersion oil, and the fibers with lengths greater than 5 μm are subsequently counted using phase contrast microscopy procedures. While it may not be completely appropriate to exclude fibers shorter than 5 μm in length when estimating potential risk to the worker, this restriction has been adopted to minimize variations due to microscopy technique.[5,60] Fibers are defined as particles having a length to diameter (aspect) ratio of at least 3 to 1.

While the membrane filter method is generally considered the best available at this time, it should be remembered that it is far from ideal. One problem with the method is the inherent difficulty in distinguishing asbestos fibers from a much greater background of other types of dust.

The other limitations derive from our conitnued ignorance of critical factors affecting the hazard:

(1) The lack of knowledge of the deposition site and criteria (*i.e.*, size aggregation and curliness) for deposition of fibrous particles in the respiratory tract system.[46-48]

(2) The lack of knowledge as to which physical property of asbestos (*i.e.*, number, surface area or mass) is most closely related to the health hazard.

(3) The lack of knowledge of translocation within the body.

(4) The size range which is important.[60]

Analytical Techniques

In many situations, separate determination of asbestos in the presence of other dusts is essential to determine the health hazard and has led to studies into analytical procedures. The techniques reported are: (a) optical microscopy (fiber counting),[5,71,61] (b) optical microscopy (fiber counting) using phase contrast illumination,[5,71,61] (c) electron microscopy,[68,81] (d) optical sizing of airborne particles,[72] (e) ash determination,[27,78,61] (f) magnesium determination,[72,75,61] (g) infrared spectroscopy,[61,82] (h) x-ray diffraction,[61] (i) trace constituents,[78] (j) orientation in a magnetic field.[83]

Microscopy offers ready discrimination between fibrous and other particles. However, it has been found that more and more fibers can be seen as the resolution is increased through the optical microscope range down into the electron microscope range, and a consistent reasonable definition of smallest size assessed is essential. Phase contrast illumination improves the visibility of fine fibers in optical microscopy.

Optical sizing of single particles by light scatter has been suggested as a method of assessing airborne fibrous dust on the basis that the majority of particles which scatter more light than a 4 μm-diameter sphere are fibers. This technique has been used routinely in textile factories,[72] but requires calibration for each particular situation.

Ash determination on gravimetric samples have been used[78] as a means of assessing asbestos when it is used mixed with organic fibers in some textile manufacture.

The determination of magnesium,[61] by atomic absorption spectrophotometry, can be used for chrysotile asbestos fibers if there are no other components containing appreciable amounts of magnesium. The technique is very sensitive.

Infrared spectroscopy and x-ray diffraction analysis of asbestos have been used successfully in some instances but interferences can readily occur and more experience is needed.

The orientation in a magnetic field and assessment by optical methods using a laser beam shows promise. Its sensitivity is already in the microgram range.

Keenan and Lynch[61] have produced a useful review of fibers identification techniques. All analytical methods have their limitations, and these must be borne in mind.

It is apparent that, at present, microscopy is the only assessment that can be used to distinguish asbestos fibers from other dust and fibers in all types of industry and it is therefore desirable that microscopic assessment continue to be the basis for standards. It is clear that as the resolution of a microscope system is improved, more fibrous particles can be seen. Without pertinent data on the relationship between fiber size and the health hazard, it is necessary to set some lower size limit on the basis of instrumental capability and repeatability. In the absence of health data it is difficult to justify the extra cost of electron as opposed to otical microscopy. A lower fiber length limit of 5 μm has been suggested as the minimum size that can be resolved by standard microscope optics with reasonable reproducibility as is discussed elsewhere in the report.

Phase contrast illumination is used to enhance the visibility of the fibers against the background of the translucent filter material and is also useful in identifying various types of fiber by their differences in refractive index.

Membrane Sampling with Phase-Contrast Assessment

Sample Size

Visual microscope assessment systems are prone to large subjective differences. To minimize these it is necessary to optimize all the variables in the system such as sample density and particle visibility. The variables should be set to give the most accurate and convenient assessment when sampling a dust cloud containing asbestos fibers at the threshold limit value. While accuracy will diminish for dust clouds of lower and higher concentrations, this is not usually of much importance in assessing the health hazard.

Selection of Counting Fields

The Guide recommends that counting fields within the wedge shaped section of the membrane filter prepared for microscopy should be selected at random along a radial line. This assumes that fibers are randomly collected at any given angular orientation from the center of the sampling filter, but may vary as a function of distance from the filter center. Although experimental data which describe the variation of particle collection per unit filter area as a function of specific location on the filter surface have not been published, geometric constraints imposed by the filter holder suggest that such variations are possible. One might expect relatively lower fiber concentration per unit filter area close to the filter edge compared with the filter center, due to the shroud and outlet configurations, (See Figure 1 of Guide) and the distribution of air flow through the filter.

Statistical reliability requires that minimum criteria be set for selection of the number and fiber concentration in the counting fields. The Asbestos Criteria Document[60] recommends that microscopy fields "... containing over 20 fibers not be counted because in addition to the fibers being counted, there are also present a number of grains, which interfere with the accuracy of the count." While this statement is generally correct, it should be used only as a guide for selecting the sampling time and not as a justification for discarding high counts. A better index of potential risk to the worker will be provided if counting fields are randomly selected. If any fields show more than 20 fibers, this information should be provided as part of the analyst's report with an indica-

tion of how seriously this condition may have interfered with the estimation of fiber concentration.

To minimize the counting error resulting from variations in fiber concentration across the membrane filter surface, and the statistical distribution of fibers within the microscopic counting field, crtieria must be defined regarding the minimum number of fields, and fibers to be counted. These criteria must be consistent with practical limitations, and with inherent errors due to other aspects of the sampling procedure. A minimum of 20 counting fields has been recommended[60,77] for the 37 mm diameter Millipore Filter Field Monitor. This sampling system has an effective filter sampling area of 855 mm² or a radius of 16.5 mm. Obtaining 20 random counting fields along a radial line would provide an average of approximately 800 μm between counting fields which are 50 to 70 μm in length. This probably provides a reasonable estimate of the total fiber concentration sampled. However, a statistical evaluation of the error introduced by varying the number of counting fields has not been reported in the literature.

Estimation of Errors

It is worthwhile to consider the various errors introduced into the final calculated fiber concentration by the several sampling and analytical procedures. Some of these can be estimated quantitatively, while others or major concern can only be discussed qualitatively. Fiber concentration(F), in fibers/cc air sampled, will normally be calculated as follows:

$$F = \frac{A_{SF} \cdot n_f}{A_{VF} \cdot n_{VF} \cdot t \cdot Q}$$

where:

A_{SF} = Effective filter area, cm²
A_{VF} = Area of viewing field, cm²
n_f = Net number of fibers counted
n_{VF} = Number of fields counted
t = Sampling time, minutes
Q = Sampling flow rate, cm³/min

A statistical estimate of the error introduced by counting a limited number of fibers can be developed. It is expected that the Poisson distribution defines the variation in particle (or fiber) concentration when looking at a selected viewing field on a sampling filter.[60] While this has been verified experimentally,[84] other investigators have noted that the distribution of dust particles counted in the microscope field is more disperse than indicated by Poisson statistics.[85,86] For a Poisson distribution, a minimum fiber count of 100 would have a standard deviation of ± 10% of the mean. For a more disperse distribution, the standard deviation would be greater, perhaps as much as ± 15%.

The sampling flow rate can usually be calibrated to be within ± 10%, based on a reasonably careful laboratory calibration using a one-liter burette, wet test or dry gas meter, or spirometer. Because of the importance of air density on flowmeter response, this calibration must simulate pressure drop, barometric pressure and temperature to be found under field conditions, so that air flow measurements will be sufficiently accurate. Since flow rates through many personal samplers pulsate, calibration of the rotameters of such samplers under steady flow conditions will introduce errors. If the sampling filter becomes heavily loaded, causing a significant increase in filter pressure drop, the laboratory calibration will be incorrect, and it may be necessary to recalibrate the sampling system after use to provide an estimate of the average flow rate during the sampling period. Under these loading conditions, particulate concentrations on the filter may make fiber counting extremely difficult. The error (± 1 standard deviation) in measuring the area of the viewing field (VF) or of the sampling filter (SF) is on the order of ± 4%.

Based on the estimated errors for the individual parameters and assuming no error in n_f or t, part of the potential error in the reported fiber concentration can be calculated using the law of propagation of error.[87]

This assumes that the error for each sampling parameter is independent of the other parameters. Using the previously defined errors, the error in fiber concentration is ± 15% for one standard deviation. To provide 95% confidence limits for sampling results, one should consider a potential error of ± 2 standard deviations or ± 30%.

This type of analysis is limited to those variables for which errors can be quantitatively approximated. Several other major sources of error exist which can only be discussed in qualitative or semi-quantitative terms. Variations in the fiber-cloud concentration as a function of time and sampling location are difficult to define. The best estimates of hazard to the worker are obtained when using personal samplers located in the immediate vicinity of the individual's breathing zone. General room samplers provide an estimate of average fiber concentration, and can be used to monitor overall performance of control procedures, but they are not adequate to estimate exposure to the individual workers. Experimental studies have quantitated variations in the concentration of particulates released from a point source as a function of distance from the release point.[88,89] These studies indicate that there are major differences in air concentration associated with small changes in location close to the source, and provide a basis for estimating the magnitude of errors inherent in estimating worker exposure based on general room samplers. Field data comparing air concentrations defined by personal samplers and general samplers for glove box work areas[90] show similar variations. While these work situations are not directly comparable to those involving asbestos operations, the results indicate the difficulties associated with relating general room air sampling data to individual exposures.

Variations in fiber concentration as a function of time during the work day will depend on the specific operations involved. To date quantitative estimates of this variation have not been developed, and the individual collecting air samples must carefully observe the work cycle in order to evaluate peak concentrations in addition to developing an estimate of the average workday exposure.

In all likelihood, the most significant errors associated with airborne asbestos concentration assays are those associated with microscopy and the variations between counters. The quality of microscopic optics, maintenance and alignment of the microscope, care in mounting the filter sample, concentration of fibers and particles, and attitude of the microscopist will significantly affect the fiber count reported. Recommended optical quality[77] can easily be exceeded in many recently made microscopes. If the sample contains a significant number of fine fibers, a high quality, well maintained microscope may make it possible to resolve up to twice as many fibers as compared to a microscope satisfying minimal specifications. Variations between different well trained counters (using the same microscope on the same samples) range from ± 20 to ± 40% in terms of a one standard deviation coefficient of variation.[91] When different facilities, employing different microscopes and counters are compared, variations of several fold can be expected.

Sample concentration is another variable affecting fiber count. If particle or fiber concentration is high, overlap and difficulty in distinguishing fibers through the particle background will occur. The significance of these effects has not been quantitated, although experience suggests that at concentrations below 5 fibers, or 100 particles per microscopic viewing field, there will be no significant interference with the count procedure. Preliminary data have also suggested that as fiber concentration increases, the effort expended by the microscopist in looking for the finer fibers by continually refocusing and scanning the viewing area decreases. Unfortunately those potential errors have not been quantitated.

This extended discussion of the potential errors associated with the fiber counting technique is designed to place the sampling results obtained in proper perspective. The technique is certainly superior to the previous impinger procedure which did not monitor the contaminant of concern, *i.e.*, the fiber concentration. However, the accuracy of the present technique should be improved in order to provide a more accurate estimate of worker exposure. To minimize the error associated with this estimate, sampling results should include the following information:

(1) Calculated fiber concentration (f/cc).
(2) Number of viewing fields with more than 20 fibers, and an estimate of effect on calculated fiber concentration.
(3) Estimated flow rate error.
(4) Total and background counts.
(5) Number of fields counted and area of viewing field.
(6) Any data (quantitative or qualitative) regarding presence of fibers less than 5 μm in length.
(7) Sampling time.
(8) Sampling flow rate.
(9) Active operations during sampling.
(10) Type(s) of fibers handled during sampling (*i.e.*, types of asbestos, and other fibrous materials present).
(11) Types of nonfibrous materials present during sampling (*i.e.*, quartz, talc, etc.) and semi-qualitative estimate of particulates (nonfibrous background) observed while counting fibers.
(12) Optics used.

Interpretation of Fiber Concentration

For a disease such as asbestosis, the development depends on long term exposure, and the object of sampling is to show that the long term exposure is not likely to exceed the threshold limit. If a large number of samples are taken, the actual exposure can be determined with reasonable accuracy, but from a few samples with a mean close to this threshold limit value, it is not possible to state whether the exposure is above or below the threshold limit.

There have been a number of studies[92-95] on sampling statistics for various hazards. One of these approaches is the National Coal Board Study (U.K.)[96] which shows that for an approved limit of 700 particles/cm^3 (ppcc) one sample indicating less than 370 ppcc or two successive samples less than 580 ppcc are sufficient to approve the working place. Approved implies that the limit of 700 ppcc will not be exceeded on more than one in ten shifts.

The principle behind this approach is applicable to all TLV sampling problems but the actual values used depend on the variability of the concentration and the measuring technique. In no case can one sample be used to justify the statement that there is no hazard from the contaminant in question unless the concentration found is very much less than the TLV and that the sample has covered the operation(s) likely to emit the given substance.

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