Asbestos in Public and Commercial Buildings:

A Literature Review and Synthesis of Current Knowledge

HEI·AR

Health Effects Institute - Asbestos Research

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The Health Effects Institute-Asbestos Research (HEI-AR) is an independent, non-profit organization formed recently to support research to determine the airborne exposure levels prevalent in buildings, to characterize peak exposures and their significance, and to evaluate the effectiveness of asbestos management and abatement strategies in a scientifically meaningful manner. HEI-AR is organized to gather and to generate reliable and objective information, and is supported jointly by the Environmental Protection Agency and a broad range of private parties that have an interest in asbestos. The congressional mandate under which HEI-AR now operates specifies that the HEI-AR's research "effort shall in no way be construed to limit or alter EPA's authority or obligation to proceed with rulemakings and to issue rules as necessary."

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1 In October 1990, Dr. Hoel became Acting Director of the NIEHS, and therefore resigned from the Panel.

From the Board of Directors

Asbestos is a family of complex minerals in the form of elongated, crystalline fibers at least some of which, when airborne and inhaled during the course of mining, manufacture, and installation, have often proved very harmful to human health. Public concern arose because many buildings have been equipped with asbestos-containing materials, which may release asbestos fibers upon being damaged or disturbed. Knowledge concerning the character and extent of the problem is seriously incomplete. There have been sharp controversies among highly qualified scientists. Accordingly, Congress charged the Health Effects Institute with undertaking a program of research

(i) to determine actual airborne asbestos fiber levels prevalent in buildings;

(ii) to characterize peak exposure levels and their significance; and

(iii) to evaluate the effectiveness of asbestos management and abatement strategies in a scientifically meaningful manner.

As a first step, Health Effects Institute-Asbestos Research appointed an Asbestos Literature Review Panel, an independent and balanced panel of experts representative of the best scientific and technical expertise, under the chairmanship of Dr. Arthur Upton of New York University, and charged the Panel with determining what is presently known, what is not known, and what is uncertain about the risks of exposure to asbestos in public buildings. HEI-AR is pleased now to release the Asbestos Literature Review Panel's Report.

The Report reveals the lack of reliable data on many points and the extraordinary difficulty in measuring asbestos exposure and determining its health effects, but it also draws some useful generalizations.

1. Asbestos containing material (ACM) within buildings in good repair is unlikely to expose office workers and other general building occupants to airborne asbestos fiber concentrations above the levels found in air outside such buildings. Although there are many variables and also many uncertainties, the added life time risk of cancer for this class of occupants in well-maintained buildings is estimated to be relatively low compared, for example, to the risks from two other pollutants, namely radon and environmental tobacco smoke.

Even though ACM in a small proportion of buildings may represent a higher potential asbestos hazard, there does not appear to be sufficient risk to the health of general occupants to justify arbitrarily removing intact ACM from well-maintained buildings.

2. Janitorial, custodial, maintenance, and renovation workers are in a different category. In the course of their work, they may experience peak exposure episodes because of disturbance or damage to ACM, which may release relatively high

concentrations of fibers. The frequency and degree of such exposure are uncertain because such episodes have seldom been monitored. Proper controls, including appropriate work practice and respiratory protective equipment, should therefore be used to minimize the exposure of such workers. Because custodial and maintenance workers may be transiently exposed to higher levels of asbestos, their added life time risk of cancer may be appreciably higher than the risk to general building occupants. The potential risk to exposed custodial and maintenance workers should therefore be the primary determinant of any remedial action.

3. Asbestos removal workers are at the highest risk of potential exposure. Good work practice and adequate respiratory protection are essential to avoid dangerously high exposure of workers involved with removal of asbestos material.

4. Determining the exposure risks in a given building and the forms of prevention or remediation warranted are site-specific tasks. Their performance customarily begins with a survey to discover any physical conditions that can lead to the disturbance of ACM, and includes a catalogue of location, accessibility, quantity, type, and condition of each ACM. Measures to control the release of asbestos fibers from the disturbance of ACM or dust should be employed routinely where needed during the operation and maintenance of buildings. Uncontrolled disturbance of ACM should be avoided. In well-maintained buildings with airborne levels of asbestos fibers similar to those found outside the buildings, removal or other abatement action, if done improperly, can cause increases of fiber levels that may persist for some time. On the other hand, in buildings where ACM has undergone continuing disturbance, appropriate abatement action may best reduce asbestos exposure of workers and other occupants.

The Report also emphasized the inadequacies of existing data, ranging from uncertainties about the representativeness of the buildings in which exposure has been measured to the need for much better understanding of the biomedical effects of different sizes and types of asbestos fibers. Three kinds of studies are recommended:

1. *Studies to define more accurately the characteristic sources and patterns of exposure, both long and short term, of various classes of building occupants, including the effects of remediation strategies.* The need for such studies is greatest in the case of custodial and maintenance workers, who may suffer peak exposures well above those of general office workers but with respect to whom few reliable data are presently available. HEI-AR has already determined to fund studies of those special situations and has issued appropriate requests for applications for the support of such research projects.

2. *Studies to improve methods for analyzing the numbers, sizes, and types of airborne asbestos fibers.* The ease and reliability of the analysis of samples can be increased, existing differences in interpretation narrowed, and the cost of analysis reduced if the counting of fibers can be automated or if resolution of optical methods of analysis can be improved. Development of a suitable technology for continuous monitoring of the levels of asbestos fibers in particular settings is also desirable.

3. *Research on the biomedical effects of asbestos with particular reference to the comparative potency of different types and sizes of fibers.* Mesothelioma and lung cancer are the diseases of greatest concern associated with indoor asbestos exposure. Recent data suggest that the risk varies with the length and width of the fiber and also with its mineralogical classification; however further research is needed to specify the differential responses in greater detail.

Archibald Cox, Chairman
William O. Baker
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Table of Contents

Statements:

Appendix 1: Review of Measurements in Buildings

Appendix 2: Nonmalignant Asbestos-Related Pleural Conditions

List of Tables and Figures

Chapter 1: Executive Summary

Tables:

Figures:

Chapter 4: Assessment of Asbestos Exposure

Tables:

Figures:

Tables:

Figures:

Chapter 6: Health Implications of Exposure to Asbestos

Tables:

Figures:

Chapter 7: Man-Made Mineral Fibers

Tables:

Chapter 8: Estimation of Risks to the Health of Building Occupants

Tables:

Figures:

Appendix 1: Review of Measurements in Buildings

Tables:

List of Abbreviations

µm	micrometer
A/C	asbestos cement
ACGIH	American Conference of Governmental Industrial Hygienists
ACM	asbestos-containing material
AHERA	Asbestos Hazard Emergency Response Act
AM	arithmetic mean
ASTM	American Society for Testing and Materials
ATS	American Thoracic Society
BOHS	British Occupational Health Society
CE	cellulose ester
CFE	colony forming efficiency
CPSC	U.S. Consumer Product Safety Commission
DEP	Department of Environmental Protection
EDXA	energy dispersive x-ray analysis
EM	electron microscopy
EPA	Environmental Protection Agency
f/mL	fibers per milliliter (>5 µm)
f-y/mL	fiber-year per milliliter
FACT	fibrous aerosol classifier/tabulator
FAM	fibrous aerosol monitor
FVC	forced vital capacity
GSA	General Services Administration, U.S. Government
HEPA	high-efficiency particulate air (filter)
HSC	U.K. Health and Safety Commission
HSE	U.K. Health and Safety Executive
IARC	International Agency for Research on Cancer
ILO	International Labor Organization
ISO	International Organization for Standards
LOD	limit of detection
MCE	mixed cellulose ester
MMMF	man-made mineral fibers
MMVF	man-made vitreous fibers
NAS	National Academy of Sciences
ND	not detected
NESHAP	National Emissions Standards for Hazardous Air Pollutants
ng/m^3	nanograms per cubic meter
NIBS	National Institute of Building Sciences
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institutes of Standards and Technology
NRC	National Research Council
NVLAP	National Voluntary Laboratory Accreditation Program
NYC	New York City
O&M	operations and maintenance program
ORC	Ontario Royal Commission

OSHA	Occupational Safety and Health Administration
PCM	phase-contrast microscopy
PCME	PCM equivalent
PCOM	phase contrast optical microscopy
PEL	permissible exposure limit
PLM	polarized light microscope
ppm	parts per million
QA	quality assurance
QC	quality control
s/L	structure(s) per liter (all sizes)
SAED	selected area electron diffraction
SCBA	self-contained breathing apparatus
SEM	scanning electron microscopy
SIO	small irregular opacities
SMR	standardized mortality ratio
SOP	standard operating procedure
TEM	transmission electron microscopy
TSI	thermal system insulation
TWA	time-weighted average
UK	United Kingdom
US	United States
VAT	vinyl asbestos tile
WHO	World Health Organization
XRD	X-ray diffraction analysis

1

Executive Summary

Asbestos in Public and Commercial Buildings: a Literature Review and Synthesis of Current Knowledge

EXECUTIVE SUMMARY

Introduction and Background

This report was prepared by the Literature Review Panel, a multidisciplinary group of experts under the auspices of the Health Effects Institute–Asbestos Research (HEI-AR). HEI-AR is an independent, nonprofit organization that was formed in 1990 to gather and generate reliable and objective information. HEI-AR is supported jointly by the Environmental Protection Agency and a broad range of private parties that have an interest in asbestos. The congressional mandate under which HEI-AR operates specifies that HEI-AR's research "effort shall in no way be construed to limit or alter [the Environmental Protection Agency's] authority or obligation to proceed with rulemakings and to issue rules as necessary."

This report represents the first step in the response to a congressional mandate (August 3, 1988) to the Health Effects Institute (HEI), and through HEI to HEI-AR, for research to:

- "determine actual airborne (asbestos fiber) levels prevalent in buildings . . .
- "characterize peak exposure episodes and their significance, and
- "evaluate the effectiveness of asbestos management and abatement strategies in a scientifically meaningful manner."

The purpose of the present report is to review and synthesize the state of knowledge as reflected in scientific articles, reports, and additional unpublished data on four issues considered pertinent to the congressional mandate:

- the concentrations of airborne asbestos fibers found in public and commercial buildings;
- the concentrations of such fibers to which building occupants, including custodial workers, maintenance workers, abatement workers, and other occupants, are exposed; the situations causing such exposures; and the potential for adverse health effects resulting therefrom;
- the possible impact that different asbestos remediation strategies may have on the exposure of building occupants to airborne asbestos and, in turn, on the risks of health effects in those exposed; and
- the significance of each form of asbestos in terms of its potential ill health effects and its implications for different remediation options in buildings.

Asbestos

The term asbestos is used for a group of fibrous, naturally occurring silicate minerals that exhibit properties rendering them useful in commerce. During the past century, asbestos has been mined, processed, and used in thousands of products. Because of the exceptionally effective insulating, fire-resistant, and reinforcing properties of asbestos-containing materials (ACM), they have been utilized widely as surface-applied finishes (for acoustical, decorative, and fire-retardant purposes), and as thermal insulation in the construction of buildings, as well as in equipment used in buildings. Although chrysotile is estimated to constitute approximately 95 percent of the asbestos used in the United States, building surveys have shown amosite and, to a lesser extent, crocidolite, to have been used with greater frequency in buildings than the total consumption figures would suggest. At least one common form of asbestos, chrysotile, is present naturally in the atmosphere.

Methodology

The Literature Review Panel has reviewed and synthesized the diverse body of scientific and technical information that is germane to asbestos in public and commercial buildings. The relevant literature is extensive and has been augmented recently by new scientific and technical findings, which have not all been published in the peer-reviewed literature. Where appropriate, rather than attempting to compile an exhaustive bibliography, the report cites previous reviews of the literature. The information provided in such reviews has been evaluated critically, and has been extended and amplified as necessary to bridge gaps and to take into account these more recent data.

In subject areas where the Panel found a paucity of published data or reviews, it has made a concerted effort to obtain and review both published and unpublished data. Published information was obtained through searches of computerized databases. Unpublished information was sought from all possible sources through announcements in scientific journals and in the HEI-AR newsletter. All of the submitted data were reviewed and are summarized in this report, as appropriate. Where data were acknowledged to be in support of litigation, the Panel has clearly indicated their nature. A supplement to include many details of the unpublished data that the report has summarized is planned for publication in the near future.

Asbestos in Public and Commercial Buildings

Under certain conditions, asbestos-containing material (ACM) can release asbestos fibers into the air of buildings, which can be inhaled by and reach the lungs of occupants. The concentrations of airborne asbestos fibers to which building occupants may, therefore, be exposed can be categorized as follows:

- low ambient concentrations, such as have recently been found in many well-maintained public buildings, and which are similar to ambient levels found outside these buildings;
- generally elevated ambient asbestos fiber concentrations, such as those produced in certain buildings by abrasion or damage to ACM, and by resuspension of released material through human activities; and
- locally elevated airborne fiber concentrations, resulting from damage, abnormal wear, or resuspension of dust; these often result from activities of certain occupational groups, including custodians and workers involved in building maintenance, or remodeling, or in asbestos removal.

For the purposes of this report, building occupants have been classified into the following five exposure categories:

C1 General occupants, who spend time in buildings but who are unlikely to disturb asbestos in place; for example, office workers.
C2 Custodians and/or janitors, who may cause increased levels of airborne asbestos fibers as a result of housekeeping activities.
C3 skilled maintenance workers, whose activities may disturb and displace ACM.
C4 Workers who are responsible for removal or remediation of ACM.
C5 Emergency personnel who may be required to enter buildings during or after extensive damage, for example, fire fighters.

Measurement of Asbestos Levels

For determination of airborne concentrations of asbestos fibers in buildings, air is customarily filtered through a membrane filter. After some manipulations of the filter, the fibers are counted using an optical phase contrast microscope (PCM) or an electron microscope (EM); both the scanning electron microscope (SEM) and the transmission electron microscope (TEM) can be used for this purpose. Because of limitations of the PCM and SEM related to visibility and identification of small or thin asbestos fibers and structures, the analytical TEM is used for asbestos analysis. Only the TEM is capable of providing accurate information on fiber numbers, dimensions, and morphology. When combined with selected area electron diffraction and energy dispersive x-ray analysis, the structural nature and the mineralogical identity of fibers can also be ascertained with the TEM; this is a great advantage for environmental asbestos analysis where other types of fibers and mineral fragments are often present. Fiber counts determined by PCM and TEM represent different indices of measurement because the resolving power of the PCM is much lower.

TEM-based air measurements have been reported in the literature in terms of mass, fiber number, or structure number; however, the results expressed in the different units cannot easily be compared. In this report, the conventional measure of exposure (numbers of fibers longer than 5 µm) for both optical and TEM measurements of fiber concentrations is given in units of fibers per milliliter (f/mL). Measurements of concentrations of asbestos structures (fibers, bundles, clusters, as well as matrices) of all sizes per liter (s/L) and calculation of asbestos mass in nanogram per cubic meter (ng/m^3) are also included where appropriate. Unless otherwise stated, measurements described in this report as f/mL refer to the counts of fibers (longer than 5 µm) and fiber-containing structures, as determined by TEM, and as reported by authors of the individual studies.

Two different protocols are used to prepare filters for TEM analysis. In the direct method, the specimen preparation procedures attempt to retain all particles in their unchanged physical state and in the same relative locations on the TEM specimen as they occupied on the original sample collection filter; thus these procedures endeavor to leave unaltered the size distribution and the state of aggregation of asbestos fibers. In the indirect method, the particulate matter is transferred from the original sample collection filter into a liquid suspension, of which an aliquot is redeposited onto a secondary filter. The secondary filter is then used to prepare a specimen for TEM examination as in the direct protocol. A higher fiber count (particularly for short fibers), and a different fiber size distribution, is observed using the indirect protocol as compared to the direct protocol. Because of similarity of protocols, fiber counts obtained with the direct preparation methods can be more easily compared with those obtained with the optical PCM.

Measurements of the concentration of airborne asbestos fibers in buildings cannot be assumed to be adequately representative of the long-term average exposures of general building occupants (C1), unless they are made during normal periods of occupation of the buildings, normal operation of air handling and mechanical equipment, and with normal levels of maintenance (C3) and custodial (C2) activities. Maintenance and custodial work may result in localized increases in airborne fiber concentrations that can influence the exposure of building occupants.

Exposure to Asbestos in Buildings

A large number of buildings in the United States and other countries have been examined for airborne asbestos fibers within the past 20 years, and have yielded many thousands of air measurements (most unpublished). However, few building environments have been individually characterized in sufficient detail or sampled with sufficient analytical sensitivity to describe adequately the exposures of general building (C1) occupants. Extensive efforts have been made to gather and interpret the available exposure data, but further research is required to establish the long-term means and distributions of asbestos fiber exposures in individual buildings. Specific details are especially lacking for episodic and point-source releases of fibers into the air of buildings from maintenance and engineering activities, from repair and renovation operations, and from normal custodial functions.

Outdoor Levels

Such data as are now available on the airborne concentrations of asbestos fibers of the dimensions most relevant to human health (that is, fibers longer than 5 µm) generally show average concentrations on the order of 0.00001 f/mL for outdoor rural air (except near asbestos-containing rock outcroppings) and average concentrations up to about 10-

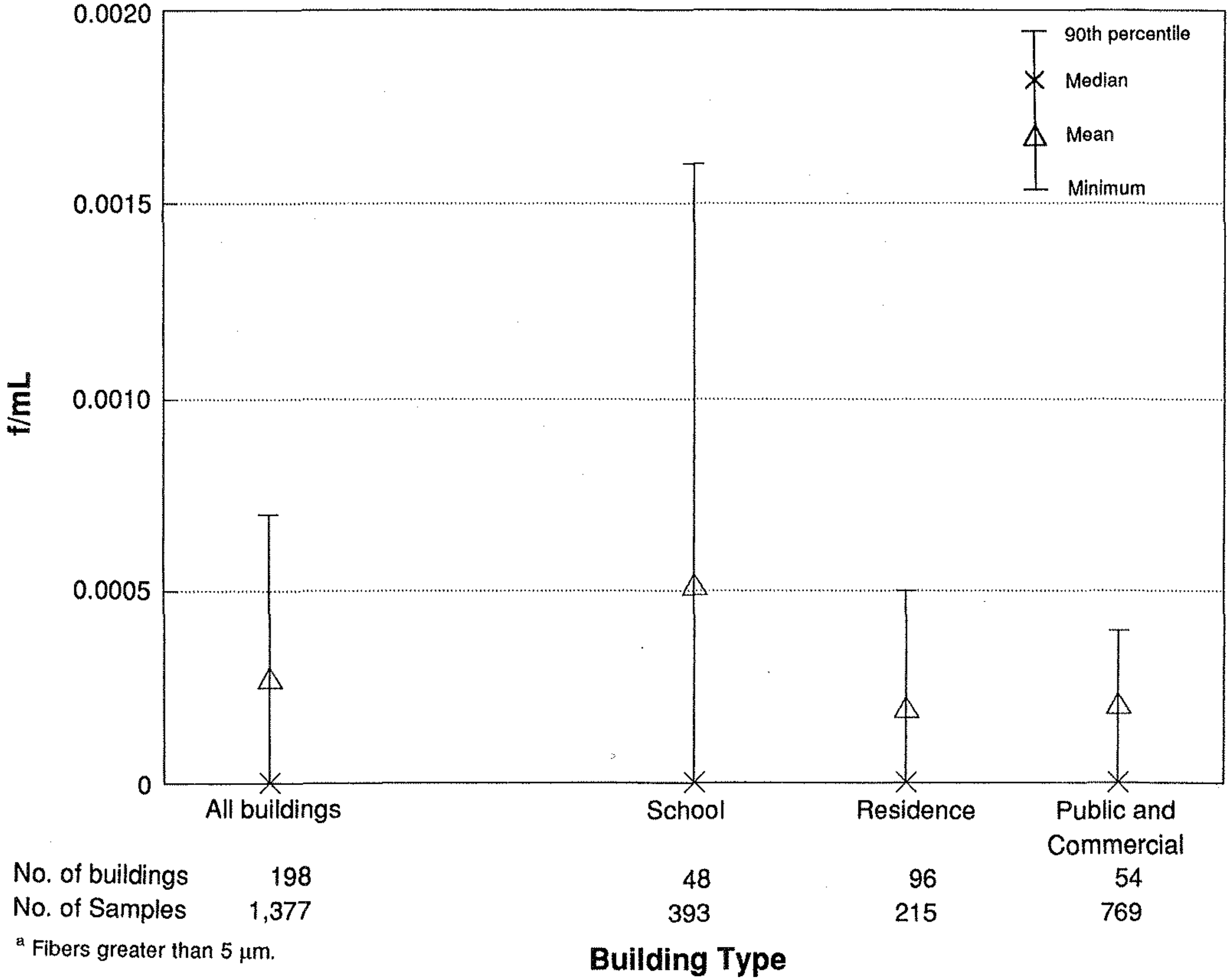
fold higher in the outdoor air of urban environments. However, outdoor urban airborne concentrations above 0.0001 f/mL have been reported in certain circumstances as a result of local sources; for example, downwind from, or close to, areas of frequent vehicle braking or activities involving the demolition or spray application of asbestos products. Outdoor concentrations measured by the indirect method for TEM specimen preparation are higher than those obtained by the direct method.

Ambient Levels in Buildings

In the course of this review, the data on ambient indoor levels of asbestos from a number of sources have been examined and analyzed, and the data from direct TEM measurements have been averaged for each of a number of individual buildings. The following data are based on 1,377 air samples obtained in 198 different ACM-containing buildings not involved in litigation (the data from buildings sampled for litigation purposes have been summarized separately in this report). The building means of the studies on the 198 buildings range from 0.00004 to 0.00243 f/mL. Grouped by building category, the mean concentrations are 0.00051, 0.00019, and 0.00020 f/mL in schools (including a few colleges), residences, and public and commercial buildings, respectively, with 90th percentiles of 0.0016, 0.0005, and 0.0004, respectively (Figure 1-1). For all data pooled, the mean exposure value is 0.00027 f/mL, with 90th and 95th percentiles of 0.0007 and 0.0014, respectively. Some of the higher values in the sampled buildings are derived from situations representative of custodial and maintenance activities. The averages reported here are sensitive to such high values; thus, if the sample with the highest value (which was collected in an area where cable was being installed) was excluded from the calculations, the average value for the concentration of fibers longer than 5 μm in public and commercial buildings would be reduced from 0.00020 to 0.00008 f/mL. Similarly, with respect to schools, if the sample with the highest value (which was collected in a mechanical room/closet) is excluded, the average is reduced from 0.00051 to 0.00038 f/mL. From the data collected for litigation purposes, arithmetic average values for 171 schools (including colleges), 10 residences, and 50 public and commercial buildings were 0.00011 f/mL, below the limit of detection, and 0.00006 f/mL, respectively. Little information was found on ambient indoor fiber counts using the indirect method for TEM sample preparation. In one study, fiber counts by the two methods of sample preparation were compared; for samples prepared using the indirect method, the fiber counts were substantially higher than the fiber counts with the direct method.

The fiber concentrations (greater than 5 μm) from direct analysis are lower than the measurements inferred from the earlier mass studies reviewed in a 1984 report from the National Research Council which concluded, after converting mass measurements to fiber concentrations, that the median exposures corresponded to 0.00007 f/mL outdoors, 0.00054 f/mL inside rooms without ACM, and 0.0006 f/mL in rooms with ACM (no estimates of average exposures were reported). The limited mass data since 1984 have median values that are lower than previously reported. The differences between the NRC estimates and those summarized here are due, in part, to the fact that the earlier studies utilized a mass-to-fiber conversion factor rather than direct counts of fibers longer than 5 μm, and were carried out in buildings which more often contained highly

Figure 1-1. Distribution of Building Average Airborne Concentrations for Nonlitigation Data by Building Type[a]



[a] Fibers greater than 5 µm.

deteriorated, friable ACM surface treatments. The extent to which occupants of some unsampled buildings are currently exposed to conditions and levels similar to those reported in the earlier mass-based studies is not known.

The extent to which the data from the sampled buildings reviewed in this report are representative of the conditions generally found in U.S. public and commercial buildings is not known. Sources of uncertainty include: types of buildings sampled, building selection strategy, sampling location within buildings, types of ACM present, extent of ACM damage, level of building activity, whether an operations and maintenance (O&M) program was established, and the extent and level of maintenance activity undertaken. In addition, other sources of uncertainty in the data relate to analytical preparation, sensitivity, and measurement errors.

Exposures of C2 and C3 Occupants

Janitorial, custodial, maintenance, and renovation personnel may disturb or damage ACM in the course of their work and thereby generate "peak" (brief, relatively high) exposure episodes. Such episodes have not often been reported and are poorly characterized as yet. With proper controls, the exposures to maintenance personnel can be kept below 0.1 f/mL, the permissible exposure limit proposed by the U.S. Occupational Safety and Health Administration; but without adequate controls, exposures can exceed 10 f/mL during some removal and repair work. Such exposures can, in principle, be reduced by an O&M program that includes both training of personnel and implementation of standard control procedures for activities that may disturb ACMs, and can also be reduced by one or several of the abatement strategies. Unless the location of ACM in a building is known, there is little opportunity for appropriate planning and implementation of procedures to avoid such "peak" exposures for workers.

Exposures of C4 and C5 Occupants

For workers involved with asbestos removal (C4 occupants), available data indicate a potential for exposure to airborne concentrations as high as 10 to 100 f/mL during dry removal with air exhaust and as high as 1 f/mL during wet removal with air exhaust. Emergency (C5) workers may also encounter situations in damaged buildings in which the airborne concentrations of asbestos fibers are high, although no data on the exposure of such workers were found. Good work practice and adequate respiratory protection are, therefore, essential to avoid exposure of such workers to high levels of asbestos.

Control of Asbestos Exposure

Although limited, the existing data suffice to support the following generalizations:

- ACM within buildings in good repair and undisturbed is unlikely to give rise to airborne asbestos fiber concentrations above the levels found outside those buildings;

- accessible ACM has the potential to be damaged;
- during processes that damage ACM, fibers can be released into the air, and the resulting elevation of fiber levels may persist subsequently for varying lengths of time;
- maintenance activities can result in localized increases in airborne asbestos levels in the vicinity of ACM, exposing the workers who are directly involved and also possibly nearby building occupants; O&M work procedures can reduce such exposures;
- removal of ACM from buildings, if improperly done, can cause generalized increases in airborne fiber levels, which may persist for varying lengths of time.

Determination of the potential for asbestos exposure in a given building situation is primarily concerned with the discovery of the physical situations that can lead directly or indirectly to the disturbance of ACM; such disturbances may be caused by untrained and unprotected individuals. This type of determination customarily involves a survey to catalogue the location, accessibility, quantity, condition, and type of each ACM in the building. The existing level of exposure in a building can be determined by air monitoring.

Determining which particular preventive measures and forms of remediation are warranted in a given situation is a site-specific and complex task. The general questions to be considered in such a determination include:

- whether the selected remediation option will be the most effective among the available options in reducing current or potential future exposures to general (C1), custodial (C2), or maintenance (C3) occupants;
- whether the process of remediation will cause workers or other occupants to experience exposures that exceed the exposures being prevented;
- whether, if ACM is left in place, the control measures will be effective and whether reasonably anticipated disturbances (whether generated by repair, renovation, or natural causes) will later create even higher levels of exposures; and
- whether, if removal of ACM takes place, any replacement materials are safer than the materials being removed, and whether the disposal of removed asbestos materials does not simply move the potential danger from one location to another.

The data on exposures to custodial (C2) or maintenance (C3) workers during specific activities can help to determine the need for, and type of, remediation appropriate to prevent exposures; such data can also provide information on the potential for increased exposure of general (C1) occupants as the result of custodial and maintenance activities.

Remediation strategies vary in their potential for disturbing asbestos; the control of such disturbance, with the aim of preventing exposures to building occupants, is less difficult with O&M programs than with enclosure or encapsulation and is most difficult with removal. The effects of abatement work on the long-term asbestos exposures of building occupants, custodians, or maintenance workers depend on project design and execution as well as building circumstances. In well-maintained buildings with long-term airborne levels of asbestos fibers similar to ambient background levels, removal or other abatement action, if done improperly, can cause increases of fiber levels which may persist for varying periods of time. On the other hand, in buildings where ACM has undergone continuing disturbance, appropriate abatement action can lead to a reduction in the asbestos exposure of workers and other occupants.

Potential Health Effects

At the relatively low concentrations of airborne asbestos fibers encountered by general (C1) building occupants, lung cancer and mesothelioma are the diseases of concern. The capacity of asbestos fibers to cause these diseases depends on a number of the physical and chemical characteristics of such fibers:

- *Fiber length:* While the differential responses to fibers of different lengths cannot yet be specified precisely, the data suggest that the risks of lung cancer and mesothelioma increase with increasing fiber length. In particular, a substantial body of experimental evidence suggests that the rates of induction of tumors and fibrosis in animals, as well as transformation of cells in vitro, increase sharply as fiber length increases above 5 µm. Thus, the conventional definition of an asbestos fiber used for industrial hygiene purposes (fibers longer than 5 µm with an aspect ratio of 3 and greater) continues to be a practical index for risk assessment; the use of this index also facilitates comparison of present observations with those in the earlier literature. Whether there is any threshold length below which there is no carcinogenic effect in humans is not known. Animal data suggest, however, that very short fibers have much less carcinogenic activity than longer fibers and may even be relatively inactive.

- *Fiber diameter:* There is clear experimental evidence that mesotheliomas occur more frequently following exposure to thin fibers than to thick fibers. Observations in humans are consistent with this finding; however, accurate human exposure data expressed in terms of fiber number and dimensions are not available, and in animal studies the dose has been measured in terms of dust mass, so that preparations containing thin fibers have included a larger number of fibers per unit mass.

- *Fiber type:* When handled in similar ways (for example, in mining or in gas mask manufacture), crocidolite has caused a greater risk of pleural mesothelioma than chrysotile or amosite; however, in the absence of adequate fiber measurements in many of these occupational cohorts, it is not clear whether there are any differences in dose-specific risk. There is also suggestive evidence that most peritoneal mesotheliomas are caused by amosite or crocidolite. For lung cancer, no consistent differences between fiber types in dose-specific risk have been established; however, there are large, unexplained differences in dose-specific risk among different occupational groups exposed to chrysotile. In particular, the risk in chrysotile miners and millers is much lower than that in chrysotile textile workers.

- *Other physico-chemical factors:* Other physico-chemical factors, such as differences in durability in lung tissue, in surface chemistry, or in surface charge, may also contribute to fiber toxicity, although their precise role remains to be established.

Risks to Building Occupants

The health effects resulting from inhalation of airborne asbestos fibers by occupants in today's buildings, and the benefits to be obtained from appropriate ACM remediation strategies, cannot be estimated with confidence from the existing data, owing to uncertainties about the relevant exposure-response relations and difficulties in estimating levels of past and current exposures. Although a threshold cannot be excluded, if a linear (no threshold) relationship between exposure and risk is assumed to exist, then the asbestos-related cancer risk to general (C1) building occupants can in principle be computed from the overall mean of average exposures in buildings. There are, however, a number of serious limitations underlying such exposure estimates:

- Historical occupational exposure data, and hence epidemiological risk estimates, are based on estimates of fiber exposure that were derived from total particle counts and, in a few cases, on the concentrations of fibers longer than 5 µm counted by *optical* microscopy. This dictated the Panel's decision to base its conclusions only on studies reporting measurements of conventional (longer than 5 µm) fibers, on the premise that environmental measurements expressed in these terms are the only ones which can be related to the historical industrial measurements on which the dose-response relationships, and hence the risk assessments, are based. At the present time, measurements of fibers 5 µm and longer, *by transmission electron microscopy* using the direct method, constitute by far the most extensive data available to the Panel for assessing exposure and risk.

- It is not known how representative the data are of the conditions generally found in U.S. public and commercial buildings because of several variables. These include types of buildings sampled, building selection strategy, sampling location within buildings, types of ACM present, extent of ACM damage, level of building activity, the level of building maintenance, and whether an O&M program was in force.

- In addition, interpretation of the data is complicated by uncertainties concerning certain aspects of the measurement techniques employed, such as the method of sample preparation, sensitivity of the analysis, and measurement errors; these uncertainties also apply to data obtained in work environments.

Within the constraints of the above reservations, estimates of risk based on linear extrapolation from effects resulting from heavy occupational exposure to asbestos in the past can, in principle, be calculated for building occupants at the different levels of exposure measured today. For asbestos workers who were exposed for 20 years at a level of 10 f/mL in the past, the lifetime increase in cancer risk is estimated on the basis of epidemiological studies to be about 200,000 per million, that is, about 2 in 10. By linear extrapolation, therefore, it may be estimated that if workers were exposed to a level 100 times lower, that is, 0.1 f/mL (which is the permissible exposure limit proposed by OSHA), the risk would be 2 in 1,000 or 2,000 per million (Table 1-1). Because the average level in most asbestos-containing public buildings which have been surveyed herein is lower by a further factor of about 500 (0.00020 f/mL, as noted above), the corresponding predicted lifetime risk for 20 years of exposure during working hours would be about 4 per million. If the highest sample was excluded from calculation of the average concentration, the risk estimate would be approximately 2 per million. Average levels in schools that have been surveyed herein are higher than those in other public buildings, approximating 0.0005 f/mL, for which the corresponding predicted lifetime risk to a child exposed during school hours would be about 6 per million. These risk estimates, although highly uncertain for the reasons indicated, can be used to compare the public health hazard posed by different levels of indoor asbestos with the risks of other environmental agents for which control strategies may also be under consideration, as discussed in Chapter 8 of this report for the examples of indoor radon and environmental tobacco smoke.

Table 1-1. Estimated Lifetime Cancer Risks for Different Scenarios of Exposure to Airborne Asbestos Fibers[a]

Conditions	Premature Cancer Deaths (Lifetime Risks) per Million Exposed Persons
Lifetime, continuous outdoor exposure	
• 0.00001 f/mL from birth (rural)	4
• 0.0001 f/mL from birth (high urban)	40
Exposure in a school containing ACM, from age 5 to 18 years (180 days/year, 5 hours/day)	
• 0.0005 f/mL (average)[b]	6
• 0.005 f/mL (high)[b]	60
Exposure in a public building containing ACM age 25 to 45 years (240 days/year, 8 hours/day)	
• 0.0002 f/mL (average)[b]	4
• 0.002 f/mL (high)[b]	40
Occupational exposure from age 25 to 45	
• 0.1 f/mL (current occupational levels)[c]	2,000
• 10 f/mL (historical industrial exposures)	200,000

[a] This table represents the combined risk (average for males and females) estimated for lung cancer and mesothelioma for building occupants exposed to airborne asbestos fibers under the circumstances specified. These estimates should be interpreted with caution because of the reservations concerning the reliability of the estimates of average levels and of the risk assessment models summarized in Chapter 8.

[b] The "average" levels for the sampled schools and buildings represent the means of building averages for the buildings reviewed herein (Figure 1.1). The "high" levels for schools and public buildings, shown as 10 times the average, are approximately equal to the average airborne levels of asbestos recorded in approximately 5 percent of schools and buildings with asbestos-containing materials (ACM) (see Chapters 4 and 8). If the single highest sample value were excluded from calculation of the average indoor asbestos concentration in public and commercial buildings, the average value is reduced from 0.00021 to 0.00008 f/mL, and the lifetime risk is approximately halved.

[c] The concentration shown (0.1 f/mL) represents the permissible exposure limit (PEL) proposed by the U.S. Occupational Safety and Health Administration. Actual worker exposure, expected to be lower, will depend on a variety of factors including work practices, and use and efficiency of respiratory protective equipment.

The above estimates apply to general building occupants (C1), and not to custodial (C2) and maintenance (C3) workers whose activities may result in episodic releases of asbestos fibers and dust. Such releases may contribute to the total exposure of all building occupants, and hence increase their long-term average exposure levels; however, there is no evidence that the occurrence of peaks in the exposure pattern has any effect on the overall risks of disease for general building occupants except insofar as they contribute to the long-term average exposures. As custodial and maintenance workers are more likely to be transiently exposed to higher levels, their added lifetime risks of cancer may be appreciably higher than those of general (C1) building occupants. However, representative data on exposures of C2 and C3 workers are not available; therefore, the Panel has not estimated the risks to such workers. Instead, the level of risk for workers that would be projected for the proposed OSHA permissible exposure limit is presented as a point of reference (Table 1-1) from which extrapolations can be made.

Although public concern over asbestos in buildings has focused primarily on potential risks to general building (C1) occupants, there does not appear to be sufficient justification on grounds of risk to the health of general occupants for arbitrarily removing intact ACM from well-maintained buildings. The potential risk to custodial and maintenance workers through exposure to airborne asbestos when ACM is disturbed is greater and, therefore, would appear to be the primary consideration in determining whether, and what type of, remedial action would be appropriate. The condition of the ACM and the circumstances of building use may also be considered in determining the appropriate control action. Measures to control the release of asbestos fibers from the disturbance of ACM, dust, or debris should be employed routinely where needed during the operation and maintenance of buildings. Uncontrolled disturbance of ACM should be avoided whenever possible.

Man-Made Mineral Fibers

Man-made mineral fibers (MMMF) and other nonasbestos fibers are now often used as asbestos substitutes in building materials. Levels of exposure to man-made glass and wool fibers have been generally found to be low in public buildings. Although some MMMF types occur in fiber sizes that can be inhaled readily into the lung, most are nonrespirable. Ceramic fibers that are thin, respirable and durable may be of concern.

Research Needs

Because of limitations in the available data on the exposure of building occupants to airborne asbestos fibers, the assessment of such exposures calls for further research. The research should include: (a) studies to improve, compare and consolidate the methodology for analyzing the numbers, sizes, and types of airborne asbestos fibers; (b) studies to define more adequately the characteristic sources and patterns of exposure—long-term as well as short-term—of building occupants in each of the various categories listed above; and (c) studies to determine how such patterns of exposure are affected by remediation strategies. HEI-AR has initiated a program of research aimed at addressing many of these issues in public and commercial buildings.

To reduce the uncertainty in estimates of the health impacts of asbestos on building occupants, there is need for further research on the biomedical effects of asbestos, with particular reference to the comparative potency of fibers of different sizes and types inhaled at low-to-intermediate levels of exposure; information yielded by lung dust measurements may be useful in this regard. The estimates of dose-response relations in this document and other published estimates are dominated by historical exposures, which were high and inadequately measured by modern standards. Such research should investigate the relevant dose-response relationships and mechanisms of asbestos-related disease, exploiting for this purpose experimental as well as epidemiological approaches. Systematic reanalysis and pooling of updated exposure and survival data on all available cohorts whose exposures were well-characterized and involved comparatively lower fiber concentrations—for instance, less than 5 f/mL—would be particularly useful.

In view of the growing numbers of different types of man-made fibers that are entering commerce to substitute for asbestos, as a result of the phase-out of asbestos itself, detailed material characterization and biological testing of such fibers should precede their widespread dissemination into the human environment.

2

Introduction

2.1 Congressional Mandate to Health Effects Institute–Asbestos Research

This report on asbestos in public and commercial buildings was prepared by the Literature Review Panel, an expert group formed by the Health Effects Institute–Asbestos Research (HEI-AR) in response to a mandate from the U.S. Congress. The mandate, dated August 3, 1988, called on HEI-AR to perform the following tasks:

1. "to determine actual airborne (asbestos) levels prevalent in buildings,"

2. "to characterize peak exposure episodes and their significance" (for potential adverse health effects on the building occupants who are exposed), and

3. "to evaluate the effectiveness of asbestos management and abatement strategies in a scientifically meaningful manner."

The above mandate was prompted by a growing public concern about the risks to human health from exposure to asbestos in buildings. This concern, which had given rise to the Asbestos Hazard Emergency Response Act (AHERA), of 1987, has subsequently intensified, in part because of uncertainty as to the particular risk abatement strategies that would be appropriate to use in given situations in schools and in public and commercial buildings (EPA 1987).

As one of the first steps in responding to its mandate, HEI-AR undertook to evaluate the status of knowledge about the issues in question through a critical review of the pertinent literature. For this purpose, the Board of Directors of HEI-AR formed, in April 1990, the Literature Review Panel, members of which were drawn from a wide range of disciplines in order to enlist the breadth of expertise needed for the task.

2.2 Charge to Panel

The charge given to the Panel was to provide, within a period of less than one year, a critical synthesis of the available information bearing on the following issues:

1. What is the level and nature of the exposure to asbestos that is experienced by building occupants?

2. What adverse health effects, if any, may be expected to result from such exposure?

3. What effects may different remediation strategies be expected to have on the exposure of building occupants to asbestos and, in turn, on the risks of adverse health effects in such persons?

4. What are the major gaps in knowledge where further research is needed?

2.3 Subject Coverage

The report that follows focuses on the above questions. Although it is necessarily broad in scope, the short time that was available for its preparation precluded an exhaustive review of all the pertinent publications in the extensive literature on asbestos. To the extent that gaps in the published literature were identified, the Panel sought to utilize other sources of information insofar as possible (this was particularly the case in the exposure and remediation areas). It will be apparent to the reader, however, that in many instances, despite the voluminous literature, the available data were not complete or conclusive enough to provide firm answers to the questions at issue.

2.4 References

Environmental Protection Agency, U.S. 1987. Asbestos-Containing Materials in Schools. Final rule and notice. Federal Register, 40 CFR 763, Vol. 42, No. 210, October 30, 1987, pp. 41826–41905.

U.S. House of Representatives. 1988. Making Appropriations for the Department of Housing and Urban Development, and for Sundry Independent Agencies, Boards, Commissions, Corporations, and Offices for the Fiscal Year Ending September 30, 1989. Report No. 100–701.

3

Format of Report and Mode of Operation of the Literature Review Panel

3.1 Format of Report

In keeping with the Panel's charge, the report begins by reviewing what is known about the levels of asbestos that may be encountered by occupants of buildings. Because asbestos exists in different forms, not all of which may be equally hazardous to human health, the report distinguishes among the various forms insofar as possible. Also, since the probability and level of exposure to asbestos are likely to be higher for building maintenance workers and custodians than for other building occupants, the report distinguishes among different categories of occupants in assessing the relevant exposure and associated risks. For the purposes of this report, building occupants have been classified into the following five exposure categories:

C1 General occupants whose working week is spent in buildings but who are unlikely to disturb asbestos in place, such as office workers;

C2 Custodians or janitors, who may cause increased levels of airborne asbestos as a result of their housekeeping duties;

C3 Skilled maintenance workers whose activities may disturb or displace asbestos-containing materials (ACM);

C4 Workers responsible for remediation of damaged ACM;

C5 Fire fighters and other emergency personnel who may be required to enter buildings during or after extensive damage.

Topics considered in relation to the exposure of building occupants, covered in this report, include the major uses of asbestos in buildings, the mechanisms through which asbestos may be released and dispersed in buildings, the resulting temporal and spatial variations in asbestos concentrations in buildings, the methods for monitoring and measuring such concentrations, the adequacy of existing data for characterizing asbestos exposure to building occupants, the extent to which comparable data for man-made mineral fibers are available, and the gaps in pertinent knowledge that call for further research.

The report then reviews the methodology for reducing or eliminating exposure to asbestos in buildings, along with relevant remediation issues. Considered in this context are the various methods that are available for remediation, the indications for remediation, the present effectiveness of each method in theory and in practice, the prospects for improvements in methodology, the extent to which the various methods are compatible with regulatory requirements, and the gaps in existing knowledge that call for further research.

The ensuing section of the report reviews the adverse health effects of exposure to asbestos, including diseases recognized to result from high-level exposure; the relationship between the numbers and types of asbestos fibers taken into the body and the resulting risk of disease; and the factors that influence the exposure-risk relationship, such as duration of exposure, age at first exposure, smoking habits, and exposure to other dusts.

The next section of the report is a brief discussion of man-made mineral fibers that are being used to replace asbestos. The technical appendices that follow this section include detailed discussion of some of the issues that are summarized in the main body of the report.

In the final section of the report, estimates are offered for the risks to human health that exposure to asbestos in buildings may pose, based on knowledge of relevant exposure-risk relationships and the underlying mechanisms of disease. The uncertainties in such risk assessments are identified, along with the research needed to resolve the uncertainties.

3.2 Mode of Operation of the Literature Review Panel

The Panel met on the following dates: April 26–27, 1990; June 13–14, 1990; August 13–16, 1990; September 17–18, 1990; November 12–13, 1990; January 31–February 2, 1991; March 11–12, 1991; and April 8–9, 1991. Part of the meeting on April 27, 1990, was open to the public and was attended by representatives of government, industry, labor, and public interest groups. The Health Effects Institute–Asbestos Research (HEI-AR) had called this public forum to announce the names of members of the Literature Review Panel and to discuss the objectives, methodology, and projected schedule of the Panel's work, to address questions and concerns to the Panel, and to make the Panel aware of any unpublished information relevant to its mission.

The Literature Review Panel's assignment has been to review and synthesize the very diverse body of scientific and technical information that is germane to asbestos in public and commercial buildings. The relevant data are extensive and have been augmented recently by important scientific and technical findings, some of which are published in the peer-reviewed literature, and some of which are not. The data are so varied that no single individual can be expected to render a sound judgment on all of its aspects. Accordingly, for some of its tasks, members of the Panel worked in smaller groups so that individuals with relevant expertise could concentrate their efforts on areas they know best.

The literature review process ensured that each topic was reviewed in detail. Because no one Panel member was knowledgeable in all subject areas to be covered, initial drafts were formulated by those members of the Panel with recognized expertise in a particular subject area. This process continued by providing opportunities for substantive discussions and exchange with other Panel members experienced in related areas. The contents of this report are therefore the product of individual contributions modified by continuous input by other Panel members.

In some subject areas, the available information could not be interpreted unambiguously; in such cases, the Panel has strived to present and, to the extent feasible, weigh all strengths and weaknesses, as well as alternative interpretations, of the available evidence. In a number of instances, Panel members differed in their interpretations of the available data and were unable to reach consensus. Where appropriate, the Panel has identified such areas as deserving of further research.

The Panel devoted considerable time as a group to the development of the Executive Summary. This section of the report was reviewed extensively by the Panel as a whole, and the Panel fully supports and endorses its conclusions, except with reference to the points raised in the statements by Drs. Nicholson and Wagner, who participated fully in discussions of the Panel, and in the preparation of the report.

Given the enormity of the task and the brief period of time available, the Panel has cited previous reviews of the literature, particularly on several aspects of the biological effects, and particularly those conducted under the auspices of national governmental agencies (such as the U.S. Environmental Protection Agency) or international organizations (such as the International Agency for Research on Cancer), rather than attempting to compile an exhaustive bibliography. The information provided in such reviews was critically evaluated by the Panel, and was extended and amplified as necessary to bridge gaps and to take into account newer data. For readers interested in further details, references to detailed reviews and guides to other relevant publications are provided.

The Panel found a paucity of published data or reviews in many other areas, for example, trends in mesothelioma incidence, asbestos ambient levels and exposure concentrations, and effectiveness of various remediation methods. In such areas, the Panel made a concerted effort to obtain and review both published and unpublished data. The Panel obtained published information through searches of computerized databases.

The Panel was aware that air data were being collected and analyzed in large numbers as a part of abatement or remediation activities or operations and maintenance programs, in support of litigation, and for other reasons. With a view towards augmenting the information from published sources, the Panel issued a request to the public, through the following journals, seeking information on indoor levels of asbestos: *Science, Applied Occupational and Environmental Hygiene*, and *American Industrial Hygiene Association Journal.* A number of organizations submitted data in response to HEI-AR's request.

A few organizations provided data to HEI-AR that they acknowledged to have been collected in support of litigation. Such data had been collected by consulting organizations under financial support from one of the parties to litigation, generally the defendants. There was disagreement among members of the Panel as to how the litigation data should be treated. Some members felt that because the consulting organizations are independent, their work would not have been biased by the sponsorship of the data collection effort, or by the use for which data were collected; others could not rule out the possibility of bias.

The Panel has, therefore, segregated and clearly indicated all the data that to its knowledge, were collected in support of litigation. Although the Panel found that the litigation data and data from all other sources were comparable and generally consistent, most of the discussion in this report, and the conclusions and summaries, are based on nonlitigation data; all exceptions to this general approach are clearly indicated. HEI-AR also plans to publish a supplement to this report in which these data will be described in greater detail.

In most cases, for both unpublished, nonlitigation data and litigation data, summary information was provided to the Panel, but in a few cases unpublished data provided to HEI-AR were analyzed by HEI-AR staff under the supervision of the Panel. All such data were reviewed by the Panel and are included in this report, as appropriate.

The inclusion of data from any organizations in this report does not constitute an endorsement, by the Panel or HEI-AR, of those organizations or of the data they have collected and made available to HEI-AR.

4

Assessment of Asbestos Exposure

4.1 Asbestos: Introduction

4.1.1 Definitions

Asbestos is a term used to describe several silicate minerals that display special qualities and properties. The mineralogy and chemistry of these fibers are summarized in Table 4-1. It is their extremely fibrous nature and unique physical-chemical properties that separate them from other silicates and impart them with commercial value. They are good thermal, acoustic, and electrical insulators (those that are low in iron), and the different varieties show good stability in both alkaline and acid environments. In particular, their high tensile strength and flexibility make them useful as reinforcing agents in building products. The availability and exceptional performance of these fibers have led to their widespread use.

Table 4-1. Commercial Asbestos Fiber Types That May be Found in Asbestos-Containing Materials in Buildings: Mineralogy and Chemistry

Mineral Name	Commercial Mineral Name for Asbestos[a]	Mineral Group	Chemical Formula	Occurrence in Buildings[b]
Chrysotile	Chrysotile	Serpentine	$(Mg)_6(OH)_8Si_4O_{10}$ (± Fe)	xxx
Riebeckite	Crocidolite	Amphibole	$Na_2(Fe^{3+})_2(Fe^{2+})_3(OH)_2Si_8O_{22}$ (± Mg)	x
Anthophyllite	Anthophyllite	Amphibole	$(Mg,Fe)_7(OH)_2Si_8O_{22}$	x
Grunerite	Amosite	Amphibole	$Fe_7(OH)_2Si_8O_{22}$ (± Mg, Mn)	xx
Actinolite	Actinolite	Amphibole	$Ca_2Fe_5(OH)_2Si_8O_{22}$ (± Mg)	x
Tremolite	Tremolite	Amphibole	$Ca_2Mg_5(OH)_2Si_8O_{22}$ (± Fe)	x

[a] Chrysotile always occurs with the asbestos habit. Actinolite asbestos is occasionally found as a contaminant of amosite from South Africa. It is not known to be exploited anywhere in the world. Tremolite asbestos is exploited commercially in Korea. Anthophyllite asbestos is no longer commercially worked anywhere in the world. Note that the amphibole minerals anthophyllite, actinolite, and tremolite do not have a separate mineral name for their asbestos varieties, as do riebeckite (crocidolite) and grunerite (amosite).

[b] Occurrence in buildings, frequency of observation: xxx = very commonly found if product is asbestos-containing; xx = commonly found; x = uncommonly found. Note that tremolite asbestos has been used in the past to manufacture gaskets.

Since 1966 (Addingley 1966), industrial hygienists have generally defined asbestos fibers as any of the minerals named in Table 4-1 that display, by phase-contrast optical microscopy (PCOM), particles of aspect ratio greater than or equal to 3:1, lengths greater than 5 micrometers (µm), and widths less than 3 µm. The original development of the definition has been discussed by the British Occupational Hygeine Society (BOHS 1968), Walton (1982) and Langer and colleagues (1991a). Originally intended as an "index of exposure" for the health effects of asbestos (the more numerous short fibers, and those with diameters below the limits of visibility in the phase-contrast microscopes used were excluded), the fiber has become the principal occupational exposure measurement for all asbestos diseases. In recent years, the debate over the classification of asbestos fibers and cleavage fragments has resulted in more specific definitions for asbestos fibers, especially for bulk samples (Langer et al. 1979; Kelse and Thompson 1989; American Thoracic Society [ATS] 1990; Wylie 1990) and air measurement (Yamate et al. 1984; 40 CFR pt 763, subpart E, appendix A, October 1987; International Standards Organization [ISO] 1991). A practical definition for the physical characteristics of asbestos has been proposed for use by the American Society for Testing Materials (ASTM 1990):

> "Asbestiform mineral fiber populations generally have the following characteristics when viewed by light microscopy: (1) many particles with aspect ratios ranging from 20:1 to 100:1 or higher (greater than 5 μm in length); (2) very thin fibrils generally less than 0.5 μm in width; and (3) in addition to the mandatory fibrillar crystal growth, two or more of the following attributes: (a) parallel fibers occurring in bundles, (b) fibers displaying splayed ends, (c) matted masses of individual fibers, and (d) fibers showing curvature."

Since the minerals tremolite, actinolite, and anthophyllite have the same name for both their asbestos and their common rock-forming varieties, there has been some confusion about the presence of asbestos in some products and environments (Occupational Safety and Health Administration [OSHA] 1990).

4.1.2 Crystallographic Properties

The asbestos character displayed by these minerals is brought about by their crystallographic properties, which are described below.

1. Chrysotile: The sheet structure of chrysotile exhibits a dimensional mismatch between the smaller silica sheet component and the superimposed larger brucite sheet. Bonding of these layers results in a structural warping, causing the components to roll upon each other. This forms a cylindrical scroll or "tubular" fibril (Whittaker and Zussman 1956; Yada 1967). Weak inter-atomic bonds hold many hundreds of these individual unit fibrils together to form the chrysotile fiber bundle. The conditions of crystallization control fiber length, and hence commercial grade.

2. Amphibole asbestos: The other commercial asbestos minerals are amphiboles, all of which consist of double-chain silicate "ribbons" of opposing silica tetrahedra which are linked by cations (Skinner et al. 1988). The amphiboles display defects (twin planes and chain-width errors) in their crystal structures that enhance their ability to reduce into the ultimate amphibole asbestos fibril (Veblen 1980; Chisholm 1983; Langer et al. 1991a,b). The monoclinic forms of asbestos possess anomalous optical properties which allow them to be distinguished from their nonasbestos counterparts by polarized light microscopy.

The crystal structure of chrysotile allows little opportunity for large-scale cation substitution. Hence, the chemistries of fibers from generically similar chrysotile deposits are similar, apart from small amounts of, for example, iron or nickel, which may substitute for magnesium in the brucite layer. In contrast, the amphiboles possess crystal structures which are more amenable to major degrees of cation substitution, that is, multiple sites accommodating cations to differing size and valence. Some varieties form complete (tremolite to actinolite) and partial (cummingtonite to grunerite) solid solutions. All of the amphibole asbestos minerals, except for anthophyllite, are monoclinic in crystal structure and are distinguishable on the basis of their chemistries. The most common commercial amphibole asbestos fibers show relatively small variations in their chemistries and thus may be reliably identified by modern analytical transmission electron microscopy (TEM).

The chemistries, structures and properties of asbestos have been reviewed in many texts (for example, Walton 1982; Chisholm 1983; Hawthorne 1983; Langer et al. 1991a).

Asbestos ores may contain other minerals as naturally associated phases. Chrysotile ores from Quebec frequently contain fibrous brucite and magnetite, whereas amosite and crocidolite from South Africa frequently contain quartz.

Each of the asbestos fiber types appears to possess a different size range in both airborne and tissue evaluations (Pooley and Clark 1980; Burdett 1986a). TEM airborne size distributions of asbestos in industry were first reported by Lynch and associates (1970) and many measurements around mines and mills were reported by Gibbs and Hwang (1975, 1980; Hwang and Gibbs 1981). These and other measurements have recently been reviewed by Berman and Chatfield (1989). Their principle conclusion in industrial environments was that approximately 9 percent (range 1 to 50 percent) of chrysotile, 4 percent (range 1 to 18 percent) of crocidolite, and 25 percent (range 8 to 43 percent) of amosite would meet the industrial hygiene definition of a fiber. More recent measurements in United Kingdom (U.K.) textile and friction plants (Rood and Scott 1990) found that only about 4 percent of chrysotile fibers fell into this category. However, a recent National Institute for Occupational Safety and Health (NIOSH) study (Dement and Wallingford 1990) of the South Carolina textile industry reported approximately 20 percent of fibers would be counted by the industrial hygiene definition. Thus, differing fibrous aerosols may be generated at industrial sites because of different fiber types and manipulation processes.

In TEM evaluations, chrysotile may form very fine fibrils which range between 0.02 and 0.08 µm in width (diameter); amosite between 0.06 and 0.35 µm; and crocidolite between 0.04 and 0.15 µm. Because the biological effects of asbestos fibers are influenced by fiber type, width, and length, each size range may have a different potential for induction of one of the asbestos diseases (Lippmann 1988; reviewed in Chapter 6). Detection of the presence of fine asbestos fibrils in samples of airborne asbestos necessitates the use of TEM at high magnifications.

4.1.3 Other Fibers

In addition to asbestos, there are many naturally-occurring and man-made mineral fibers (MMMF) which may be present in building atmospheres or used in building and commercial products. The most commonly encountered are synthetic and natural organic fibers from clothing, gypsum (calcium sulfate dihydrate) fibers from plaster, man-made mineral fibers used in insulation (see Chapter 7), and clay mineral fibers used in buildings and absorbent products. In addition, the outdoor environment can be a further source of fibers; for example, they can come from the local geology (amphibole fibers and mineral fragments are common contaminants in mining operations), flora (various seasonal organic fibers), fauna (skeletal fragments from diatoms near the seashore and from diatomaceous earth), combustion sources (calcium sulfate and mullite), and industry (chromium and iron oxide fibers).

Many new commercial fibers have been produced over the last 20 years, as direct substitutes for asbestos fibers in existing products, and also for use in high-temperature refractory and composite products (Health and Safety Executive [HSE] 1986; Hodgson 1987). Ceramic and carbon-based synthetic fibers (for example, Kevlar) are not likely to be present in most buildings as building construction materials. Cellulose fibers have been increasingly used (for example, in board and spray-insulation products), but primarily it is mineral products (many of which are fibrous) and MMMF that have replaced many of the insulation and reinforcing uses of asbestos.

Table 4-2. Asbestos-Containing Materials Found in Buildings[a]

Subdivision	Generic Name	Asbestos (%)	Dates of use	Binder/Sizing
Surfacing material	Sprayed- or troweled-on	1 – 95	1935 – 1970	Sodium silicate, portland cement, organic binders
Preformed thermal insulating products	Batts, blocks, and pipe covering			
	85% magnesia	16	1926 – 1949	Magnesium carbonate
	Calcium silicate	6 – 8	1949 – 1971	Calcium silicate
Textiles	Curtains[b] (theatre, welding)	60 – 65	1945 – present	Cotton
Cementitious concrete-like products	Extrusion panels	8	1965 – 1977	Portland cement
	corrugated	20 – 45	1930 – present	Portland cement
	flat	40 – 50	1930 – present	Portland cement
	flexible	30 – 50	1930 – present	Portland cement
	flexible perforated	30 – 50	1930 – present	Portland cement
	laminated (outer surface)	35 – 50	1930 – present	Portland cement
	pipe	20 – 15	1935 – present	Portland cement
Paper products	Corrugated			
	high temperature	90	1935 – present	Sodium silicate
	moderate temperature	35 – 70	1910 – present	Starch
	Indented	98	1935 – present	Cotton and organic binder
	Millboard	80 – 85	1925 – present	Starch, lime, clay
Asbestos-containing compounds	Caulking putties	30	1930 – present	Linseed oil
	Adhesive (cold applied)	5 – 25	1945 – present	Asphalt
	Joint compound		1945 – 1975	Asphalt
	Spackles	3 – 5	1930 – 1975	Starch, casein, synthetic resins
	Cement, insulation	20 – 100	1900 – 1973	Clay
	Cement, finishing	55	1920 – 1973	Clay
	Cement, magnesia	15	1926 – 1950	Magnesium carbonate
Flooring tile and sheet goods	Vinyl/asbestos tile	21	1960 – present	Poly(vinyl)-chloride
	Asphalt/asbestos tile	26 – 33	1920 – present	Asphalt
	Sheet goods/resilient	30	1950 – present	Dry oils
Wall covering	Vinyl wallpaper	6 – 8	Unknown to present	—
Paints and coatings	Roof coating	4 – 7	1900 – present	Asphalt
	airtight	15	1940 – present	Asphalt

[a] Adapted from EPA (1985).

[b] Laboratory aprons, gloves, cord, rope, fire blankets, and curtains may be common in schools.

Mineral products such as diatomite, perlite and vermiculite are widely used in thermal insulation. Palygorskite and sepiolite have been used in some cement products. Micas and wollastonite are used in some high-temperature products, and talc has been used as an extender in paint. Chrysotile and, more recently, other minerals have been used as reinforcers and as fillers in floor and ceiling tiles.

4.1.4 Types of Asbestos Products in Buildings

There are many asbestos-containing products that may be found in buildings today (Tables 4-2 and 4-3). The major uses in buildings include: thermal system insulation, surface treatments (such as structural fireproofing, and acoustical and decorative finishes), and other materials (such as cement sheet and insulating board products, floor and ceiling tiles, and asbestos-containing felts). A number of construction products may also contain asbestos such as, spackling, patching, and plastering compounds used in dry-wall construction and interior repair (see overview in Spengler et al. 1989). Thermal system insulation and surface treatments (fireproofing, acoustical and decorative finishes) stand out in importance for their potential for fiber release and subsequent exposure to occupants. Many formulations of these products contain mineral and MMMFs in combination with the asbestos and binders.

Under the Asbestos Information Act, manufacturers of asbestos-containing materials (ACM) were required to file proprietary product compositions with the U.S. Environmental Protection Agency (EPA). This information has been published (Federal Register, February 13, 1990) or is available for inspection.

Table 4-3. Asbestos-Containing Products Found in Buildings by Physical State[a]

Unbound Asbestos in Inorganic Mixtures	Bound Asbestos Composites[b]	Asbestos Textiles
Surface treatments[c]	Thermal systems insulation	Packings (valves and flanges)
Fireproofing (steel structures)	Insulating products: boiler covers, cements, pipe lagging	Plumbing cords and ropes
Acoustical applications	Vinyl tiles and floor coverings	Electrical wire insulation
Decorative surfaces	Ceiling tiles	
Equipment lagging	Ceiling and wall boards	
Moisture barrier	Cement products	
Dry applications	Papers (including pipe covering)	
Feathered (generally friable)	Acoustic plasters	
Wet applications	Spackling, patching, taping compounds	
Tamped (generally nonfriable)		
Untamped		

[a] This classification is modified from a scheme used in the International Program on Chemical Safety, Environment Health Criteria 53: Asbestos and Other Natural Mineral Fibres. United Nations Environment Program, International Labor Office, World Health Organization, Geneva (1986).

[b] All generally nonfriable.

[c] Note that "surface treatments" in the United States also includes asbestos bound in cements and plasters. The use of the word "unbound" for these applications is European in origin.

Table 4-4. Some Materials Commonly Used in Insulation Products

Asbestos-containing materials[a]	Inorganic and nonfibrous
Amosite and silica (pipe and block)	Perlite
Chrysotile and cellulose (pipe)	Vermiculite
Amosite and other asbestos, including *crocidolite* (pipe, block, lagging)	Gypsum pellets
	Diatomaceous earth
Magnesia block (pipe and lagging) *amosite* + *chrysotile* *chrysotile*	Calcium silicate
	Organic formulations
Braids, papers, sponges, *all* fiber types (irregular surfaces)	Cellulose
Spray applications (all surfaces); *all* fiber types (irregular surfaces)	Polystyrene[b]
	Polyurethane[b]
Lagging matts and blankets (all surfaces)	Vinyl chloride
Cements (all surfaces), *chrysotile* + *crocidolite*	Cork
Man-made vitreous fiber	Rubber
Alumina and silica ceramic fiber	Gilsonite (bitumen)
Fibrous glasses; wools (mineral, rock, slag)	Polyvinyl (acetate)
Siliceous fibers	

[a] Use of principally chrysotile and amosite. Some crocidolite found as well.

[b] Used as cellular foams or beads.

4.1.4.1 Composition of Asbestos-Containing Thermal Systems Insulation

Over 120 formulations of thermal system insulation products, utilizing dozens of natural and synthetic materials, have been developed and marketed in the United States since the middle decades of this century. Many of the more exotic ones have been developed as specialty items (see Malloy 1969). Most products have been developed for use as thermal insulation, electrical insulation, fire retardants, moisture and weather barriers, and as acoustical dampening media. Each of these applications requires specific design and calls for materials best suited for the intended purpose. Occasionally, insulation marketed in the United States is designated by form and consumer description. Some common materials used in insulation products in the United States are listed in Table 4-4.

Information on the frequency of the occurrence of specific asbestos products and the extent of their use was obtained in a field survey of 1,520 work sites in New York City–owned buildings and structures undertaken by the New York City (NYC) Department of Personnel (1984) in 1984. Twelve trained city inspectors collected approximately 2,500 specimens during the time period March through September 1984. Specimens were obtained from police stations, fire houses, sanitation facilities, day care centers, libraries, and a range of other buildings and structures owned by the City. Of the 1,264 thermal insulation materials analyzed (Table 4-5), 37 percent (466) were found to be free of asbestos and composed of man-made mineral and/or cellulose fiber. Chrysotile asbestos was identified in 37 percent (470); 22 percent (276) of the products contained a mixture of asbestos fiber types (over 99 percent of these 276 specimens contained amosite, whereas seven contained crocidolite) (see Table 4-5). Amphibole asbestos was identified as the only asbestos type in four percent (52) of the 1,264 insulation products analyzed (amosite was present in 94 percent [49] of these, whereas crocidolite was observed in eight percent [4]). Of the materials examined in New York City, some two thirds contained asbestos. When mixed asbestos types or amphibole asbestos only were found in insulating products, 3.4 percent contained crocidolite (11/328). The types of vitreous fibers found in insulation products were not characterized.

This study suggests that there is a potential exposure to all forms of asbestos, especially from thermal insulation products. It should be noted that New York City may not be representative of the rest of the nation in the use of thermal systems insulation.

Table 4-5. Mineral Composition of 1,264 Thermal Insulation Products Found in Some New York City–Owned Buildings and Structures[a]

	Nonasbestos-Containing Thermal Products[b]	Asbestos-Containing Thermal Products				
		Chrysotile Only	Mixed Asbestos Fibers[c]	Amphibole Asbestos Only[d]	Total	Total[e]
N	466	470	276	52	798	1,264
Percent of all products	36.87	37.18	21.84	4.11	63.14	100.0
Percent of asbestos-containing products	—	58.9	34.6	6.5	100	—

[a] Based on Table 12 in Langer and Nolan (1989). Data obtained from: *Citywide Asbestos Evaluation Program Survey Results* (NYC Department of Personnel 1984). Mineral assays by Dr. AN Rohl utilizing polarized light microscopy and continuous scan x-ray diffraction.

[b] These are made with glasses and wools; cellulose and borate mixtures; other materials. These formulations do not contain asbestos.

[c] Mixed asbestos fibers (chrysotile + amphibole asbestos): Chrysotile + amosite (*N* = 269); chrysotile + amosite + crocidolite (*N* = 5); chrysotile + crocidolite (*N* = 2). 274/276 contain amosite (99.3%); 7/276 contain crocidolite (2.5%).

[d] Amphibole asbestos only: Amosite (*N* = 48); crocidolite (*N* = 3); amosite + crocidolite (*N* = 1). 49/52 contain amosite (94.2%); 4/52 contain crocidolite (7.7%).

[e] Crocidolite presence in amphibole asbestos-containing products: 11/328 (3.4%).

4.1.4.2 Composition of Asbestos-Containing Surfacing Materials

Asbestos-containing spray application was introduced into the United States in the mid-1930s. It was used over the next several decades principally for decorative and acoustical purposes in restaurants, hotels, and public buildings. Subsequently, the material was also found to be an effective insulation coating to protect structural steel during fires, and a number of formulations were tested and given fire resistance ratings by Underwriters

Laboratory. Around 1950, sprayed-on asbestos-containing formulations started to come into widespread use for fire protection of structural steel in the construction industry (Nicholson et al. 1976).

There were three principal methods used for applying asbestos-containing surface treatments:

1. In the "dry spray method," the asbestos was dumped from shipping bags into a large hopper at the construction site, where the mineral was mixed with a variety of binders and was subsequently blown onto a surface. As the dry mixture of materials was air-forced through a nozzle, it was forced through a focused ring of fine water jets so that mixing, and binder activation, took place at the point of application. Material produced in this manner typically had a fibrous consistency, with either an open, a fibrous or a smooth, consolidated surface.

2. The other spray application technique was called the "wet method." The material was premixed with water in a hopper at the job site with the asbestos, binder, and other components of the formulation. This water-saturated mixture was then applied in a wet state. Portland cement, gypsum, lime, bentonite, and other substances were used as binders, holding together the lightweight material. Perlite and vermiculite were used as well. The end product was usually a plaster with a textured or smooth surface (Nicholson et al. 1976).

3. ACM surface material was also trowel-applied to a lath system. This was used both as the primary method of installation and as a finishing process after an initial wet spray application. Trowelled surfaces ranged from smooth to rough.

The surface treatment materials found in New York City consisted mainly of fireproofing, acoustic plasters, decorative sprays, and acoustical applications. One thousand, one hundred ninety-nine (1,199) surface materials found in New York City-owned buildings and structures were analyzed in 1984 (New York City Department of Personnel 1984; Table 4–6). More than 90 percent of these materials contained no asbestos. These surfaces were covered with man-made mineral fibers, cements, cellulose formulations, vermiculite formulations, and plasters, alone or in various combinations. Only 115 of the 1,199 surface materials were found to contain asbestos (Table 4-6). Of these, 73 percent contained chrysotile only, whereas the remaining 27 percent contained one or more amphibole asbestos fibers. Of the 10 mixed asbestos fiber-type formulations, all consisted of chrysotile mixed with amosite. Of 21 amphibole asbestos formulations, 19 were amosite only. These were confined to ceiling tiles. Crocidolite was found in two of the asbestos-containing formulations.

In the New York City study, only approximately 3.3 percent (19 of 571) surface applications required "corrective action" as compared to 83.1 percent (501 of 574) of the thermal system materials.

4.1.5 Surveys of Asbestos Products in Buildings

The EPA has offered guidance for surveying and assessing asbestos in buildings (see sections 5.1 and 5.2). Schools have been particularly targeted, and under the Asbestos Hazard Emergency Response Act (AHERA), were given a specific timetable to both survey and produce plans to deal with the ACMs. The EPA is currently auditing compliance with this requirement. The AHERA also required EPA to assess the extent and condition of ACMs present in public and commercial buildings. This information was obtained from a

Table 4-6. Mineral Composition of 1,199 Surface Materials Found in Some New York City–Owned Buildings and Structures[a]

	Nonasbestos-Containing Surface Materials[b]	Asbestos-Containing Surface Materials				Total
		Chrysotile Only	Mixed Asbestos Fibers[c]	Amphibole Asbestos Only[d]	Total	
N	1,084	84	10	21	115	1,199
Percent of all products	90.41	7.01	0.85	1.75	9.59	100
Percent of asbestos-containing products	—	73.0	9.6	17.4	100	—

[a] Based on Langer and Nolan (1989). Data obtained from: *Citywide Asbestos Evaluation Program Survey Results* (NYC Department of Personnel 1984). Mineral assays by Dr. AN Rohl utilizing polarized light microscopy and continuous scan x-ray diffraction.

[b] These surfaces were covered with materials containing glasses and wools, Portland cement, cellulose, vermiculite, and plaster; alone or in combination.

[c] Mixed asbestos fibers: Chrysotile + amosite (*N* = 10).

[d] Amphibole asbestos only: Amosite (*N* = 19; most in ceiling tiles); crocidolite (*N* = 1); amosite + crocidolite (*N* = 1).

previous statistical survey of a building population (EPA 1984) which was designed to estimate the number of buildings with friable ACMs, the area covered by such material and the percentage of asbestos contained within the various product categories (sprayed or trowelled-on surfacing, thermal systems insulation and ceiling tile). Estimates were made from a relatively small sample consisting of 231 buildings: 66 federal government, 55 residential and 110 private nonresidential buildings. The sample excluded schools, state and local government buildings and residences of fewer than 10 units. It was estimated that 733,000 buildings (± 200,000), approximately 20 percent of the 3.6 million total population of US public and commercial buildings, had some type of friable ACM in the above categories (EPA 1988a; see Table 4-7).

A study by the Philadelphia Department of Health (1988) of 839 city owned or occupied buildings found that approximately 47 percent contained friable ACM. A study for the California Department of Health Services (1990), based on 207 public buildings estimated that some 78 percent of the population of public buildings built prior to 1976 contained some ACM and that 56 percent contained some friable ACM. It was also estimated that approximately one third of the buildings containing ACM had areas where the material had been damaged. New York City Department of Environmental Protection conducted a study (City of New York DEP 1988) on a sample of 886 buildings from an estimated population of 800,000 buildings in New York City. Sixteen categories of buildings were used for stratification (schools and dwellings of less than two families were excluded). A much greater percentage (67 percent) of buildings contained asbestos than was found in the EPA study. The majority of the material (84 percent) was thermal systems insulation (272 million ft^2), of which half (51 percent) was present in mechanical rooms. Only 13 percent of this material by area was judged to be in "good condition," 68 percent was judged in "fair condition," and 19 percent was judged to be in "poor condition." Of the other friable material, approximately 15 percent (48.6 million ft^2) was surfacing material, with most of this (85 percent) in office buildings. In contrast to the thermal systems insulation, only 1 percent was judged to be in "poor condition." Similar features were encountered and described in the first New York City survey (1984). Ceiling tile containing asbestos accounted for 1 percent (3 million ft^2), with most judged to be in "good condition." The terminology in the New York City document was unique to this study and details were not provided.

The New York, California, and Philadelphia studies show that the extent of the friable ACM in public buildings may be greater than measured by the EPA study. The estimate of buildings containing ACM will increase greatly if other "nonfriable" ACMs are taken into account (for example, floor tile, asbestos cement boards, and pipes and drywall taping compounds). Important findings from these studies include the frequent use of friable surfacing in multi-storied buildings and the high proportion of damage to thermal systems insulation, most of which is accessible only to maintenance personnel. Many other surveys have been carried out, particularly in schools, but there has been no attempt to correlate these data to give a better estimate of the area and condition of ACMs in buildings.

Table 4-7. Location and Condition of Friable Asbestos-Containing Materials in U.S. Public and Commercial Buildings[a,b]

	Condition of Friable ACM: Percent of Total Population and Number of Buildings		
Location and Type of ACM	Present	Some Slight Damage	Some Significant Damage
All areas (friable)	20 (733,200)	14 (501,000)	9 (317,000)
Fan and boiler rooms (friable)	13 (462,000)	10 (360,000)	8 (282,000)
Public areas (friable)	13 (454,000)	8 (272,000)	2 (85,000)
Sprayed or trowelled coatings (friable)	5	2	0
Pipe or boiler insulation (friable)	16	13	9
Floor tile (nonfriable)	42	—	—

[a] Total population: 3.6 million; sample population: 231.

[b] Source: Burdett and associates (1989b); reprinted with permission.

4.2 Units of Measurement for Airborne Asbestos

Because the health hazards of asbestos depend upon asbestos inhalation, airborne concentrations provide a calculation of risk in a given measurement. Asbestos air concentrations have been expressed in a variety of ways. In this report, asbestos mass concentrations are expressed in units of nanograms per cubic meter (ng/m^3). For fibers analyzed by phase contrast microscopy (PCM), fiber concentrations are expressed in accordance with the conventional industrial hygiene definition (aspect ratio ≥ 3, length > 5 μm, width < 3 μm).

For asbestos fibers analyzed by the TEM, the concentration has been expressed in a number of different units in the literature, such as:

1. Fibers > 5 μm long and with aspect ratios ≥ 3:1;
2. Fibers > 5 μm long and with aspect ratios ≥ 5:1;
3. Structures > 5 μm long and with aspect ratios ≥ 3:1;
4. Structures > 5 μm long and with aspect ratios ≥ 5:1;
5. Fibers > 5 μm long, with widths ≥ 0.25 μm and aspect ratios ≥ 3:1;
6. Structures > 5 μm long, with widths ≥ 0.3 μm and aspect ratios ≥ 5:1;
7. PCM-equivalent or optically-equivalent fibers (as in 5 and 6);
8. All fibers with a ≥ 3:1 aspect ratio;
9. All structures > 0.5 μm long and with an aspect ratio ≥ 3:1;
10. All structures > 0.5 μm long and with an aspect ratio ≥ 5:1;
11. Mass of fibers both including and excluding matrices.

In this report, the concentration of asbestos fibers (and structures) longer than 5 μm have been expressed in units of fibers per milliliter (f/mL), and, unless otherwise stated, all discussions of asbestos concentrations refer to fibers (and structures) longer than 5 μm. Where the concentrations of *all* asbestos fibers (and structures) are reported, the results have been expressed as structures per liter (s/L).

Several aspects of information on TEM air concentrations deserve further comment. First, the term "structure" refers to asbestos fiber, cluster, bundle and matrix. This term, first used by Yamate and associates (1984) introduces complications in that the size determination may or may not be representative of the asbestos material and may include other nonasbestos material. This problem has been simplified by taking the approach of counting structures as though they were fibers. It should be noted that the term "structure" is used here only in a morphologic sense, and that it has no bearing on molecular arrangement in asbestos fibers.

Second, with respect to the concentration of *all* asbestos structures (expressed as s/L in this report), it has become the practice in recent years to designate a particle as an asbestos structure only if a minimum length of 0.5 μm of an asbestos fiber is visible and can be identified. It is not possible to account for the differences in reported results that are due to the lack of a minimum length criterion in earlier studies. The results could have been either too high or too low compared with those obtained using current definitions, in terms of fibers per milliliter of air, (f/mL).

Third, in general, the superior visibility and resolution of the fibers when analyzed by the TEM allows fibers below the normal limit of PCM visibility to be counted and analyzed. Therefore, TEM counts of asbestos fibers greater than 5 μm long frequently represent an overestimate of PCM-equivalent fiber counts. Depending on the asbestos type and source, there is a wide variation in the numbers of asbestos fibers greater than 5 μm long that are visible by PCM and those visible by TEM. For chrysotile and crocidolite in industrial and mining situations, this ratio is frequently 2:1 to 10:1 (Hwang and Wang 1983; Berman and Chatfield 1989; Rogers 1990). The main exception to this appears to be chrysotile present in building and friction products where ratios of 1.3:1 to 1.6:1 were reported by Marconi and colleagues (1983). Dement and Wallingford (1990) reported an overall ratio of 1.07:1 for chrysotile in the asbestos textile, and the friction products and cement products industries. Amosite fibers tend to have larger fiber widths; the increased fiber count ratio is often less than 2:1 (Burdett 1986a; Paik et al. 1983). In this report, where available, fiber concentration data in terms of PCM or optically equivalent fibers have been noted in the text.

Finally, for calculation of risk from exposure to airborne asbestos, the Panel has focused on fibers longer than 5 µm. The Panel's decision was based on two major factors. The exposure-response relationships observed in epidemiologic studies are the basis for risk estimation of asbestos; the exposure data in such studies have been expressed in terms of fibers longer than 5 µm. In addition, toxicity data suggest that shorter fibers are less toxic than longer fibers (see section 6.3, Data from Experiments with Laboratory Animals and Cultured Cells). The use of concentrations of fibers longer than 5 µm to estimate risk should not be taken to suggest that there is a sharp cut-off in toxicity below this length; toxicity is most likely to be a continuous and rapidly rising function of length, and fibers below 5 µm in length may well exhibit some toxicity. The precise value of 5 µm was originally arbitrarily selected for reporting PCM fiber counts, and has no particular significance other than a delineation of minimum fiber length for calculation of an exposure index. The concentrations of asbestos fibers longer than 5 µm, determined by the TEM, are summarized in the text and tables of this report, and such concentrations are used as the index of exposure for calculation of risks. It should be noted that the vast majority of fibers found in asbestos mines and factories and in buildings with ACM are shorter than 5 µm; other descriptors of concentration that account for all fibers irrespective of length, such as mass concentration and numbers of fibers (and structures) of all lengths are also summarized in this Report.

It is important to note that TEM measurements are based on observations of morphology, combined with some degree of identification before any fiber is classified as asbestos. There are considerable variations among studies in the literature as to what combination of observations was accepted as satisfactory identification of asbestos, and how these fibers were then counted. It should also be recognized that precise identification of chrysotile is typically less problematic than it is for the amphiboles. The various analytical methods used so far have been vague to some degree in the specifications for identification of fibers. There appears to be a tendency for earlier studies to classify some fibers as asbestos based on morphology, including the characteristic tubular appearance, while later studies adopted a more rigorous identification requirement that the fiber or structure must have either a characteristic electron diffraction pattern or energy dispersive x-ray spectrum. The way the identification was carried out, the criteria for classification of the fibers as asbestos, the type of equipment used, and the operating procedures of the analyst all influence the numerical and mass concentrations produced. It is also important to note that the optical PCM microscope does not discriminate between fiber types, and where significant numbers of nonasbestos fibers are present (for example, in public and commercial buildings), PCM fiber counts will overestimate the industrial hygiene fraction of asbestos fibers by varying amounts.

4.3 Persons Exposed to Asbestos in Buildings

For most purposes, occupants of buildings can be grouped into three categories:

C1 General building occupants, such as office workers, visitors, students and teachers.

C2 Housekeeping or custodial employees, who may come into contact with or disturb materials, and cause increased airborne asbestos levels, in the course of cleaning, dusting, replacing fixtures, and other housekeeping activities.

C3 Maintenance workers, who may disturb ACM in the course of making repairs, installing new equipment, or during renovation activities.

Two other categories not often dealt with in the context of occupancy have been identified.

C4 Abatement and remediation workers or others involved in the removal or renovation of structures with ACM.

C5 Emergency personnel, such as firefighters, who may be required to enter the building during or after extensive damage.

C1 occupants are by far the most numerous of the building occupants. Persons in this group may sometimes work in areas in which certain forms of ACM are present, for example, vinyl-asbestos floor coverings and texture-coatings on walls, but they are unlikely to directly disturb other types of ACM in the course of their usual activities in buildings. Most data available to the Panel on exposure of C1 occupants had been collected in schools, offices and residential buildings; data from other public and commercial buildings (for example, shopping malls, theaters, airports, churches, hospitals, factories, etc.) were generally not available.

There are smaller numbers of C2 and C3 employees. These persons are more likely to come into contact with and disturb asbestos-containing materials during the course of their normal work assignments, especially during maintenance and custodial activities. They may or may not know that they are disturbing ACM and, if they do, they may or may not have the equipment or the expertise to take the appropriate precautions to minimize their exposure to airborne asbestos. Exposures of such workers can be high, and warrants special attention.

Persons in categories C2 to C5 fall under either OSHA 29 CFR 1926.58 or 1910.1001 regulations for personal monitoring if their exposures exceed the permissible exposure limit (PEL) (0.2 f/mL time-weighted average [TWA]) or the excursion limit (1 f/mL) in a half hour, as determined by PCM using the OSHA reference method (Appendix B to 1926.58). Persons in category C1 are covered by the OSHA 29 CFR 1910.1001 if they reasonably may be expected to be exposed to airborne concentrations above 0.1 f/mL. In some states, C1 persons are also protected by an ambient standard of 0.01 f/mL by PCM, or a TEM standard very similar to the Asbestos Hazard Emergency Response Act (AHERA) post-abatement clearance criteria.

4.4 Asbestos Sampling and Analytical Methodologies

Sampling and analysis of the airborne concentrations of fibers released from ACMs form the basis of the industrial hygiene measurement of exposure, as well as the estimate of exposure used for epidemiologic and risk assessment purposes. They are, therefore, discussed in depth.

4.4.1 Air Sampling Strategies

There are several important aspects of air sampling for asbestos fibers that need to be considered in the design of a sampling program. These include: objectives of air sampling, sampler configuration and design, personal versus area sampling, scheduling of sample collection, statistical design, and record keeping and quality assurance.

4.4.1.1 Objectives of Air Sampling

There are several different objectives that can be addressed in evaluating actual or potential exposures to airborne asbestos. These include the following:

1. Measurements of the personal exposures of individuals at particular risk or of those who serve as sentinels for groups having similar exposures. These are most appropriate for categories C2 and C3.

2. Measurements of ambient concentrations in areas occupied by persons at potential risk. Time-weighted average exposures can be calculated by combining time-activity pattern data on individuals or groups and the asbestos concentrations in the areas in which they spend their time. These are most appropriate for category C1.

3. Source-related measurements. These can range from sampling the air in the immediate proximity, to active disturbance of ACM to determine the extent of fiber release into the air under specific circumstances, to field collection and laboratory dispersion and analysis of bulk ACM that might be disturbed by human actions. Such measurements can indicate the potential for human exposure, but not exposures per se.

4.4.1.2 Sampler Configuration and Design

The basic objective of the sampler is to facilitate the uniform deposition of a representative sample of airborne asbestos onto the filter surface. Approaches that have been used include open-faced filter cassettes and cassettes with an inlet cowl or retainer ring, generally constructed of conductive plastic.

An option that warrants serious consideration at this time, is the use of an aerodynamic size-selective inlet to prevent access to the filter of background particles and fibers that are too large to penetrate the upper respiratory tract. Size-selective inlets to accomplish this task have been designed to meet the essentially equivalent criteria of the American Conference of Governmental Industrial Hygienists (ACGIH 1984) and the International Standards Organization (ISO 1983; ISO/CEN 1991). Both Tillman (1982) and Iles (1990) have studied fiber deposition in cyclone and elutriator samplers. Use of size-selective inlets will make it easier to distinguish asbestos fibers, clusters, and matrices of health significance from airborne debris that would otherwise obscure the viewing field. This approach has already been used by Sébastien and associates (1984) and Baxter and colleagues (1984) for indirect analysis of static (area) samples.

The inlet efficiencies of the cowl or open-faced sampler are expected to approximate the inspirable definition (the fraction of total particulates that enter the oral and nasal cavities), with high efficiency for the smaller respirable fraction that penetrates into the lung. An important influence on the inlet efficiency is whether the sampler is used as a personal or static sampler, because the performance, when attached to a large human body, may differ markedly due to local turbulence and air currents. Personal samplers are often attached to various areas of the upper torso at varying orientations, from horizontal on the top of the shoulder to near vertical on the chest. These factors, when combined with a wide variety of work practices, can give variations in results. Vaughan and colleagues (1990) compared variations between opposite-shoulder personal samples on a robotic dummy acting as an observer and the inter-sample variations in a static array at 23 industrial locations. Approximately 95 percent of the mass measurements on each shoulder were within a 2.2-fold variation and 95 percent of the static samples were within 1.9-fold variation. The inter-sampler variations increase on workers who are closer to the source of the dust. The precision in the above sampling relates to mass on the whole filter, but with fiber counting additional variance may be observed due to the distribution of fibers on the filter and the method of analysis.

There has been some controversy over the effect of the cowl on the inlet efficiency and, in particular, wall losses. Theoretical (Baron and Deye 1990a; Tannahill et al. 1990a), laboratory (Baron and Deye 1990b; Wang et al. 1990), and field studies (Knight et al. 1985; Gonzalez-Fernandez and Martin 1986; Tannahill et al. 1990a) have not found evidence for significant wall losses with asbestos fibers except with highly charged aerosols in low-humidity conditions; when there was a leak in the seal between the filter and cowl (Wang et al. 1990); or when oversampling and particle fall-off in the cassette was suspected (Seixas et al. 1987; Baron 1987). Because the cowl may act as an elutriator to large particles, samples taken during periods of considerable disturbance in contaminated situations may result in reduced counts or, in the case of a cowl that is not vertically oriented, increased deposition on the cowl. This may be the explanation for a reduction in fiber count associated with the use of a cowl, as reported by Speight and Marsh (1984). In wind tunnel studies of static cowled samplers, Wang and coworkers (1990) reported trends which showed a reduction (0.7-fold at vertical:horizontal) in collection when oriented from the iso-axial position and a reduction in the particle count from the top to the bottom of the collection filter. These variations from the ideal situation are found in most sampling inlets and in the turbulent environment of everyday sampling, and may not be important. The conductive cowl sampler was originally developed by the asbestos industry to protect personal sampler filters from damage and it is not necessary, or required by regulation, for static air monitoring of asbestos. With the much larger ceramic (Cornett et al. 1989) and man-made mineral fibers (MMMF) (Robbins et al. 1990), increased collection in the cowl has been found.

The performance of existing designs of open and size-selective personal samplers compared against the newly agreed ISO/CEN (1991) definitions of respirable and thoracic fractions needs to be measured (see Soderholm 1989), and whether or not the filter deposit is sufficiently uniform to permit unbiased direct analysis measurements must be determined.

4.4.1.3 Personal Versus Area Sampling

Building employees who disturb ACM in the course of their work assignments will be exposed to highly variable air concentrations. The only accepted way to determine their exposures is to use personal monitors that draw air samples from the employees' breathing zones using battery-powered pumps.

For building occupants not engaged in physical contact with ACM, the concentrations of fibers in the air they breathe should be more uniform. Samples collected at representative fixed locations within the areas occupied by general building occupants (C1) may provide adequate estimates of personal exposures. Such an approach has advantages of efficiency and practicality, as compared with personal sampling. In addition, it is possible to achieve higher sampling rates. Studies suggest that personal exposures tend to be higher than simultaneously-measured area concentrations (Spengler et al. 1989). In the only available study reporting simultaneous personal and area sampling results for asbestos (Corn et al. 1991), no difference was observed between the concentrations measured by the two types of monitors.

4.4.1.4 Scheduling of Sample Collection

For building employees who disturb ACM, OSHA requires that both long-term (work-shift) personal samples and short-term (30-minute) samples should be collected during days when their work tasks are likely to cause elevated exposures. If concentrations approach or exceed the occupational PEL and there is more than one source of elevated exposure during the work shift, then shorter-term personal sampling at each specific operation involving contact with ACM may be needed to determine and remedy the major sources of exposure. In any case, careful notation should be made concerning the work locations, the work activities performed, and their duration during each sampling interval. Johnson and colleagues (1982) have shown that the sampling rate is directly correlated to the concentration measured over a range of 1-16 L/minute, and different flow rates can be used to achieve the required analytical sensitivity.

For general building occupants, air concentrations should be measured over relatively long time intervals corresponding to occupancy cycles, that is, at least one full day or long enough to capture typical building activity patterns. Long sampling times have two distinct advantages: (1) relatively large sample volumes decrease the lower limit of detection (LOD) by increasing the assay sensitivity; and (2) the effects of intermittent fiber-generating activities that cause transient elevations of concentrations are more likely to be captured in the cumulative and average exposure estimates.

For buildings whose ventilation patterns change with the seasons, it may be necessary to conduct sampling surveys in different seasons. Furthermore, at each survey of general occupant exposure, outdoor air samples, preferably near the building's fresh air inlets, should be collected in order to determine the extent to which outdoor sources contribute to indoor fiber concentrations.

4.4.1.5 Statistical Design

If a building survey of airborne asbestos concentrations is to be undertaken, an underlying statistical design for sampling should be formulated. The nature of the study design will depend on the purpose of the study. One important consideration is the definition of the reference "population" that is to be sampled. This might be, for example, a well-defined subset of U.S. buildings, general occupants of a particular building, a specific category of tradespeople, etc. The important point is that the population of interest should be defined as clearly as possible at the outset. Then, statistical sampling strategies (for example, stratified random selection) can be used to select a representative sample of that population for study. The need for multiple (spatial) or repeated (temporal) sampling should be evaluated with respect to the purposes of the study. Estimation of the sample size needed in a particular study should take into account the purpose of the study (for example, to estimate the mean exposure to a specified degree of confidence; to demonstrate compliance with an exposure limit) and the expected temporal and spatial variability in measurements. Standard methods for sample size calculation have been described in the statistical literature (for example, Cohen 1977). Because of the analytical limitations for single sample analysis when evaluating the concentration of fibers greater than 5 μm, many of the samples are generally below the analytical sensitivity; an appropriate statistical strategy, such as that proposed by Rao and colleagues (1991), may be considered when interpreting such censored data.

4.4.1.6 Record Keeping and Quality Assurance

Proper interpretation of air sampling data depends upon full consideration of all of the information relevant to the sample. The data can be used for compliance testing, trend analysis, correlation with building maintenance activities, use of air conditioners and space heating facilities, and so forth. Thus, all air sampling data should be coded by type, location, sampling rate, duration, relevant activity at the time of sample collection, et cetera. Flow calibration data for the samplers should also be recorded, and each batch of samples collected in the field should be accompanied by field blanks to test for possible filter contamination in manufacture or field handling. Many of these aspects are included in EPA guidance documents (for example, EPA 1985a, 1985b, 1987) and, to a large extent, are covered by the acceptance criteria for analysis of bulk and airborne asbestos samples required of laboratories in the National Voluntary Laboratory Accreditation Program (NVLAP). However, the TEM and polarized light microscope (PLM) laboratories have no control over the sample collection, and the laboratories are placed in the difficult position of refusing analysis (and potential future business) if the samples do not meet specified quality assurance criteria.

4.4.2 Standard Methods for Air Sample Analysis

4.4.2.1 Background Considerations

The primary purpose of measurements of airborne asbestos is to evaluate the potential for, or extent of, human exposure to airborne fibers. The measurement strategy should be developed with recognition of the following:

1. Inhaled airborne fibers within certain specific size ranges can cause lung fibrosis, lung cancer, and mesothelioma after their deposition in the lungs (see Chapter 6; Lippmann 1988).

2. The extent and nature of the health effects caused by asbestos fibers deposited in the lungs depends on the number of fibers deposited in specific lung regions and their physical-chemical properties. Important variables include the lengths, diameters, composition, surface chemistry and durability of the fibers, and, at high exposure levels, whether or not they, and other inhaled particles, accumulate to a degree sufficient to alter normal particle clearance rates and pathways (Stöber et al. 1990; Lippmann and Timbrell 1990).

3. Other particles coexist in air, so that asbestos fibers may only be present to levels of less than one part per million. The total volume of air in ambient air that can be sampled for direct PCM or TEM analysis is constrained by the concentrations of these other particles.

4. The extent of the hazard from exposure to asbestos depends on the inhalation and lung deposition of the fibers. For individuals with dust exposures high enough to cause impaired particle clearance, the peak concentration over a shorter interval (for example, a work shift) may also be important, and additional sampling to determine the extent of the peaks may be warranted.

5. In order to identify, measure, and count the fibers of interest in air samples, microscopes must be used. In the past 20 years, most fiber concentration measurements, especially those made for occupational exposure assessment, have been made by PCM, and reported as f/mL for all fibers longer than 5 µm. The resolving power and contrast

enhancement of such microscopes have a practical lower detection limit of 0.2 to 0.3 μm diameter (Burdett 1982; LeGuen et al. 1980; Hwang and Gibbs 1981; Rooker et al. 1982; Kenny et al. 1987; Pang 1988), although this diameter limit may not be achieved under less than ideal conditions for chrysotile. In recent years, measurements have also been made, primarily in Europe, with the scanning electron microscope (SEM). Depending on the operating conditions, the limit of visibility for asbestos fibers in the SEM is between 0.1 and 0.2 μm (Small 1982; Asbestos International Association (AIA) 1984; Verein Deutscher Ingenieur [VDI] 1986; Cherrie et al. 1989), the same point at which the collection of energy dispersive x-ray analysis (EDXA) spectra to determine fiber chemistry can also become increasingly difficult. Other than in the United States, TEM has been regarded as a research tool, but the EPA has been instrumental in promoting the technique for routine clearance measurements after an abatement action (EPA 1983, 1985a, 1985b, 1987). Modern TEM has a resolution of approximately 0.2 nm, many times below the thinnest asbestos fiber diameter (approximately 10 nm).

6. The different mineralogical forms of asbestos, and non-asbestos mineral fibers, can usually be unambiguously identified in the analytical TEM. Both structural information, obtained by electron diffraction analysis, and chemistry are required for this purpose. SEM-EDXA systems can identify the chemistry of fibers with diameters over 0.1 μm. The technique is compromised if other silicate particles are nearby or nonasbestos analogues are present. No identification of fiber type is possible by PCM, except to classify fibers into broad morphological categories.

4.4.2.2 Optical Microscopy

Beginning in the 1920s, optical microscopy measurements of total particulates were made in asbestos factories and mines. Short-duration area samples were collected using impactors, thermal precipitators, and impingers. The importance of long fibers for asbestosis was first appreciated in the 1930s (Dreessen et al. 1938). Fiber counting was introduced into the workplace in a somewhat uncoordinated fashion in the 1950s, with the fiber definition standardized by the Asbestosis Research Council in 1958 (Walton 1982). A membrane filter, phase-contrast method started to be used in the 1960s (Ayer et al. 1965; Holmes 1965); a detailed method was published by the Asbestosis Research Council (ARC 1971), after review by Addingley (1966) in association with the British Occupational Hygiene Society (BOHS 1968). The method has undergone various revisions to improve precision, such as adding a specialized eyepiece graticule (Becket et al. 1976; Walton and Becket 1977), a test slide (LeGuen et al. 1984), improved mounting techniques (LeGuen and Galvin 1982; NIOSH 7400 1985), and improved counting methods (Crawford 1985, Cherrie et al. 1989). The net effect of these improvements has been to increase the fiber count and give a de facto tightening of the legal and recommended occupational exposure limits. A recent study (Rogers 1990) suggests up to 10-fold increases in current analysis over historic fiber counts on thermal precipitator samples. The improvement in fiber detection and counting efficiency by the current PCM protocol is not usually taken into account when making risk calculations based on previous estimates of exposure.

The membrane filter, PCM method is the accepted standard method for measurements in occupational settings, and has been used to obtain the "index" of exposure for epidemiological surveys and occupational risk estimates. It has, however, been widely rejected as a method of environmental assay for ambient measurement in buildings and outdoors, because of its inability to positively identify fibers as asbestos and its limited power of resolution.

4.4.2.3 Scanning Electron Microscopy

Several approaches have been used to analyze air sample filters for asbestos using the SEM. The SEM is a less expensive instrument than the TEM, the specimen preparation required is simple, and fibers can be identified, within certain limits, by EDXA. Commercially available SEMs can achieve resolutions better than 5 nm, and field emission instruments are capable of resolutions down to 0.9 nm. Since the diameters of the smallest fibrils of asbestos are approximately 10 nm, the SEM appears to have adequate resolution for detection of asbestos fibers. However, there are considerations other than resolution that make the SEM unsuitable for determination of asbestos in air samples.

Detection of a small asbestos fiber on the surface of an air filter, using any type of microscope, requires that both resolution and contrast be sufficient. When the SEM is operated at high magnifications, a compromise must be made between image resolution and the signal presented to the image-forming system. This compromise leads to a routine detectability for small diameter fibers on the viewing screen that is often only slightly better than that achievable in the PCOM (that is, approximately 0.2 µm) (Middleton 1982; Small 1982; Teichert 1982; Small et al. 1983). The full resolution of the instrument can be achieved, permitting the detection of the smallest asbestos fibers, but only if each field of view is photographed using a time exposure of about one minute or more. In order to produce real-time images at the magnification required, the beam current must be increased, and at the required high beam currents, the resolution is degraded (Lee 1978). Real-time operation is required, because each fiber must be identified. The image quality can be improved by using heavy metals, such as gold, to coat the surface of the filter, but this coating compromises the interpretation of the x-ray spectra on which fiber identification is based, and may even obscure objects on the filter.

Energy dispersive x-ray analysis is the only technique available in the SEM by which fibers can be identified. Identification of fibers by this technique alone has some serious limitations. The approximate chemical composition, derived from an EDXA spectrum, is frequently not sufficient to discriminate between asbestos varieties and some other relatively common minerals (Ruud et al. 1976). In addition, when attempts are made to identify a fiber by the use of EDXA, contributions to the EDXA spectrum may be made by other particulates close to the fiber under examination. The composite EDXA spectrum thus obtained can lead to ambiguities in identification. Definitive identification of asbestos fibers can often be achieved only by a combination of chemical and electron diffraction data, and this combination of identification techniques is available only in the analytical TEM. The limitations of the two instrumental approaches have been reviewed by Chatfield and Dillon (1978).

Methods for determination of airborne asbestos fiber concentrations using the SEM have been developed for both polycarbonate (Spurny and Frank 1970; Konig 1980) and MCE filters (LeGuen et al. 1980). Polycarbonate filters have a smooth surface, and are useful media for particle collection and observation in the SEM; the filters are coated with either carbon or gold to prevent localized charging when viewed in the SEM. This method has been widely used for environmental surveys (for example, Spurny et al. 1980; LeGuen and Burdett 1981; Altree-Williams and Preston 1985; Felbermayer 1983; Spurny 1984; Cherrie et al 1989; Spurny et al. 1989; Rodelspurger et al. 1990). Other sampling media have been developed for asbestos analysis (Konig et al. 1980; LeGuen et al. 1980). The performance and merits of the methods were assessed in an international laboratory comparison (Teichert 1982). The method developed by Konig and associates (1980) is based on the use of a polycarbonate filter coated with gold prior to sampling. This method became the basis of the Asbestos International Association Method RTM-2 (AIA 1984) and the method specified by the German Association of Engineers (VDI 1986). These methods specify that the range of fiber sizes determined includes only those greater than 2.5 µm in length and greater than 0.2 µm in diameter. The VDI 1986 method is specified in Germany for measurements of asbestos in ambient air. Small and colleagues (1983; Small 1986), in their investigations of the fundamental limitations of the SEM for asbestos fiber measurements, concluded that the contrast limitations could be overcome only by the use of thin film specimens prepared in the same way as for TEM observation. Cherrie and coworkers (1989) used the conventional method, in which a gold coating was applied to the filter after collection of the air sample, and found that good agreement between SEM and TEM fiber concentrations could be obtained using pure asbestos dispersions, provided that only fibers longer than 5 µm were considered, and viewed at magnifications of 10,000 or above. It is noteworthy, however, that the Cherrie and coworkers (1989) study did not demonstrate comparability of SEM and TEM methodologies using environmental samples.

The limitations in fiber visibility and ambiguities of fiber identification are serious disadvantages of the SEM analytical procedures, and in the United States these methods were abandoned in favor of the TEM method. However, in situations where only fibers thicker than about 0.2 µm are to be detected, and where fiber identification requirements are limited to discrimination between chemically different species such as asbestos and gypsum, the SEM can be a valid procedure for obtaining an approximate measure of the asbestos component.

4.4.2.4 Transmission Electron Microscopy Analytical Methodologies

The TEM provides the most complete analyses currently available for airborne asbestos. The very high resolving power of the TEM, and its ability to provide the mineralogical identity of asbestos (when combined with selected area diffraction [SAED] and EDXA), make the TEM the method of choice for analysis of airborne asbestos samples.

Two different procedures are used for preparation of samples for TEM analysis. Direct-transfer methods are intended to retain all particles in the same relative positions with respect to each other on the final TEM specimen as they were on the original filter, with a minimum of alteration to the particulate matter as it existed in the airborne state. Indirect methods for preparation of TEM specimens involve dispersal of the particulate matter from the original filter into a liquid suspension and redeposition of this dispersion onto intermediate filters. TEM specimens are prepared from the intermediate filters by one of the direct-transfer TEM preparation procedures. By using various proportions of the liquid dispersion, indirect methods have the ability to either concentrate or dilute the original material to give a range of filter loadings for analysis.

Development of Transmission Electron Microscopy Methods

Various direct and indirect methodologies have been used to measure airborne asbestos concentrations. The differences between these methodologies are primarily in the type of the filter medium used for sample collection and the steps in the specimen preparation procedure. Fiber counting criteria, size measurement, and identification methods are similar for all of the methods.

Early work on airborne asbestos fiber concentrations in ambient atmospheres and buildings (Nicholson et al. 1971, 1975, 1976; Sébastien et al. 1976, 1980) was performed using indirect methods of TEM specimen preparation. The indirect methods were used for three reasons. First, at the time of the earliest work, methods for direct-transfer TEM specimen preparation were not well-characterized. Second, when adequate air volumes were collected to achieve the desired sensitivity, the filters were frequently so heavily loaded with nonasbestos particulate matter that TEM grids could not be prepared by direct-transfer TEM specimen preparation methods. Finally, at least some of the organic and other particulate matter could be removed during sample preparation by the indirect method, thus providing selective concentration of the asbestos.

Air samples destined for preparation by an indirect method may be collected on either polycarbonate or cellulose ester (CE) filters. The particulate matter from the filter surface can be removed either by complete ashing of the filter and dispersal of the residual ash in a liquid, or by immersing the filter in a liquid and dispersing the particulate by agitating the container, either manually or by the use of an ultrasonic bath. TEM specimen grids are then prepared using a variety of procedures. In the early studies, this involved the use of centrifugation, or "drop," methods, which were originally used in connection with water sample analysis (Cunningham and Pontefract 1976; Maurer 1976; Melton 1976). In the centrifugation method, a high speed centrifuge ($> 8000 \times g$) was used to deposit particulate and fibers from an aqueous suspension directly on to carbon-coated grids held at the bottom of a centrifuge tube. The "drop" methods consisted of direct deposition of a small droplet (approximately 3 µL) of an aqueous suspension of the fibers onto a carbon–coated grid by micropipetting, followed by evaporation of the droplet. These methods were abandoned because it was not possible to achieve reliable quantification (Maurer 1976; Cook and Marklund 1982; Finn et al. 1984a) and because the filtration methods offered a more reproducible procedure for transfer of particulate to a TEM grid.

Rickards (1973) published details and results of an air sampling method involving high volume sampling with an electrostatic precipitator, followed by evaporating a drop of the ultrasonically-dispersed sample onto a carbon coated grid. A similar collection technique was used by LeGuen and Burdett (1981) for measurements in buildings and of outdoor air (Burdett et al. 1984). A centrifuge method of sample preparation was used (Burdett and Rood 1983a) that gave mass concentrations that were comparable to a direct-transfer method in field comparisons (Burdett and Rood 1983b; Burdett 1984).

The early measurements by Nicholson and associates (1971) were made using an indirect TEM specimen procedure known as the "rubout" method. Air samples, collected using mixed cellulose ester (MCE) filters, were ashed in a low-temperature plasma asher, the residual ash was dispersed in a solution of nitrocellulose, and the dispersion was spread as uniformly as possible on an optical microscope slide. After the solvent had evaporated, a portion of the film containing the particles from the ashed filter was mounted on a TEM grid for examination. This method had inherent difficulties in quantification, in that the uniformity of the thin film of cellulose nitrate could not be controlled easily, and it was also necessary to use a "recovery factor," derived from standards (Nicholson et al. 1975), to correct the fiber count for the fact that the thin film does not contain all of the original particulate matter. This method was abandoned, in part because filtration provided more reproducible results.

In the studies of Sébastien and coworkers (1976) on ambient and building atmospheres, the residual ash from the sample collection filter was ultrasonically dispersed in water for two hours and the aqueous dispersion was filtered through a previously carbon coated polycarbonate filter. The polycarbonate filter was carbon coated again, a portion was placed on a TEM grid, and the filter medium was extracted using chloroform dropped directly onto the grid.

Many of the TEM analyses for the EPA reports in the 1980s were carried out by an indirect method developed and used by the Battelle Laboratories (Thompson and Morgan 1971).

The method involved air sampling onto 37 mm diameter MCE filters. A quadrant of the filter was cut out and ashed in a low-temperature plasma asher in a test tube, and then ultrasonically resuspended in distilled filtered water prior to filtration onto a polycarbonate filter. The filter was then carbon coated and the polycarbonate was dissolved with chloroform in a Jaffe washer. The partial breakup of complex asbestos structures did increase the total numerical asbestos structure count; however, the method did not fully separate all complex asbestos structures, and thus the mass contribution of such structures was underrepresented in estimating the mass concentration (Constant et al. 1983).

Current indirect preparation methods are similar to the procedures used by the Battelle Laboratories (Constant et al. 1983), but vary mostly in the way the low-temperature ashed deposit is resuspended. Steen (1981) and Steen and coworkers (1983) used ultrasonic treatment with a surfactant. In the Kohyama (1989) study, the filter was adhered (face-down) to a glass slide prior to etching, and the ashed deposit was scraped off and ultrasonically resuspended in isopropanol prior to filtration onto a polycarbonate filter. Aliquots of this suspension are then filtered through either 0.2 µm pore size polycarbonate or 0.22 µm pore size cellulose ester filters, thus providing filters with suitable particulate loadings for analysis. The filters then are prepared by one of the direct-transfer methods.

Transmission electron microscopy specimen preparation, in common use for direct-transfer methods and for the intermediate filter of indirect preparation methods, is based on carbon extraction replication. In this process, a carbon coating is deposited on the surface of the filter by vacuum evaporation, and the filter medium is dissolved away in a solvent, usually by a slow wicking method (Jaffé 1948) or by a condensation washing method (Beaman and File 1976). The TEM specimen consists of the carbon film, to which is attached all of the particulate matter originally present on the surface of the original sample filter.

Determination of airborne asbestos concentrations by collection of air samples using MCE filters, and direct transfer of the collected particulate matter to TEM specimen grids, was first published by Holt and Young (1973). The method used was similar to that published by Ortiz and Isom (1974). This method consisted of collapsing the sponge texture of the cellulose ester filter by exposure to acetone vapor, thus yielding a featureless layer of filter polymer with the collected particles embedded in the surface. The surface was then carbon coated, portions of the collapsed filter were mounted on TEM grids, and then they were extracted with acetone to remove the filter polymer. Unfortunately, during this filter-collapsing procedure, many of the particles and fibers become buried in the filter polymer, and those completely buried do not transfer to the TEM specimen.

The first published methodology for determination of the numerical concentration of asbestos fibers in ambient atmospheres by a direct method was sponsored by the EPA (Samudra et al. 1977). This methodology recommended air sampling using a 0.4 µm pore size polycarbonate filter and preparation of TEM specimen grids by carbon coating, followed by chloroform extraction to remove the filter polymer. The Samudra methodology was revised shortly after it was issued (Samudra et al. 1978), and later evaluated under EPA sponsorship, resulting in a revised draft methodology (Yamate et al. 1984). The Yamate draft method incorporated into the fiber-counting criteria the concept of "asbestos structures," in recognition of the fact that airborne asbestos is frequently present as clusters, or aggregates with other types of particulate, rather than as single fibers. Yamate specified that these different types of structures be counted separately, and procedures were defined for calculation of the asbestos fiber mass. Unfortunately, in most circumstances, these mass calculations are imprecise because most of the mass of asbestos is usually contributed by a few large asbestos-containing structures which are difficult, or impossible, to measure. The Yamate Draft Interim Method became the de facto standard analytical TEM procedure for airborne measurements in the United States, but was never formally advanced from its draft status by the EPA.

To minimize fiber losses during the acetone membrane-collapsing procedure, a short etching treatment was introduced before carbon coating of the filter (Burdett 1982; Middleton and Jackson 1982; Burdett and Rood 1983b). The procedure published as the NIOSH 7402 method (1986) used the acetone filter-collapsing method, and also incorporated the plasma-etching step, although in the most recent revision of this method (NIOSH 1989) the plasma-etching step has been deleted. The elimination of the plasma-etching step reflects the fact that NIOSH Method 7402 is intended only as a supporting methodology to identify optically-visible fibers found during PCM examinations of filters.

The Asbestos Hazard Emergency Response Act (AHERA) specifies that airborne asbestos concentrations be determined using the TEM at the end of asbestos abatement projects. A standard operating procedure for TEM analyses in connection with research projects on abatement practices was published by Chatfield and Clark (1987). Along with the methodologies of Yamate and colleagues (1984), NIOSH 7402 (1986), and Burdett and Rood (1983a), this standard operating procedure was used as the framework in the development of the TEM methodology to be used in conjunction with AHERA (EPA 1987). The intent of the AHERA methodology was to provide the "least burdensome" TEM analytical procedure for final clearance of asbestos abatement work-sites. In response to the "least burdensome" requirement, a few aspects of the TEM methodology were simplified:

1. A minimum fiber length of 0.5 µm was specified. It had been shown (Steel and Small 1985) that fibers shorter than about 1 µm were overlooked by TEM operators, and in one international interlaboratory exchange it was clear that, left to their own devices with instructions to count all fibers, operators varied in their perception of lower fiber-length limits (Chatfield 1985a).

2. Apart from the ability to discount fibers shorter than 0.5 µm and to specify those longer than 5 µm, there was no requirement for measurement or reporting of fiber dimensions.

3. A minimum value of 0.005 s/mL was specified for the analytical sensitivity. Clearly, virtually any analytical sensitivity can be achieved if sufficient analytical effort is expended, but cost considerations limit the value that can be achieved routinely. Moreover, the direct-transfer analytical protocols can be used only if the sample collection filter has a particulate loading below a specified limit. This analytical sensitivity was considered to represent the optimum combination of feasibility and cost.

4. The fiber-counting criteria were clarified. It was recognized that if abatement site clearance standards were to be set very low, the point at which the individual fibers constituting a cluster or matrix structure were counted individually, or were considered to be a single, complex asbestos structure, could be the determining factor in a site clearance. Accordingly, the fiber-counting rules were specified (arbitrarily) to define the point at which this transition occurs.

As of August 1, 1990, laboratories performing TEM analyses for abatement clearance in U.S. schools must be accredited by the National Voluntary Laboratory Accreditation Program (NVLAP). The NVLAP program (National Institutes of Standards and Technology 1989) specifies extensive quality assurance requirements, such as recording of grid opening map references so that individual grid openings can be relocated and audited, and also specifies a small percentage of verified fiber-counting (Steel and Small 1985). Quality assurance guidelines for TEM asbestos laboratories have been published by the EPA (Chesson and Chatfield 1989).

At the international level, the International Organization for Standardization (ISO), to which the United States is a signatory, has developed a TEM analytical procedure for determination of asbestos in ambient atmospheres (ISO 1989). This method has achieved the status of a Draft Proposal, and is currently undergoing minor revisions prior to submission for approval as a Draft International Standard. This methodology incorporates fiber-counting criteria that attempt to document the nature and sizes of the complex asbestos structures found in air samples, and it also addresses the requirements of several countries in which ambient air standards or guidelines for asbestos in air have been established. The ISO methodology is a direct-transfer TEM preparation procedure, but several countries requested that a separate indirect TEM specimen preparation methodology be developed by the ISO working group, and this is currently being written.

As part of the EPA Superfund method for determining asbestos in ambient air, a methodology has been written to address the analytical requirements for risk estimation (Chatfield and Berman 1989). Because of the very low numbers of long fibers found in ambient atmospheres, and the requirements to provide statistically valid fiber counts at these very low concentrations, the methodology incorporates indirect procedures for TEM specimen preparation. The methodology also incorporates fiber-counting criteria very similar to those specified by the ISO method.

Comparison of Direct and Indirect Transmission Electron Microscopy Analysis Protocols

Indirect analysis differs from direct analysis, in that some additional manipulations are carried out during the indirect sample preparation. These manipulations usually involve the sample collection filter being ashed and the residue redispersed in a liquid. Several aliquots may then be withdrawn and filtered to optimize the particulate loading for the TEM analysis. Both direct and indirect methods may transfer the particulates from the filter to an electron transparent carbon film and carry out the counting and identification of the asbestos fibers using identical procedures. The differences between the results obtained from the two methods are due to various factors, which are discussed below.

Since the direct preparation methods prepare the TEM grids for analysis directly from the original sample filter, the particulate loading must be adjusted by varying the rate and/or duration of air sampling. Filters with loadings of particulate matter that are acceptable for TEM analysis can be obtained by monitoring the color of the filter. In situations which are important, two or more samples can be collected simultaneously at different flow rates, to give a range of filter loadings. Because the indirect analysis can adjust the particulate loadings during the sample preparation, longer sampling periods can be employed. The indirect method can also be used to concentrate samples or combine several filters, to give a building average based on a single analysis. However, the possibility of contribution of additional debris from filter residue, and the potential for increased contamination must be considered.

The effects of the intermediate sample preparation stages on the particulates collected give rise to much of the difference in the results. In the absence of an overloaded filter or asbestos-containing floor tile debris, the direct method can give asbestos fiber and structure concentrations, as well as size distribution data, which can be considered representative of the aerosol to which the building occupants are exposed. The direct analysis also offers useful additional information about the potential source and state of aggregation of the asbestos fibers and structures.

The indirect method has an advantage in that the very small amounts of asbestos present in environmental samples can be concentrated during the sample preparation by removing the organic and soluble particulates. Additional treatment such as acid washing can be used to remove carbonate particles and other acid-soluble particles (for example, limestone). Thus, greater filter loadings and better analytical sensitivity can be obtained than with the direct analysis, based on the same area being examined during the TEM analysis. The degree to which the sample can be concentrated, depends on the types of particles collected. It is the effects of these additional preparation steps which may remove the matrix material in which the asbestos is embedded or encapsulated, or release asbestos due to mechanical break-up of ACM debris, which result in some of the differences. In addition, depending on the conditions of preparation, indirect methods may result in longitudinal splitting and separation of the chrysotile fibrils; the longitudinal splitting occurs readily in aqueous suspension, particularly if surfactants are used.

In laboratory preparations of pure chrysotile (Chatfield 1983a, 1985a; Burdett 1986e), it has been shown that the effects of indirect preparation on the longitudinal subdivision of long fibers can be minimized so that the important "index of exposure" of PCM-equivalent asbestos fibers can be estimated with less than a factor of two increase. It is not known whether this observation is widely applicable in a variety of occupational and environmental situations, where the asbestos is often present in matrices. However, if it is applicable, it would allow greater flexibility in the long-term sampling of buildings and outdoor environments, and also of short-term peak events (Sébastien et al. 1986; Guillemin et al. 1989; Kohyama 1989).

Data based on laboratory suspensions of pure chrysotile asbestos show that the fiber size distribution may be greatly affected by the indirect preparation procedures. When this occurs, the main effect of the indirect procedure is to greatly increase the number of fibers counted below 2.5 μm in length. The magnitude of this effect depends on the type of asbestos, the nature of the ACMs present, and the nature of the preparation method. Chatfield (1983a) reported a factor of five increase in the total number of fibers. Chatfield (1985a) showed that for pure commercial chrysotile from a vibrating bed generator, fiber counts of structures below 0.5 μm in length increased by a factor of 17 and in the 0.5 to 1.0 μm length range by a factor of 9, but reduced to 1.6 in the 2.5 to 5.0 μm range. Burdett (1986e) used similar samples and found that even when care was taken to minimize the disruption, a factor of six increase in fibers longer than 0.5 μm was possible. Similar increases, using environmental samples collected in mining regions of Quebec, have been reported by Sébastien and colleagues (1984). It is important to note that much larger increases in fiber numbers by the indirect preparation methods will occur across the whole range of fiber lengths if surfactant and strong mechanical agitation treatments are used.

A few studies have made comparisons between the direct and indirect methods using actual building samples. These were recently reviewed by Chesson and associates (1990a), who reported increases in the total numbers of fibers ranging from 3.8 to 1670 times, but who commented that both the analytical protocols and the nature of the asbestos varied within these studies. Only two of the studies reported by Chesson and associates provided fiber size information, but both indicated increases in the numbers of fibers longer than 5 μm when samples were prepared by indirect methods. In the reanalysis of samples from the GSA study (Chesson et al. 1990b), there appeared to be an approximately constant increase in chrysotile structures by a factor of 9-18 times across all lengths. In contrast to the situation for chrysotile, the amphibole asbestos counts did not change. Amphibole fibers have been found to be much less affected by the indirect preparation (Cook and Marklund 1982), but disaggregation of matrices and clusters can occur depending on the type of ACM present.

In air sample filters collected in the ambient environment of building atmospheres, asbestos fibers generally represent only a small proportion of the number of particles present, and are generally found as complex groupings of fibers, bundles, clusters, and matrices associated with particles of other components of the material. Some analysts contend that these factors, as well as the overlapping of fibers by other particles or aggregates, may interfere with the counting, sizing, and identification of fibers, and may, using current counting rules, result in an underestimation of fiber counts. Cherrie and coworkers (1986) and Iles and Johnston (1983) have studied this issue using the PCM. There are insufficient data to estimate the overall impact, or the relative significance of such effects by TEM, particularly in the environment of buildings.

The large increase in fiber numbers, often free of their matrix material, means that identification and counting are simplified by the indirect sample preparation procedures, as compared to the analysis of directly-prepared samples. This effect is significant in buildings, as many of the asbestos structures encountered are asbestos fibers attached to, or embedded in, a matrix or particle. Also, the limit of detection and precision of analysis are considerably improved due to the increase in numbers, as well as the more uniform distribution on the filter, of countable asbestos structures. The precision of counting is also increased due to the greater number of simple fiber structures, whereas the direct method has a much greater percentage of complex multiple fiber structures to classify, and serious biases are introduced due to the limitations of the current counting rules. Because of these factors, indirectly-prepared filters are more likely to have a uniform spatial distribution of fibers. However, the only available analysis of this issue on samples collected in different industrial settings showed that, with sufficient fibers, a direct method gave an adequate approximation to Poisson distribution (Marconi et al. 1983).

Data interpretation is an important issue for mass analysis. The increase in fiber number and the changes to the size distribution resulting from the indirect preparations used, led many of the earlier investigators to report results only in terms of mass concentration. Although low mass detection limits were possible, the large numbers of small fibers dominated the analysis and few, if any, of the asbestos fibers that would be visible by PCM were counted. This would mean that the mass estimates could be a serious under or overestimate based on the chance occurrence of one large fiber in the filter area analyzed by the TEM (Burdett 1982; Chatfield 1986a). This is an even more serious problem in directly-prepared samples. There may be some merit in attempting to examine a greater area of the sample for the relatively few large fibers, to improve the overall precision of the mass analysis.

For both methods, it is important that some realistic calibration and estimate of fiber losses and contamination levels be undertaken. Fiber losses associated with filter collapsing in the direct preparation method have been observed (Chatfield 1983a); such losses can be minimized by a short plasma-etching treatment following filter collapsing (Middleton and Jackson 1982; Burdett and Rood 1983a). If asbestos is attached to or embedded in particles of other materials, and if these other materials are dissolved or oxidized during the specimen preparation, fibers will be released from the particles and counted as larger numbers of separate asbestos structures. Other processes, such as ashing, ultrasonic treatment and aqueous dispersal, may all have effects of the measurement, depending on the nature of the particulate materials, the type of asbestos, and the degree of its subdivision. If care is not taken, any step in TEM specimen preparation procedure may result in failure to transfer fibers efficiently to the TEM specimen grids, or contamination may be introduced (Anderson et al. 1989).

Transmission Electron Microscopy Methodologies as Applied to Building Measurements

Before a TEM methodology for measurement of any airborne fiber species can be designed, the purpose of making the measurement should be clear. If the purpose is for risk estimation, the method should be directed towards precise measurement of the concentration of the range of fiber sizes that are considered to pose the risk. If the purpose is to determine whether *any* fibers of the species are present in the atmosphere, then the method should be directed towards the most sensitive measurement of the fiber species regardless of fiber dimensions. These two goals cannot be achieved in the same measurement, given the extreme complexity of the particulate aerosol dispersion which we are attempting to measure.

In general, a measurement made by direct-transfer methodology is an attempt to examine and describe the airborne particulate *exposure as present in the building air.* A measurement made by the indirect procedure is an attempt to optimize the quantification by manipulating the collected particulates. This makes the asbestos structure concentration and size distribution difficult to interpret, but some authors feel that this may give a more realistic measure of the dose to the lungs because the deposited dust may release fibers when it comes in contact with lung fluids that include surfactants. Indirect procedures can also be seen as an attempt to measure the total amount of airborne asbestos, even if the asbestos structures are nonrespirable or contained in large aggregates. It is hardly surprising, therefore, that the two procedures have sometimes produced results (Chesson et al. 1990a), which are poorly correlated and may produce order of magnitude differences (indirect greater than direct) when examining the same sample.

To a large extent, the purpose and aim of the measurements will determine which method of sample preparation is most applicable. Since for the last 20 years occupational measurements have been analyzed by direct PCM fiber count and all the dose-response data in epidemiological studies is expressed by this "index of exposure", there appears to be some relevance in attempting to continue to measure a similar "index" in buildings. With appropriate laboratory protocols, specimen preparation using the direct methods can be done such that there is minimal effect on collected particulates and the state of particle aggregation, and size distributions are comparable to samples evaluated for occupational hygiene purposes. However, the lower asbestos concentrations and the greater level of aggregation with other particulates observed in building atmospheres as compared with some industrial settings, along with changes in counting rules, may limit the direct comparability of the two methods.

Both direct and indirect sample preparation procedures have been shown to produce nearly equivalent results when used to measure fibers longer than 5 µm in laboratory comparisons of pure chrysotile asbestos fibers (Chatfield 1983a, 1985a; Sébastien et al. 1984; Burdett 1986e). At present, it is unclear whether the same situation exists for the more complex matrices and clusters that are typically released from the ACMs in buildings, as even the most careful treatment will lead to release of fibers from any organic and soluble matrix components. The influence of asbestos fibers released from large nonrespirable particles as a result of the indirect preparation must also be taken into account, as this can be a major reason for differences among samples taken during active disturbance of ACM.

Both methods will be required in future work if the situation in buildings is to be clarified. At present, there is insufficient knowledge to determine which approach gives the most appropriate measure of exposure and lung burden; these areas represent an important topic for research.

4.4.2.5 Automation of Scanning Electron Microscopy/Transmission Electron Microscopy

It is well-recognized that asbestos analysis by SEM or TEM is a labor-intensive task that incorporates elements of operator subjectivity. Accordingly, it is possible that automation of specimen scanning and fiber identification could provide improvements in analysis costs, turnaround time, and data reproducibility. However, automation of this procedure is complex. An automated system must be capable of detecting widely separated asbestos structures among a preponderance of other types of particles, and also provide reliable identification and feature measurement.

Automation of optical and SEM techniques for the analysis of asbestos fibers has been an area of active research and development; Dixon and Taylor (1979), Stott and colleagues (1981), and Kenny (1988), have developed algorithms for this purpose. Of these, none have resulted in widespread routine implementation for the analysis of air samples. NIOSH and HSE use the "Magiscan" to assist with routine PCM counting and quality control standardization (Baron 1987; Kenny 1984; Crawford 1985), although complete automation of this simple procedure has still not been achieved. Several semi-automated SEM and EDXA packages are commercially available.

In the case of TEM analysis of asbestos, the situation is even more complex. In addition to the detection of fibers being a candidate for automation, the collection and interpretation of chemical and structural data after the fiber is detected are amenable to automated techniques. Very little work has been reported in automated detection of asbestos fibers in the TEM, but there has been a substantial amount of instrumental development by manufacturers, permitting automated analysis of the x-ray spectrum and SAED patterns. Although fully-automated asbestos analysis may be technically feasible, substantial research would be needed to develop a system that would function at a low enough cost to be economically viable. This will likely require development of methods for selective concentration of the fibers, as well as more rapid x-ray detection to improve the speed of detection and selection of asbestos structures. Any instrument developed must be able to recognize overlapping, complex structures, as well as isolated fibers.

4.4.2.6 Fiber Alignment and Light Scattering Methods

Nonmicroscopic methods for measurement of asbestos fiber concentrations that have been proposed include electrical or magnetic alignment of fibers, combined with either x-ray diffraction or light scattering.

It was found that the detection limit of x-ray diffraction for chrysotile asbestos can be improved by electrically aligning the fibers before the x-ray measurements are made (Birks et al. 1975). This method was found to have limitations for analysis of environmental samples because at appropriate levels of concentration, the other particles in the sample interfered with the fiber alignment.

High-voltage electrodes are used to align fibers in the fibrous aerosol monitor (FAM) (Lilienfeld et al. 1979), a real-time instrument stated to be capable of counting fibers down to concentrations of 0.0001 f/cc with a 1,000-minute sample. Fibers are rotated by an oscillating electrical field and the scattering pattern from a parallel helium-neon laser is interpreted in term of particle morphology. The instrument development was funded by NIOSH and because it lacked fiber identification capability, it was intended for use in occupational asbestos environments. It has been widely promoted for use in abatement work to monitor airborne fiber concentrations, both inside and outside enclosures. The instrument, in its early format, gave reasonable correlations for experimentally-generated fibrous aerosols but did not always perform well when challenged with different field conditions (Droz 1982; Iles and Shenton-Taylor 1986), and on-site calibration (using the membrane filter in the instrument) against PCM is necessary. Some workers have reported comparable results with PCM (Kohyama 1989). Along with other light-scattering instruments, the FAM has potential for monitoring short-term events and peaks (Guillemin et al. 1989). Further development of the instrument has been recently funded by the EPA, to improve performance and to develop identification capabilities (Lilienfeld and Steg 1990).

A new real-time instrument based on optical diffraction is currently coming into production. In the Fibrous Aerosol Classifier/Tabulator (FACT), fibrous structures are aligned in an electric field and illuminated by a near infrared semiconductor laser. Fibrous structures are then recognized by classification of the optical diffraction pattern obtained from each structure. Currently, no information on the performance of this instrument is available for each situation in which it is used (Dutoit 1982).

Magnetic alignment of fibers in liquid suspension, combined with light scattering techniques, has been shown to provide a useful method of measurement for samples at occupational levels of concentration (Timbrell 1975), and this technique evolved into a production instrument (Gale and Timbrell 1980). Unfortunately, this instrument requires extensive calibration for each situation in which it is used. The magnetic alignment-light scattering technique was further refined for application to environmental asbestos samples (Chatfield and Riis 1982, 1983), and it was found possible to extend its sensitivity down to 0.2 ng of chrysotile. Alignment of fibers by shear forces have been reported by Baron (1983) for the aerosol particle sizer (APS), and in an inertial spectrometer (INSPEC) (Prodi et al. 1982). This method of alignment, followed by electrostatic precipitation onto a glass slide for light-scattering measurements, is the basis for a fiber monitor under development in the United Kingdom (Rood and Walker, 1990).

The fiber alignment methods based on electric fields or aerodynamic effects do not provide an identification of the fiber type. Moreover, calibration against PCM is required for each new monitoring situation. The magnetic alignment methods offer some degree of discrimination between individual fiber types. The dynamic magnetic alignment methods can also provide information on fiber dimensions and aspect ratios (Chatfield and Riis 1982, 1983). However, the presence of clusters, matrices, and other nonasbestos materials will limit the application of the alignment techniques.

4.4.3 Surface Dust Sampling and Analysis

Surface dust analysis can assist in the identification of potential sources of human exposure. The EPA has consistently discouraged airborne measurements of asbestos for building assessment (EPA 1980, 1985c, 1990) in favor of inspection and evaluation. Unfortunately, both the algorithm and decision-tree/bush approaches have been shown to have no meaningful correlation to exposure measurements when tested against extensive airborne monitoring at control sites (Pinchin 1982; Constant et al. 1983; Findley et al. 1983; Guillemin et al. 1989). This has led to the investigation of surface dust as a possible indicator of contaminated buildings.

Surface dust evaluation can play an important role as an indicator of pollution and of the effectiveness of remedial actions. An early example of measurement of settled asbestos dust was the brushing or scraping of dust deposits from the least accessible (and therefore uncleaned) horizontal surfaces, such as roof beams, for microscopical analysis (Drinker and Hatch 1936; Hurlbut and Williams 1935). More recently, the evaluation of relatively small amounts of surface-dust-containing radionuclides (Fish 1967) and the importance of surface cleanliness for microelectronics (Mittal 1979, 1987) have been the subject of large symposia. Literature contributions are also available from aerosol physics, powder technology, forensic science, and microbiology.

Surface dust sampling techniques are still ill-defined, have variable collection efficiency, and are surface-dependent (Sansone 1987). A variety of techniques have been used to sample asbestos-containing surface dust (for example, surface wipes, microvacuuming, tape lift, strippable spray compounds, surface removal for ultrasonic treatment) and have been reviewed by Guth (1988, 1990) and by Burdett and associates (1989a). Sampling surface dust is a particular problem as there is no expectation of uniform dispersion, and many samples must be taken and either separately analyzed or combined in a single analysis. The latter may give misleading results. Sampling efficiencies of several dust collection methods were measured by Olcerst (1988), using neutron-activated chrysotile. This technique, however, provides a mass collection efficiency, and the value cannot be related to the numerical fiber concentrations on the surface being sampled. Based on the application of geostatistical theory, Schnieder and colleagues (1989, 1990) offer a way in which surface dust sampling schemes could be designed, implemented, and interpreted, but the cost of large numbers of analyses may limit any use for asbestos.

Surface dust analysis, at present, is based on interim indirect preparation methods (Clark 1990; ASTM 1990) which Chesson and colleagues (1990a) report to cause increases in the numbers of countable fibers. The number of asbestos fibers liberated depends on the nature of the asbestos material present in the asbestos dust (for example, soluble matrix materials will liberate many more fibers than insoluble matrices). Also, the methodology has not been standardized, and small variations in methodology can give large interlaboratory differences.

4.4.4 Bulk Sampling and Analysis

Bulk specimens (and settled dusts) may be quantitatively characterized for their asbestos content by standard methodologies (EPA 1982) incorporating both x-ray diffraction analysis (XRD) and PLM. Generally, more material is required for XRD analysis than for PLM.

Bulk sampling schemes generally include testing for asbestos content of suspect materials accessible to maintenance personnel; the number, frequency, and timing of samples required depends upon the individual site (see EPA 1980, 1983, 1985a, 1987).

Continuous scan x-ray diffractometry, employing a high-intensity x-ray source, a curved crystal monochrometer, and an interfaced computer with appropriate software for profile search and peak fitting, may generate data that are both accurate and reproducible (Howard 1989). Depending on the fiber type and the matrix materials, asbestos fibers may be detectable down to about 1 percent of the specimen mass (Rohl et al. 1976a, 1977; Davis 1990). The use of the step scan technique, over specific peaks and regions of the pattern, may further increase the detectability in some circumstances to as low as 0.1 percent. However, many of the components common in building materials interfere with the analysis, and extensive specimen preparation may be required in order to obtain reliable results. Moreover, amphibole minerals pose some mutual interferences, and other interfering minerals may give overestimates of the asbestos content (Middleton 1982b; Puledda and Marconi, 1990). It must also be recognized that x-ray diffraction does not discriminate between the asbestos and nonasbestos varieties of the same mineral species.

A microscopist knowledgeable in the principles of optical crystallography, using a research-quality polarized light microscope and suitable immersion oils with known refractive indices, can reliably analyze many types of bulk samples for asbestos (EPA Interim Bulk Method [EPA 1983]; McCrone 1987). There are classes of ACM, however, that are either difficult or impossible to analyze by routine PLM. Many types of texture coat, for example, contain low concentrations of chrysotile comminuted to fiber diameters close to and below optical resolution, and resilient floor tiles may have substantial concentrations of chrysotile not detectable by PLM. For these types of materials, PLM cannot be considered a reliable analytical technique for determination of asbestos. It has been reported that PLM is capable of identifying fibers down to approximately 0.8 µm in diameter (Rooker et al. 1982). Quantification of asbestos content is currently estimated visually (and subjectively) by the microscopist, and/or by point counting, which is now required (NESHAP 1990). Neither of these quantification techniques is satisfactory for low percentage samples, and where accurate quantification is required for these types of samples, alternative techniques, such as gravimetry, must be used. Provided suitable standards are available, x-ray diffraction can sometimes offer a more precise and accurate means of quantification than can currently be achieved by PLM, but this is not necessary for decision-making in the majority of situations.

4.5 Mechanisms of Release

Primary release is a process by which a particle leaves the ACM and becomes airborne. Primary release mechanisms include impact, abrasion, fallout, vibration, air erosion, and fire damage. If the particle settles and then becomes resuspended, it is termed secondary release, and often involves a human activity. In samples taken in unoccupied buildings, or during periods of little activity in occupied buildings, only fallout, vibrational and air erosion releases would normally contribute to airborne levels. In occupied buildings, a combination of primary and secondary release takes place. The greater the level of disturbance of settled dust by building occupants, the greater the component due to secondary release will be.

4.5.1 Primary Releases in Buildings Due to Active Disturbance

Impact and abrasion of accessible ACM have been shown to give increased levels of airborne fibers in many measurements of maintenance activities (for example, Sawyer 1977; Pinchin 1982; Paik et al. 1983; CONSAD 1984, 1985, 1990), removal activities (for example, Ewing and Simpson 1985; Piper et al. 1989; OSHA 1990), building environments (Nicholson et al. 1975; Burdett 1986b; Jaffrey 1988), and laboratory tests (Falgout 1985).

Fallout is a term used to describe a release and the subsequent settling of particles under the force of gravity. Release of single particles occurs when a force greater than the cohesive forces of the matrix is applied. Delamination occurs when the adhesive forces to the substrate are exceeded. Cohesive and adhesive forces for small particles, especially for respirable particles, are quite strong (Walker and Fish 1967).

Over time, general mechanical vibration may overcome the adhesion of the ACM and result in delamination or fallout, but no measurements on the frequency of this event have been documented. In the absence of other, more direct, disturbances, it is doubtful if the normal vibrations of a building structure are sufficient in amplitude or frequency to cause release of a measurable concentration of airborne asbestos fibers from an ACM.

The release of fibers by air erosion at the velocities normally present in buildings has been shown to be minimal, even on friable sprayed surfaces in return-air plenums (Nicholson et al. 1975; Sébastien et al. 1980; Burdett and Jaffrey 1986), at ventilation outlets directed across friable sprayed ACM (Guillemin et al. 1989), and in specific experiments (Burdett 1986b; Keyes and Chesson 1990). The exception to this observation is weathered asbestos cement sheet used on the exterior of buildings, where acid rain can leach away the cement matrix, thus leaving exposed fibers on the surface of the material.

Fire damage is thought to be an infrequent but considerable release mechanism, but this is not well-documented. The occupant exposure is usually limited, unless the building is reoccupied or refitted while still contaminated.

In summary, of the possible primary release mechanisms, the available data suggest that impact and abrasion are likely to be important in the primary release of fibers inside occupied buildings, whereas general mechanical vibration and air erosion do not appear to be important primary release mechanisms.

4.5.2 Releases from External Sources

Asbestos fibers are present at various levels of concentration in many water supplies. These asbestos fibers are often of natural origin, but they may be a consequence of industrial waste discharges into potable water sources. If the pH, alkalinity, and hardness of the water are within specific ranges, asbestos fibers can be released into water supplies as a consequence of leaching of the cement component from the interior of asbestos cement water distribution pipes. For technical reasons, asbestos cement water pipe incorporates a mixture of chrysotile and an amphibole asbestos. The amphibole is usually crocidolite, although some pipe was manufactured using amosite as a replacement for the crocidolite. The majority of asbestos fibers found in water supplies are chrysotile. However, if the waterborne asbestos originates from erosion of the interior of the water pipes, chrysotile may also be accompanied by crocidolite or amosite. The concentrations of asbestos found in water supplies range from 0.1 to 3000 million fibers per liter (f/L) (Cunningham and Pontefract 1971; Kay 1973; Chatfield and Dillon 1978b; Webber et al. 1988). Where significant fiber concentrations were found, the fiber length median was generally between 0.5 µm and 1 µm; fibers longer than 5 µm were also present in the distributions. Accordingly, the aerosolization of water from faucets and showers, or secondary resuspension of deposits remaining after evaporation of water, may give rise to indoor air concentrations of asbestos fibers.

Webber and colleagues (1988) made air measurements in two groups of three residences, one of which had an average waterborne concentration of 24 million f/L, and the other an average of 1.1 million f/L. The mean values from a combination of background, showering, and vacuuming activities showed that houses with the more polluted water supply gave fiber and mass concentrations approximately four times higher (0.12 and 0.037 s/mL, and 1.7 and 0.31 ng/m^3, respectively) than the others.

The release of fibers from external asbestos cement (A/C) products due to weathering can be an important external source of asbestos contamination that can be carried or can infiltrate into the building environment. Nicholson and colleagues (1978, 1979) found that weathered asbestos cement sheet products washed out from gutters and onto walkways were an important source of chrysotile carried by foot or wind into a classroom in Puerto

Rico. Spurny and coworkers (1989) found increased ambient air concentrations in the vicinity of buildings with asbestos cement products on their exterior. Other authors have confirmed this observation (Felbermayer 1983; Poeschal 1984; Brown 1987). Spurny and associates (1988, 1989) summarized the SEM measurements of fibers more than 5 µm long near the surface of asbestos cement (0.5 to 1.0 m). A mean value of 0.00075 f/mL was reported with a range of 0.0002 to 0.0012 f/mL, with approximately 12 percent exceeding 0.001 f/mL. Using a specialized sampling device that fitted on corrugated asbestos cement sheet, emission rates at wind velocities of 2+ 1.2 m/sec were measured on 62 buildings with various grades of weathering; a mean emission level from 200 samples was 14.2×10^6 $f/m^2/hr$, with a range of 0.08 to 225×10^6 $f/m^2/hr$. An estimate of corrosion velocity of asbestos cement sheet due to weathering is 0.024 mm/yr (Spurny 1984), and has led to an estimate of $3g/m^2/year$ for 10^{10} m^2 of European A/C roofing, equivalent to an environmental release of 3×10^4 metric tons per year. The majority of this material would be washed off and become deposited on the adjacent ground or introduced into the waste water system.

Emissions from nearby building demolition, industrial sources, waste sites, naturally-occurring deposits of asbestos-containing rocks, and various other sources may infiltrate into buildings as either dust or suspended particles. In some instances, the building may act as a shield against a polluted outdoor environment.

4.5.3 Secondary Releases to the Building Environment

Sébastien and colleagues (1976, 1980) and Sawyer and Spooner (1978) have discussed the principal mechanisms by which asbestos becomes airborne. In a study of 21 Paris buildings, Sébastien and colleagues (1976, 1980) reported several examples where resuspension of material from horizontal surfaces appeared to be the main source of asbestos pollution and concluded that nonoccupational building environments should be measured under conditions of normal occupation and usage. Sawyer (1977), and an EPA guidance document (Sawyer and Spooner 1978), along with Sébastien and colleagues (1976, 1980) and Nicholson and colleagues (1978), found that the resuspension of settled dust due to maintenance, custodial, and removal activities was a source of elevated concentrations of asbestos. Guillemin and associates (1989) also demonstrated the importance of resuspension by correlating airborne dust levels with floor vibration due to human activities. It has been shown that settled dust can be resuspended by high-velocity air blowers (Karaffa et al. 1986) and by other disturbance methods (Stewart 1984; Prentice and Gonsalves 1985; Burdett and Scott 1988).

4.5.3.1 Resuspension of Surface Dust: Interpretational Considerations

The physics of fiber deposition and resuspension must be understood in order to interpret the relevance of surface dust concentrations. There are many approaches to modelling airborne concentrations from surface dust deposits, but there is little published information to assess the effectiveness of such models. The most common and extreme approach is known as the closed box model, in which the room is regarded as a sealed environment in which all settled dust fibers become instantaneously airborne, and the worst-case instantaneous concentration is calculated (Guth 1990). Various other open systems have been hypothesized and calculations made, but all the models are dependent on the integrity of the surface dust sampling and analysis.

Resuspension of particles is still poorly understood. Bagnold (1960) showed that the cohesive forces between particles below 80 µm are dominant and the adhesive forces between a single particle and the surface are complex and depend on the microscopic, physical, and chemical properties of the particle as well as the humidity (Corn and Stein 1967). Various authors have shown that vibration and air currents normally encountered in buildings are insufficient to resuspend individual dust particles adhering to surfaces (Masironi and Fish 1967; Corn and Stein 1967; Walker and Fish 1967), and physical disturbance by human activity is the dominant method of resuspension in most buildings.

The most direct approach to assessing surface dust is to physically resuspend the material. A worst-case method (Guth 1988; Marshall 1988) would be similar to the aggressive sampling recommended by the EPA (EPA 1985a, 1985b, 1987) at the end of an abatement activity. However, dry sweeping and dusting of surfaces are efficient means to resuspend settled dust. The relationship between airborne and surface dust levels can be investigated by measuring the surface dust asbestos concentration prior to disturbance and then computing the ratio of settled (area) concentration to the disturbed airborne (volume) concentration. This ratio is called the resuspension factor and has units of inverse length (for example, m^{-1}). For asbestos, the resuspension factor is hard to determine because of difficulties in short-term sampling and the interpretation of the analytical results, but the practice has been extensively used in the nuclear industry, where measurements can be easily made (see Sansone 1987 for a summary). Resuspension factors of 10^{-4} to 10^{-6} are common. Only one study in the literature deals with resuspension factors for asbestos (Carter 1970). Values of 1 to 5 x 10^{-3} were found for contaminated clothing and handling contaminated material. A recent EPA experiment (Kominsky et al. 1990) can be interpreted to give resuspension factors of 10^{-4} to 10^{-5} during dry and wet high-efficiency particulate air (HEPA) vacuum cleaning with heavily contaminated carpets. However, interpretation of these studies is complex and, in any case, the results are probably more relevant to operations and maintenance program (O&M) activities (for example, HEPA vacuuming) than to typical activities of regular building occupants.

The contribution of surface dust to the airborne environment from resuspension of settled dust has been carefully reviewed by Sansone (1987), who concluded that the resuspension of surface contamination in a health context is usually of minor, if not negligible, importance. However, in public buildings where low airborne concentrations are found, the relative contribution from surface dust to airborne levels is thought to be significant. Sébastien and colleagues (1980) and Gazzi and Crockford (1987) found that airborne asbestos levels in the same area were higher during occupation as compared to quiescent conditions; nearly all airborne measurements in the literature have been taken during normal occupation and therefore include the contribution from resuspended surface dust. This contribution has been estimated by Guth (1990) to represent less than one percent of the settled dust available for resuspension.

Other than time-activity monitoring, a viable way to examine the effect of human activity on airborne fiber concentrations is to monitor the dust or fiber levels produced using real-time particle or fiber counters while monitoring vibrational disturbances on geophone recorders. Guillemin and associates (1989) found significant increases in monitored particulate matter by the FAM and PCM during periods of activity when compared to inactive periods, but did not show a corresponding increase in TEM asbestos fiber concentrations. Other studies have been reported to detect higher than normal concentrations in areas of exceptional activity, such as band rooms, gymnasiums, and stages in schools (Corn et al. 1991).

4.5.4 Assessment of Potential for Release

Visual inspection techniques have been unsuccessful in predicting airborne concentrations of asbestos fibers (Pinchin 1982; Constant et al. 1983; Findley et al. 1983; Guillemin et al. 1989). The Constant study, in particular, found no correlation with the surveyed parameters, except with a parameter established during data assessment and termed friability/releasability. This has led to further research to determine test methods and to carry out laboratory and field tests to quantitatively measure the friability of spray-applied ACM (Rossiter et al. 1987, 1988). Four parameters were measured (compression/shear, indentation, abrasion, and impact) using a variety of tools (torque screwdriver, penetrometer, and rebound hammer). Other surface releasability field tests have been based on powdering the surface by hand (EPA 1985a). A friable ACM is defined in terms of its releasability as "any material containing more than one percent asbestos by weight that hand pressure can crumble, pulverize, or reduce to powder when dry" (40 CFR 61, Subpart M).

Some limited laboratory experiments have been conducted to measure the releasability of various ACM products when subjected to work activities (Falgout 1985; Burdett and Scott 1988; Jaffrey 1988) such as, sawing, grinding, drilling, and cutting with wheels (Falgout 1985).

4.5.5 Evidence for Past Airborne Release

Other than signs of visible damage to the ACM, the evaluation of past airborne release most often requires the determination of the asbestos content of surface dusts. Interpretation of surface dust measurements is a controversial issue. Some contend that the measurements offer a means of evaluating past airborne concentrations, on the assumption that any asbestos found in surface dust must have originated from long-term settling of emissions from ACM. Others contend that the asbestos found in surface dust may have originated from other sources, including debris left behind after original construction was completed, past uncontrolled maintenance activities, and debris produced by abrasion of asbestos-containing floor tile. Such materials could then be dispersed during normal operation of the building.

Assuming that surfaces in a building are shown to be contaminated by asbestos-containing dust, can this information be used to predict past or future airborne concentrations of asbestos? Clearly, fallout and resuspension of surface dust will be controlled by the type of disturbance, the nature of the dust, and the particle size distribution. Unfortunately, the bulk techniques as practiced, provide a measure of the asbestos content but no indication of the amount that can be inhaled into the lungs. Methods need to be developed that permit extraction of the inspirable fraction of the dust without modification of the associated size or related source information. If this is accomplished, the methods could provide useful data on past releases and some basis for developing indicators of potential release.

Perhaps the most practical method by which evidence of past airborne release can be obtained, would be to use collection devices set out for known time periods, or a measurement of surface concentration separated by known time intervals. There are major problems with either approach, in that sample integrity is almost impossible to maintain. Collection plates cannot be monitored continuously for the required exposure periods of several months, and, thus, they may be subject to either accidental interference or even deliberate sabotage. Analyses of the contents of collection plates are also performed by indirect TEM preparation methods, and such analysis does not provide discrimination between large fragments of ACM and inhalable airborne dust. Wilmoth and colleagues (1988) reported an example showing increased collection with length of exposure. The positioning of the plates can, in principle, allow investigation of specific release or resuspension mechanisms.

4.6 Airborne Asbestos Levels in Nonoccupational Settings

The published literature on TEM airborne asbestos levels is surprisingly sparse, considering the many thousands of unpublished measurements made over the last few years. The interpretation of available data is compromised by several factors:

1. Early measurements were made using indirect methods of TEM specimen preparation, with the intention of reporting results in terms of mass concentrations calculated from fibril and fiber counts. The more recent results have reported concentrations in terms of fiber or structure numbers, and sometimes fibers greater than 5 μm have been separately tabulated.

2. Many of the measurements were made using statistically inappropriate fiber-counting strategies for determination of mass or over 5 μm-long fiber concentrations. Depending on the method of sample preparation, the effect of these inappropriate fiber-counting strategies on the results vary.

3. The results obtained from indirect methods of specimen preparation are usually more sensitive to the presence of asbestos than those from the corresponding direct method. If aggregates or matrices are present that contain asbestos, indirect methods of specimen preparation can cause disintegration of these structures, resulting in large increases in the numbers of short fibers. The observed number of fibers longer than 5 μm generally also increase, but by some smaller proportion. It is unclear whether this increase is due to disintegration of complex structures, the effects of fiber-counting criteria, an improved ability to detect and identify the long fibers because of reduced amounts of debris, or a combination of these factors.

4. Much of the early data are possibly compromised by the sporadic presence of asbestos contamination on unused filters. The indirect analytical procedures that involved filter ashing were particularly prone to introduction of extraneous chrysotile contamination.

5. Fiber-counting criteria and identification procedures have varied among the studies.

6. The analytical sensitivities of indirect samples for fibers over 5 μm long have usually been an order of magnitude above the building and outdoor levels. The results of samples analyzed by the direct method must, in many cases, be pooled to arrive at an analytical sensitivity sufficient to measure prevailing building or background levels. Such pooling assumes that all samples in a building represented the same environment - this assumption may not always be valid.

4.6.1 Background Concentrations of Asbestos

Outdoor ambient concentrations of asbestos fibers can be unambiguously monitored only by analytical TEM, but SEM-EDXA measurements of fibers over 5 μm long have also been included, as there are relatively few measurements of this size of fiber. There are now over 20 published papers in which the authors have specifically attempted to measure asbestos concentrations in the outside ambient air. These studies and their results are tabulated in

Table 4-8. However, many background measurements are also taken indoors and outdoors for comparison with known emission sources, as recommended by the EPA (EPA 1985a, 1985b, 1987). Few of these results have been published, and often, the measurements were not made with sufficient analytical sensitivity. Accordingly, only reports containing data from substantial numbers of background samples, from which a lower overall analytical sensitivity can be calculated, have been included in Table 4-8.

The data in Table 4-8 have been collected for various purposes and cover a range of environments, from remote Pacific islands to urban air levels in the vicinity of spray asbestos application. Also, there are wide variations and limitations in the analytical techniques and analytical sensitivities employed. The problem of asbestos-contaminated membrane filters the media on which many of the samples were collected and prepared, should be recognized (EPA 1986a; Chatfield 1975). Therefore, no attempt has been made at in-depth comparisons among data sets in this overview, and only the generalized trends are discussed. It must be emphasized that the background outdoor concentrations for each building study are important for establishing whether or not the indoor concentrations (reported in sections 4.6.2, Asbestos mass concentration measurements in building atmospheres, and 4.6.3, Numerical Asbestos Fiber Concentrations in Building Atmospheres) are elevated.

As demonstrated by the analysis of Antarctic ice samples by Kohyama (1989), chrysotile asbestos has been a ubiquitous pollutant of the environment at reasonably constant levels for at least the last 10,000 years. Snow sample analysis has shown that outdoor ambient backgrounds in urban areas of Japan are one to two orders of magnitude higher than in rural areas. Chrysotile has also been detected in the Greenland ice cap (Bowes et al. 1977).

Air sampling measurements in rural and urban locations show the same trend. Individual samples from rural or remote locations with no natural asbestos sources rarely exceed asbestos mass concentrations of 1 ng/m^3. Median concentrations are usually 1 or 2 orders of magnitude lower, depending on the numbers of samples and the analytical sensitivity achieved. Rarely are fibers over 5 µm long found in rural environments (Chatfield 1983b), but if they are found, a single fiber will often exceed a mass concentration of 1 ng/m^3. The infrequency of large fibers makes the use of conversion factors between mass and over 5 µm-long fibers inappropriate in remote environments.

Higher levels of airborne asbestos have been reported in urban areas, as there are both greater concentration of ACMs and active mechanisms of release (for example, car brakes and weathered asbestos cement roofing). A greater proportion of the samples exceed 1 ng/m^3; for example, Sébastien and colleagues (1980) found that 25 of 126 measurements (20 percent) in Paris equalled or exceeded 1 ng/m^3. Early measurements in U.S. cities were even higher, with 78.7 percent (100/127 samples) and 67.4 percent (126/187 samples) exceeding 1 ng/m^3 (Nicholson 1971; Nicholson and Pundsack 1973; Nicholson et al. 1978). The higher levels in United States cities have been documented in other mass studies. For example, Constant and associates (1983) found that 44 percent of samples (14/32) exceeded 1 ng/m^3 in samples taken outside schools in Texas. For mass analysis, the number of samples exceeding 1 ng/m^3 appears to be a useful dividing line between rural and urban environments (Nicholson 1971; Nicholson and Pundsack 1973; Nicholson et al. 1978). When assigning polluted mass levels in buildings that exceeded urban backgrounds, Sébastien and coworkers (1980) found that 99 percent of urban Paris measurements were below 7 ng/m^3, and Nicholson and associates (1978) found that 98.5 percent of a set of U.S. urban measurements were below 20 ng/m^3.

Table 4-8. Published Background Concentrations of Asbestos

Environmental Setting	Median of Reported Concentrations[a] (s/L)	Median: PCME (f/mL)	Median: ng/m^3	Range of Reported Concentrations[b] s/L	Range: PCME (f/mL)	Range: ng/m^3	Analytical Sensitivity[c]	Preparation Technique	Reference
Urban environments									
Outside schools	25	0.00005[d]	0.12	0 – 2000	—	0 – 8	—	indirect	Tuckfield et al. 1988
Outside schools	10	0.0003[d]	0.08	0 – 100	0 – 0.008[d]	0 – 0.9	—	indirect	Chesson et al. 1985
Outside schools	4	—	0.02	0 – 10	—	0 – 0.07	—	indirect	Chesson et al. 1986
Outside schools	—	—	0.5	—	—	0 – 100	—	—	Constant et al. 1983
Outside public buildings	< 0.01	—	—	—	—	—	—	direct	Hatfield et al. 1988
Urban	2	< 0.002	0.03	0 – 8	0 – 0.004	0 – 20	2	direct	Chatfield 1983b
Urban Toronto	6	< 0.002[f]	0.07	0 – 45	0 – 0.004[f]	0 – 0.3	2	direct	Chatfield 1983b
Urban Paris	—	—	0.4	—	—	0.1 – 9	—	indirect	Sébastien et al. 1979
Urban	—	—	1	—	—	1 – 10	—	—	Nicholson et al. 1979
Urban	—	—	—	0 – 10[g]	—	—	—	—	Steen et al. 1983
New York	—	—	10	—	—	0 – 100	—	—	Nicholson et al. 1971
U.S. cities	—	—	1	—	—	0 – 50	—	—	Nicholson et al. 1975
U.S. cities	—	—	3	—	—	0 – 15	—	—	EPA 1974
Canadian cities	—	0.0007[f,h]	—	—	0.0006 – 0.0009[f,i]	—	—	indirect	Sebastien et al. 1986
Canadian cities	—	0.0001[f,h]	1[h]	—	0 – 0.003[f]	0 – 6	—	—	Nicholson 1988
English cities	—	—	—	—	—	0.1 – 1	—	—	Rickards 1972, 1973
German cities	3[e]	—	—	0 – 10	—	—	—	—	Friedrichs et al. 1983
Urban Switzerland	—	0.0004[f,h]	0.75[f,h]	—	—	—	—	—	Litistorf et al. 1985
Upwind of asbestos plants	0.2	—	0.03	0 – 11	—	0 – 170	0.3	—	John et al. 1976a
Urban England	—	—	< 1	—	—	< 1	< 1	direct	Burdett et al. 1984

Table 4-8 (Continued). Published Background Concentrations of Asbestos

Environmental Setting	Median of Reported Concentrations[a]			Range of Reported Concentrations[b]			Analytical Sensitivity[c]	Preparation Technique	Reference
	(s/L)	PCME (f/mL)	ng/m³	s/L	PCME (f/mL)	ng/m³			
Urban traffic and braking site 1	4.0[h]	0.0004[f,h]	—	< 2 – 31.7	—	—	0.05 0.00005	direct	Jaffrey 1990
Urban traffic and braking site 1	—	—	2[h]	—	—	1 – 8	0.1	indirect	Burdett et al. 1984
Urban traffic and braking site 2	0.5[h]	0.00016[f,h]	—	—	0 – 0.00016[f,h]	—	0.00008	direct	Jaffrey 1989
Residential Japan	19.8	—	0.23	< 4 – 111	—	< 0.02 – 9.89	—	indirect	Kohyama 1989
Industrial area Japan	14.0	—	0.18	< 4 – 91	—	< 0.02 – 10	—	indirect	Kohyama 1989
Urban U.S.: 70 school sites	2[h]	0[h]	0.1[h]	0 8.6[j]	0	0 – 0.39[j]	—	direct	Corn et al. 1991
Rural environments									
Agricultural Japan	21.8	—	0.17	7 – 47	—	0.08 – 0.29	—	indirect	Kohyama 1989
Rural England	—	—	< 1	—	—	< 1	—	—	Burdett et al. 1984
Upwind background England (2 sites)	—	—	< 1 4[h]	—	—	< 1 3 – 5	—	—	Burdett et al. 1984
Suburban	0.6	< 0.0006[d]	0.003	0 – 6	0 – 0.0002	0 – 9	0.6	indirect	Chatfield 1983
Remote	< 0.4	< 0.0004	-	0 – 0.4	< 0.0004	0 – 0.008	0.4	direct	Chatfield 1983
Remote	—	—	0.03	—	—	0.1 – 2	—	—	Sébastien 1985
Remote	—	—	—	0.03 – 0.9	—	—	—	direct	Spurny and Stöber 1978
Rural Ontario	2	< 0.002[f]	0.002	0 – 30	< 0.002[f]	0 – 0.2	2	direct	Chatfield 1983
Rural	—	—	—	0 – 0.3[g]	—	—	—	—	Steen et al. 1983
Rural Austria	—	< 0.0001[f,h]	—	—	—	—	—	—	Felbermeyer 1983

Table 4-8 (Continued). Published Background Concentrations of Asbestos

Source: Adapted from Berman and Chatfield (1989).

[a] Values represent estimated medians for the range of concentrations reported in the study. In some cases, values represent the median of a range of averages. In other cases, only mean values could be derived.

[b] The lowest and highest values reported in each study are shown as the range of reported concentrations. In some cases, the values represent a range of averages from multiple locations.

[c] Values are estimated averages of the analytical sensitivities reported for each measurement in the study.

[d] Based on PCM analyses rather than TEM analyses.

[e] Values derived from a single measurement.

[f] Total structures greater than 5 µm rather than PCM equivalent structures.

[g] Values are estimated values.

[h] Values are the mean of a range of concentrations, not the median.

[i] Range of means of multiple samples from several locations.

[j] This represents the 95th percentile.

Higher measurements in urban backgrounds have been associated with local sources, such as the spraying of asbestos insulation in a study in New York City (Nicholson et al. 1971), the possible releases from car braking (Lynch 1968; Murchio et al. 1973; Alste et al. 1976; Sébastien et al. 1976; Bruckman and Rubino 1978; Teichert 1982; Williams and Muhlbaier 1982; Chatfield 1983b; Baxter et al. 1984; Burdett et al. 1984; Kohyama 1989; Jaffrey 1990), the releases from A/C cladding (Spurny 1989; Spurny et al. 1989), and demolition (Wilmoth et al. 1991a,b). Other more obvious sources such as mining (John et al. 1976a; Sébastien et al. 1986; Kohyama 1989), manufacturing facilities (Rickards 1972, 1973; Sébastien et al. 1980; Burdett et al. 1984, Marfels et al. 1984; Kohyama 1989), the release from local rocks or crushed aggregate (John et al. 1976b; Rohl et al. 1977; Cooper et al. 1979) and from waste sites (Burdett et al. 1984) have also given localized increases in both urban and rural environments.

Some of the higher urban background levels were reported by Sébastien and colleagues (1986). As a part of a longer study to monitor airborne asbestos levels at several locations in Canada, the authors obtained successive 4-week samples over a year in Montreal and in a rural (non-mining) area. The 10 samples collected in Montreal gave results, using an indirect preparation method, from below the analytical sensitivity (< 0.0005 f/mL) to 0.0057 f/mL; the mean value was 0.0012 f/mL and the median was 0.0011 f/mL. The nine samples collected at the rural site gave a mean of 0.0006 f/mL and a median below the analytical sensitivity. It is not known whether the measurements reported by Sébastien and associates (1986) were high due to limitations of the analytical sensitivity, or whether the unusually long sampling time had recorded peak events; however, peak events would not be expected to occur in rural areas. Unfortunately, no blank counts were reported to assess whether or not the reported levels were statistically significant.

SEM measurements of urban backgrounds reported by Rödelsperger and associates (1989) found 48 possible asbestos fibers longer than 5 µm in 155 ambient measurements. This gave average concentrations of between 0.000013 and 0.00011 f/mL in large cities, based on measurements by three laboratories.

More recent measurements by direct methods appear to give lower levels of all asbestos structures (Table 4-8). Many of these studies reported median rather than mean concentrations, with a range of median values of 0.01 to 6 s/L, compared with 4 to 25 s/L by indirect methods.

In contrast to chrysotile, the presence of commercial amphibole fibers in rural or urban samples is extremely rare and is usually a sign that some specific local source or laboratory contamination is present.

4.6.2 Asbestos Mass Concentration Measurements in Building Atmospheres

Risk assessments based on extrapolations from occupational data to measured mass concentrations in buildings (EPA 1980, 1986b; U.S. Consumer Products Safety Commission [CPSC] 1983; National Research Council [NRC] 1984) were used as the rationale for promoting a series of guidance documents and information activities, which culminated in the passage of the AHERA in 1986. These mass concentration studies were reviewed in detail by the NRC (1984) (see also Table 4-9).

Table 4-9. Summary of Transmission Electron Microscopy Airborne Asbestos Mass Concentrations in Buildings[a]

Sample Set	Collection Period Site Classification	Number of Samples/ Method of Analysis	Arithmetic Mean Concentration[b] (ng/m³)	Median Concentration (ng/m³)	References
U.S. buildings with friable asbestos in plenums or as surfacing materials	1974	54 Indirect	48C	19.2C	Nicholson et al. 1975, 1976
U.S. buildings with cementitious asbestos material in plenums or as surfacing materials	1974	28 Indirect	15C	7.9C	Nicholson et al. 1975, 1976
New Jersey schools with damaged asbestos surfacing materials in pupil use areas	1977	27 Indirect	217C	121.5C	Nicholson et al. 1978, 1979
Buildings with asbestos materials in Paris, France	1976 – 1977	135 Indirect	35 (25C, 10A)	1.8	Sébastien et al. 1980
U.S. school rooms/areas with undamaged asbestos surfacing material	1980 – 1981	54 Indirect	183 (179C, 4A)	62.5	Constant et al. 1983
U.S. school rooms/areas in buildings without asbestos surfacing material	1980 – 1981	31 Indirect	61 (53C, 8A)	16.3	Constant et al. 1983
Ontario schools with asbestos surfacing materials	1982	63 Direct	2.1	—	Pinchin 1982; Ontario Royal Commission 1984
Ontario office and school buildings with asbestos	1977 – 1982	55 Direct	1.1[c]	—	Chatfield 1986c
4 schools prior to removal (acoustic plaster)	1983 Asbestos (Nonasbestos)	13 (4) Indirect	0.05C (0.45C)	0.3C (0.095C)	Chesson et al. 1984
2 schools prior to encapsulation (sprayed friable ACM on ceiling)	1984 painted unpainted no ACM	14 9 3 Indirect	24.4 18.5 1.2	6.7 2.7 1.2	Chesson et al. 1986

Table 4-9 (Continued). Summary of Transmission Electron Microscopy Airborne Asbestos Mass Concentrations in Buildings[a]

Sample Set	Collection Period Site Classification	Number of Samples/ Method of Analysis	Arithmetic Mean Concentration[b] (ng/m³)	Median Concentration (ng/m³)	References
U.K. schools, laboratories and factories with sprayed ACM	1983 – 1985	114 Direct	1.5		Burdett and Jaffrey 1986
6 suburban U.S. schools prior to removal	1985 Asbestos (Nonasbestos)	26 (6) Indirect	33.6C (57.0C)	22.2C (11.3C)	Tuckfield et al. 1988
6 Swiss buildings with unknown types of ACM	1987	7 Indirect	19.3	2.1	Guillemin et al. 1989

[a] Source: Adapted from Nicholson (1989).

[b] C = chrysotile; A = amphibole.

[c] Two further samples had concentrations of 640 and 360 ng/m³, the latter being from a single fiber, giving an arithmetic mean of 18.6 ng/m³.

4.6.2.1 Early U.S. Studies in Buildings

Sawyer and Spooner (1978) reported three results averaging 79 ng/m³ (range 40 to 110) in an office building with ceiling material containing 18 percent chrysotile; they also reported measurements between 2.5 and 200 ng/m³ in an unspecified number of New York office buildings with asbestos in ventilation systems. Custodial activity at a school gave two measurements of 186 and 1100 ng/m³, and heavy housekeeping in an apartment building gave a single measurement of 296 ng/m³. No outside ambient samples were reported for these sites.

A more extensive series of TEM measurements of asbestos mass concentrations by Nicholson and coworkers were summarized in the NRC (1984) report, and more recently again by Nicholson (1989) (see also Table 4-9). The latter summary is given below:

> "Most of the earlier studies focused on the potentially more severe exposures and were thus not representative of all building circumstances. In other studies, buildings were also chosen for sampling by nonrandom criteria and similarly do not provide a representative sample of all buildings. Overall, the studies present a reasonably consistent picture. In buildings with evidence of severe damage or deterioration, the probability of detecting contamination was high. On the other hand, if the surfacing material or thermal insulation was undamaged, had suffered only minor damage or the surface had been sealed to prevent dusting, excess air concentrations were rarely detected.

"Nicholson and coworkers (1975, 1976) analyzed 116 samples of indoor and outdoor air collected in and around 19 commercial and public buildings in 5 U.S. cities. The buildings studied were chosen by local or federal air pollution control agencies solely on the basis of ease of access (they belonged to the Government or the owners were willing to allow the tests to be carried out). The choice was thus not random, but neither was any building selected because of a perceived hazard. After collection, the samples were coded by the EPA so that the sites from which they were collected were not known when they were analyzed. The results provided no evidence of contamination of buildings with cementitious or plaster-like surfacing material, but the air concentrations in some buildings with surfacing material consisting of a loosely bonded mat were greater than those of control samples and samples collected in buildings with cementitious/plaster material. In this set of samples, and that considered below, open-face filters were utilized. The possibility that some nonrespirable asbestos material contributed to the mass cannot be excluded.

"Nicholson and colleagues (1978, 1979a) collected 25 samples in primary and secondary schools. The sampling was conducted so as to reflect the general ambient background of schools with substantially damaged surfacing material. Sample collection was observed in order to ensure that the material collected did not reflect an unusual release of fibers near the sampler. However, the schools were in operation during the sampling and normal student activity (except for vandalism) took place during the course of sampling. Two short-term samples of custodial sweeping showed even higher concentrations than those listed, but the results were uncertain because of low sample volume." (p. 248)

The results from the 25 school samples referred to above (Nicholson et al. 1978, 1979a) were from 10 schools selected primarily for visible damage of the asbestos surface. The study of 19 buildings (Nicholson et al. 1975, 1976) showed that the average levels exceeded the authors' criteria for polluted level (20 ng/m^3) in seven of the buildings, but two of these also had high outside ambient levels. Significantly, about half (47 percent) of the friable sprayed sites were above the polluted level. Cementitious sprayed sites had only 10 percent of samples above the polluted level, which was similar to ambient levels outside the buildings (14 percent exceeded the polluted level).

4.6.2.2 Review of Paris Buildings

Sébastien and associates (1976, 1980) reported results from 21 Paris buildings (Table 4-9). It is important to note that all monitoring took place after written enquiries from building owners were submitted to the Paris Authority. The authors note that: "The buildings were not chosen by statistically representative random sampling. The results have been analyzed retrospectively."

Degradation of the asbestos material was often apparent, or the buildings had been recently sprayed with asbestos, and the simplified treatment of the data set (for example, survey averages and cumulative frequency distributions) overlooks some important points. For example, 66 of the 132 samples from buildings with sprayed asbestos were taken in one building (A), where severe degradation of the friable sprayed asbestos was present in parts of the building, with minimal ventilation. A remarkable lowering of measured levels (below background) was found upon monitoring specific sites before, and two years after, protection of the sprayed material by a layer of plaster, followed by cleanup. Values dropped from 751 ng/m^3 to 1 ng/m^3, and from 518 ng/m^3 to 0.1 ng/m^3 after the work was done, even though the original material was still in place. Detailed inspection of the data reported by Sébastien and colleagues (1980) suggests that, of all the buildings without substantial visual degradation of the ACM or recent (under 2 years) spraying with asbestos, only one building exceeded the outdoor ambient "polluted" level of 7 ng/m^3 (this excludes a railway station where frequent braking would be expected to elevate asbestos levels).

Sixteen samples were taken from seven control buildings with no asbestos, and 19 ambient samples were taken outside 10 of the asbestos-containing buildings. Both groups also had one measurement above 7 ng/m^3.

Sébastien and colleagues (1979) updated the earlier study, reporting a total of 158 samples in 33 buildings sprayed with ACM and 33 samples in 10 control buildings. It is difficult to tell which buildings were new, as only the maximum result was reported for each building. Of the 33 ACM-sprayed buildings, 26 had fewer than five samples taken (usually with five days of continuous sampling). Approximately one-third of the buildings (10/33) had a maximum concentration of under 7 ng/m^3. Nine of the 10 control buildings had maximum concentrations under 7 ng/m^3. Several building characteristics were compared with the measured levels. Considering greater than 7 ng/m^3 as the criterion for a "polluted" building, damaged sprayed-on material was highly indicative of giving at least one sample above the "polluted" level (11 out of 12 buildings), whereas only 11 of the 21 buildings with no visible damage to the spray coating gave at least one sample above the "polluted" level. There was also a high probability of finding a building polluted if the coatings were accessible (nine of the nine polluted buildings). It should be noted that many of the buildings had sprayed friable crocidolite or amosite. Such amphibole fibers exhibit a larger range of fiber diameters than chrysotile fibers, and would tend to reduce the statistical reliability of mass concentrations.

4.6.2.3 Review of the Constant Study

The study by Constant and associates (1983) was the first statistically-designed study to measure asbestos levels in buildings. However, there was still a degree of selection, in that the schools were from the Houston district only, and emphasis was placed on areas where occupation was greatest and where levels of activity were higher. Teachers' areas, mechanical rooms, boiler rooms, and rest rooms were excluded from the study. Samples were collected from areas previously selected in the survey design stage. Bulk samples were also collected to confirm the asbestos type present, and the area was scored by a team of assessors using the EPA Algorithm. There were 25 schools studied, all of which contained ACM. Within these schools, 48 sites were sampled in rooms with ACM. None of these sites had severe damage to the ACM, 16 sample sites had moderate damage, and 32 sample sites had no damage. Many of these areas had ceiling insulation which was thought to be rarely accessible and often nonfriable. In addition, there were 19 indoor control sample sites in rooms without ACM, and 25 ambient outdoor sample sites.

The airborne concentrations of chrysotile were elevated in rooms with ACM (arithmetic mean [AM] = 179.5 ng/m^3) and at the indoor control sites (AM = 53.1 ng/m^3), compared to the outside ambient atmosphere (AM = 6.1 ng/m^3). The median values for chrysotile were 92.7 at ACM sites, 21.8 at control sites, and 0.9 ng/m^3 outdoors. These values are higher than those quoted subsequently by the NRC (1984) and Nicholson (1989); the reason for this difference is not known.

The interpretation of these data is complicated by the possibility that some samples were vandalized. Vandalism of the equipment was mentioned several times in the Constant study. Subsequent analysis of some samples by direct methods (Burdett 1986e; Lee 1987; Chesson et al. 1990a), while verifying that considerable concentrations of asbestos were present, also gave evidence of very large matrices and pieces of ACM, inconsistent with airborne deposition, on several indoor samples. The samples taken were unattended during school hours for five days. Considering that there was relatively little damage to the ACM in these schools, this report is atypical of the earlier mass concentration data. The ambient outdoor background average was higher than that found in Paris (AM 6.1 ng/m^3 compared to 0.96 ng/m^3). However, it is unlikely that the tampering could account for the large number of sites with elevated concentrations, and some other source or laboratory artifact may have contributed to the elevated levels of asbestos.

4.6.2.4 Other Mass Measurements in Buildings by Indirect Methods

Bruckman (1979) reported levels of under 1 ng/m^3 from four air samples collected in an indoor swimming pool covered with a ceiling sprayed with friable ACM. Bozzelli and Russell (1982) found average levels of 24 ng/m^3 in three U.S. schools (range 5 to 39 ng/m^3) prior to removal of the friable spray. LeGuen and Burdett (1981), in a survey of 10 public and private buildings, measured mass concentrations of below the LOD for TEM analysis (< 1 ng/m^3) at three sites and below the detection of a SEM (< 10 ng/m^3) and an x-ray diffraction (< 1,000 ng/m^3) method at all the other sites. Sébastien and colleagues (1982) reported a case of apparent chrysotile release from asbestos-containing floor tile; measurements at four sites were reported as 8, 21, 25, and 170 ng/m^3. The six-floor, 5400 m^2, building was originally investigated for emissions from friable sprayed crocidolite, and the corresponding measurements for crocidolite were 0.2, 0.5, 0.9, and 33 ng/m^3. Dufour (1984) reported results from buildings containing vinyl asbestos floor tile and found at least one measurement over 7 ng/m^3 in nine of the 15 buildings sampled (some buildings also contained friable sprayed ACM containing chrysotile). Three EPA studies of the effectiveness of remediation reported results prior to work, under normal occupation. Chesson and colleagues (1985) reported levels from 24 sites in 4 schools with sprayed acoustic plaster. The concentrations in rooms with ACM were 0.1 to 0.4 ng/m^3, lower than those found in control rooms and outdoors. A second study in one school (Chesson et al. 1986) reported geometric mean concentrations of 6.7, 2.7, and 1.2 ng/m^3 for rooms with unpainted, painted and no ACM, respectively. Tuckfield and associates (1988) measured levels in six schools prior to removal of asbestos and reported an arithmetic mean concentration of 39.7 ng/m^3, with a range of 15.4 to 60.9 ng/m^3 (geometric mean = 22.2 ng/m^3) (see Chapter 5 for a more extensive discussion of this study).

4.6.2.5 Mass Measurements By Direct Transmission Electron Microscopy Methods

Mass concentrations of asbestos in buildings have also been determined by direct analysis. Although the methods are designed to measure the fiber number, the mass has often been calculated for comparison with the earlier indirect mass evaluations. However, mass measurements made by direct transfer methods may be less precise for a variety of reasons. In many cases, the mass values reported in the studies discussed in this section may be on the basis of only one fiber. In addition, many of the structures found are complex, and much of the asbestos in complex structures cannot be seen in the TEM.

The work of Pinchin (1982) was summarized by the report of the Ontario Royal Commission (ORC 1984) where 63 samples from 19 Canadian schools with asbestos surfacing material had an average concentration of less than 1 ng/m^3 (range: not detected [ND] to 11.0 ng/m^3). Inspection of these buildings showed that there were minimal problems in all but six buildings, and no correlation was found with a variety of algorithms tested. Chatfield (1986c) summarized measurements from a number of studies. In a 44-floor office building with sprayed chrysotile/mineral wool on the underside of the floors and the steel structure, 12 of the 13 indoor samples were below the analytical sensitivity or less than 1 ng/m^3; a single fiber in one sample gave a level of 126 ng/m^3. On resampling 5 years later, all 15 samples were below the analytical sensitivity or less than 1 ng/m^3. In a further study, a 55-floor office building gave levels of less than 1 ng/m^3, except in an area undergoing cable installation, which was described as a "construction area" in the original publication (Chatfield, personal communication 1991), where a mass concentration of 103.2 ng/m^3 was obtained. Concentrations of asbestos monitored in 2 schools and 2 colleges were generally higher than those reported in other buildings, with 11 of the 21 samples exceeding 1 ng/m^3.

Burdett and Jaffrey (1986) reported mass concentration measurements from a subset of building containing sprayed/trowelled asbestos insulation. Additional data from this study were provided to the Panel by Dr. Burdett and analyzed for this report. Twelve buildings with a total of 122 samples gave a range of arithmetic mean building concentrations of less than 0.1 to 15 ng/m^3, with seven buildings (58 percent) and approximately 90 percent of samples below 1 ng/m^3. Although mass was not reported in the study of public buildings by Hatfield and associates (1988), the low numbers of asbestos fibers detected in the study of 49 buildings suggest that mass concentrations were low as well.

4.6.3 Numerical Asbestos Fiber Concentrations in Building Atmospheres

The available literature on the numerical concentrations of airborne asbestos fibers in building atmospheres consists of seven reports. The studies are reviewed in section 4.6.3.1, with the aim of describing the purpose or design of the survey, the analytical sensitivities or LOD of the measurements made, any bias in the sample design, and any statistically significant differences detected in comparisons with outdoor air and building controls. In addition, the data were critically reviewed to detect whether or not the highest observed concentrations were due to the activities of, or were representative of exposures to, C1 occupants.

There are various differences among the studies in the types of filter media used, the method of preparation, the identification criteria used to classify a particle as asbestos, the size definition of countable fibers (for example, some studies counted all particles of asbestos with substantially parallel sides and aspect ratios 3:1 or greater, while others counted particles of lengths greater than 0.5 µm and with aspect ratios equal to or exceeding 5:1), the counting protocol and definition of bundles and clusters, and the performance of the instrument and analyst. It is normal practice to reduce these errors through quality assurance/ quality control (QA/QC) procedures and inter-laboratory exchanges. When this was done on filters with laboratory dispersions of asbestos, results generally within 95 percent Poisson confidence limits were achieved by Canadian and U.K. laboratories (Burdett 1986e).

The data discussed in section 4.6.3.1 and summarized in Table 4-10 have been collated from various published and unpublished sources; the data and calculation of averages are also discussed in section 4.6.3.4 and Appendix 1. Data are included in tables only where it is known that the TEM specimens were prepared by a direct-transfer procedure. Complete sample information is not available for every study. The concentrations of fibers longer than 5 µm are generally derived from very low fiber counts, and with few exceptions the analytical sensitivities were such that detection of one fiber corresponded to concentrations in the range of 0.0005 to 0.005 f/mL.

Table 4-10. Summary of Building Average Airborne Asbestos Concentrations by Direct Transmission Electron Microscopy Analysis (Nonlitigation)

	Indoor Data					Outdoor Data			
		All Asbestos Structures (s/L)		Asbestos Fibers > 5 μm Long (f/mL)			Mean Concentration		
Site Description	No. of Samples	Range	Mean	Range	Mean	No. of Samples	All Structures (s/L)	Fibers > 5 μm Long (f/mL)	Reference
19 Canadian buildings (mostly schools) with friable sprayed ACM	63	ND[d] – 202	22.1	ND – 0.003	0.00042	0	—	—	Pinchin 1982
2 Ontario high-rise office buildings with ACM	33	5.5 – 48.4	27.0	0.0002 – 0.0065	0.0034[a]	4	ND	ND	Chatfield 1986c
2 Ontario colleges with ACM	7	28.2 – 57.8	43.0	0.0005 – 0.008	0.0043	1	17	ND	Chatfield 1986c
3 Ontario schools with ACM	14	3.7 – 55.2	28.3	ND – 0.0014	0.0006	1	ND	ND	Chatfield 1986c
12 U.K. nonresidential buildings with ACM	96 (all structures) 101 (fibers > 5 μm)	ND – 45	8.2	ND – 0.0017	0.00032	15	1.8	0.00007	Burdett and Jaffrey 1986
3 U.K. residences with ACM	20 (all structures) 36 (fibers > 5 μm)	2.6 – 10.6	6.4	ND – 0.0007	0.0004	2	—	0.0005[b]	Burdett and Jaffrey 1986
24 U.K. buildings (all residential but one) with ACM in warm air heaters	71 (all structures) 79 (fibers > 5 μm)	ND – 7	1.1	ND – 0.0011	0.00021	9	1.7	ND	Burdett and Jaffrey 1986
4 U.K. buildings without ACM	17	ND – 1.3	0.3	ND – 0.0007	0.00018	2	—	ND	Burdett and Jaffrey 1986
11 U.K. buildings with friable sprayed/trowelled ACM[c]	96 (all structures) 117 (fibers > 5 μm)	ND – 45	9.1	0.00003 – 0.0017	0.00040	14	1.5	0.00015	Burdett and Jaffrey 1986
25 U.K. residences with amosite-containing board	25	—	—	ND – 0.0025	0.00030	0	—	—	Gazzi and Crockford 1987
5 U.K. residences without ACM	5	—	—	ND	ND	0	—	—	Gazzi and Crockford 1987

Table 4-10 (Continued). Summary of Building Average Airborne Asbestos Concentrations by Direct Transmission Electron Microscopy Analysis (Nonlitigation)

Site Description	Indoor Data					Outdoor Data			Reference
	No. of Samples	All Asbestos Structures (s/L)		Asbestos Fibers > 5 µm Long (f/mL)		No. of Samples	Mean Concentration		
		Range	Mean	Range	Mean		All Structures (s/L)	Fibers > 5 µm Long (f/mL)	
15 San Francisco residences (houses) with ACM	30	ND – 17	4.6	ND	ND	15	4.7	ND	CPSC 1987
15 Cleveland residences (houses) with ACM	30	ND – 13	5.5	ND – 0.002	0.00023	15	6.2	ND	CPSC 1987
15 Philadelphia residences (houses) with ACM	29	ND – 20	4.7	ND – 0.001	0.00007	15	3.7	ND	CPSC 1987
37 public buildings with damaged ACM	256	—	0.73	ND – 0.00056	0.00005	48	0.39	0.00010	Hatfield et al. 1988; Crump and Farrar 1989; Chesson et al. 1990b
6 public buildings with undamaged ACM	42	—	0.59	ND – 0.00028	0.00005				
6 public buildings without ACM	42	—	0.99	ND	ND				
1 office building with ACM	328	—	1.9	—	0.00004	0	—	—	McCrone Environmental Services 1991
19 schools with ACM	269	0.7 – 177	13.9	ND – 0.0016	0.0002	0	—	—	McCrone Environmental Services 1991

[a] Excluding one high sample in a construction area, the mean is 0.0001 fibers/mL.

[b] Some ACM on landing where outdoor sample was collected.

[c] These buildings represent a subgroup from among the 15 U.K. nonresidential and residential buildings in Burdett and Jaffrey (1986).

[d] ND = Not detected.

4.6.3.1 Review of Published Studies

Nonlitigation

The earliest published measurements of numerical asbestos concentrations in building atmospheres appear to be those reported by Pinchin (1982) in a study for the Royal Commission on Matters of Health and Safety Arising from the Use of Asbestos in Ontario (also published by the Ontario Royal Commission 1984). These measurements were made using the direct-transfer TEM methodology. In 19 school buildings containing spray-applied cementitious and friable surface insulation, the concentrations of asbestos fibers of all lengths ranged up to 202 s/L, with 18 of the building averages being above the analytical sensitivity. The concentrations of asbestos fibers longer than 5 µm ranged up to 0.003 f/mL, with only five of the 19 buildings above the analytical sensitivity; the mean building concentration was 0.00042 f/mL. High concentrations of short fibers did not necessarily correlate with those samples in which fibers longer than 5 µm were detected. No details of the building conditions or individual sample results were given, but sampling was generally carried out during normal occupation.

Chatfield (1986c) reported other measurements made in Ontario office, college, and school buildings. The maximum building average concentration of asbestos fibers of all lengths was 58 s/L, and for asbestos fibers longer than 5 µm was 0.008 f/mL. As in the case of the buildings studied by Pinchin, it was usual to detect measurable concentrations of short fibers, but for many of the measurements the concentrations of asbestos fibers longer than 5 µm were below the detection limits. Seven of the samples reported by Chatfield (1986c) were identified in the original publication as being collected in construction areas, but the nature of the construction acitivity is not described. However, the sample with the highest concentration (0.042 f/mL), although identified as a construction sample, was taken during installation of computer cables while normal office activity was going on (Chatfield, personal communication, 1991).

Three samples from a total of 33 (nine percent) taken in high-rise office buildings with friable sprayed asbestos contained at least one fiber longer than 5 µm, but each of these samples were taken while "construction" was ongoing. The average concentration in the high rise buildings was 0.0034 f/mL; excluding the highest sample value, the average became 0.0001 f/mL. From the schools and colleges without specialized disturbances of asbestos, five of 21 samples exceeded 0.001 f/mL (23 percent), but no reason for this was found except that the highest sample, 0.02 f/mL, was taken in a mechanical room/closet. The mean for schools and colleges combined was 0.0021 f/mL for fibers longer than 5 µm; if this one high sample were excluded, the mean would be 0.0008 f/mL. By and large, sampling was done during periods of normal building use and occupation. No fibers were detected in the six outdoor samples collected.

Burdett and Jaffrey (1986) summarized measurements made in 43 buildings in England, 39 of which contained asbestos. The buildings were subdivided into the following categories: nonresidential buildings containing asbestos, residential buildings containing asbestos, buildings with warm air heaters containing asbestos, buildings without asbestos-containing materials, and buildings with sprayed asbestos. The nonresidential buildings studied included offices, laboratories, and factories. Buildings were chosen on the basis of availability and perceived asbestos problems. Whenever possible, a full workday sample was attempted during normal occupation, with multiple-point sampling, using a combination of available pumps in areas with the greatest presence and damage to the asbestos. The lack of standardization of sample volume meant that the analytical sensitivity varied, and building averages were calculated based on the total number of fibers in each building divided by the total volume of air analyzed in that building (see Appendix 1). The range for the individual measurements at each site was also given. This study used a dual analysis method to measure all asbestos structures by scanning ten 100 μm × 100 μm square EM grid openings at a magnification of 17,000, and both asbestos and nonasbestos fibers over 5μm long by scanning 100 grid openings at greater than 1,000 magnification. The highest building average (0.0017 f/mL) was based on data from a school darkroom in which visibly damaged asbestos was present. Three buildings had individual measurements over 0.001 f/mL (based on a LOD of at least four fibers). Nine of the 39 buildings had building averages for all asbestos structures above this LOD.

A study published by Gazzi and Crockford (1987) used similar methods to Burdett and Jaffrey (1986) but chose buildings from among a well-defined population of 1400 residential apartments in the United Kingdom. There were amosite-containing insulation boards in airing cupboards (heated cupboards in which linen is stored to prevent it from becoming damp) and over a service duct inside each apartment. The panels on the floor of the warm air cupboard formed a return air plenum for the warm air heating. Single samples were collected in 25 occupied apartments for either an eight-hour period during the day or a 16-hour period at night, at rates of 10 and 5 L/minute, respectively. No statistical survey design was mentioned other than that larger apartments (that is, four bedrooms with children) were chosen in an effort to sample maximum activity levels. Nineteen apartments were at or below the analytical sensitivity (1 fiber counted) and the two highest values found were 0.0025 and 0.0019 f/mL (no explanation for the higher concentrations was given). All other measurements were below 0.001 f/mL, with less than four fibers counted. The samplers were left unsupervised during the sampling. The authors found that the measurements just failed to reach the commonly accepted level of statistical significance, but felt that the amosite fibers detected were indicative of releases above the background and would have been significant had the study population been larger. No measurements of all sizes of asbestos structures were made.

An EPA study of 49 General Services Administration buildings (often referred to as the GSA study) has been reported by a number of authors (Hatfield et al. 1988; Crump and Farrar 1989; Chesson et al. 1990b). The survey used a random design, but the buildings were limited to the GSA building stock and the study was stratified to measure 37 buildings containing friable damaged ACM, 6 buildings with friable ACM in good condition, and 6 buildings with no friable ACM. Fifteen buildings had only asbestos-containing thermal system insulation, one building contained only surfacing materials, and 28 buildings contained both. Seven locations (two samples per location with volumes of 5 and 2.5 m^3) were monitored inside, and one location was monitored outside each building. Sampling was conducted over two consecutive eight-hour weekdays with the building occupied. Half of the indoor samples were located near the most damaged ACMs and the rest were located in adjacent public areas. Approximately 75 percent of locations and 40 percent of the indoor samples were in areas normally only accessible to maintenance workers. Nearly all the higher-volume samples were analyzed, with an analytical sensitivity of 0.0013 f/mL or 1.3 s/L for individual samples. Site averages could be obtained with sensitivities of 0.0002 f/mL or 0.2 s/L for each site.

Seven fibers over 5μm long were found in the 387 air samples analyzed (three chrysotile and four amphibole); five were found in buildings and two were found in outdoor samples. An additional four fibers were sized as equal to 5 μm. No samples exceeded 0.001 f/mL, and mean values measured indoors were not significantly different from the outdoor means (Crump and Farrar 1989). The Panel calculated the mean concentrations for fibers longer than 5 μm to be 0.00005, 0.00005, ND, and 0.00010 f/mL in buildings with damaged ACM, buildings with undamaged ACM, buildings without ACM, and outdoors, respectively. Note that the numbers reported here are different from those reported by Crump and Farrar (1989), who reported concentrations for fibers greater than or equal to 5 µm (Crump 1991, personal communication). A greater number of all asbestos structures was present, with the highest number in a single sample of 11, giving a concentration of 33 s/L; this result was recorded in a building with no ACM. The next highest concentration was 13 s/L. There is some debate about whether there were any marginal statistical differences between the total number of asbestos structures found in buildings with ACM and and those found in the outdoor or control buildings (Chesson et al. 1990b; Crump and Farrar 1989).

A stratified subset of 30 of the 406 samples collected in the EPA study of government buildings was later selected for reanalysis by an indirect transfer procedure. Two of these 30 samples were field blanks, and four were outdoor samples. The remainder were randomly selected from interior samples, but the selection was stratified to include samples with a range of reported asbestos structure concentrations. The comparison of these results with those from the original direct-transfer analyses was reported by Chesson and colleagues (1990a). The concentrations of chrysotile structures yielded by the indirect preparation were between nine and 18 times higher for each of the size ranges measured. The results for amphibole fibers did not change significantly between the two preparations. The characteristics of direct and indirect TEM specimen preparation methods are discussed in section 4.4.2.4 (Transmision Electron Microscopy Analytical Methodologies); as discussed there, in comparison with the direct preparation method, higher numbers of fibers are generally reported when samples are analyzed using the indirect method. There are insufficient data to explain fully the differences in results from the two types of preparation and the different asbestos types.

This study was specifically designed to over-sample buildings with damaged ACM (37 out of the total of 49 buildings), creating a possible positive bias with respect to the total population of GSA buildings. In addition, samplers were often located near the most damaged ACM in a building. Many such areas were in mechanical rooms and other rooms not normally accessible to C1 occupants. The level of human activity in such areas was not reported. One possible negative bias is that the GSA had recently introduced a handbook on O&M procedures, but it is not known to what degree these procedures were implemented.

The only study to use indirect methods was that of Guillemin and associates (1989). Nine of the buildings studied contained friable insulation and were investigated by owners, and three were controls with no known ACM. Air samples were examined by PCM, SEM, and TEM, and continuous information was obtained on total fiber levels using a fibrous aerosol monitor. Air samples were collected during normal building daytime activity over periods of one to four days. The analytical sensitivity varied from 0.00006 to 0.008 f/mL. The authors used an indirect TEM specimen preparation published by Steen and colleagues (1983), which is claimed not to affect the numbers of asbestos fibers longer than 5 µm. However, no data were presented to support this claim, and since this method uses both surfactants and ultrasonic treatment, modification of the fiber size distribution and number count would be expected. Different magnifications were used for the TEM analysis on different samples. Thus, this study is difficult to compare with other studies summarized here because of the differences in the analytical methodology. One school gave the highest level of all fibers, but no PCM equivalent fibers, and only one fiber over 5 µm long, were detected. When fibers were measured at high magnification, only one of 327 chrysotile fibers in buildings with friable ACM was over 5 µm long (0.3 percent), but in buildings with no known asbestos source 6 of 132 fibers were over 5 µm long (4.5 percent). In low magnification counts, concentrations of asbestos fibers longer than or equal to 5 µm in buildings varied from 0.00012 to 0.00859 f/mL.

Litigation

Corn and colleagues (1991) recently published a study of 71 school buildings where samples were collected in support of litigation. Sampling took place over two consecutive days to collect a volume of at least 2000 liters of air at each site with the building in normal use. The range of sample volumes was reported to be 600 to 2,500 liters of air, and the average air volume was 1900 liters. This presumably resulted in a range of analytical sensitivity that, although not mentioned, was probably on the order of 0.003 f/mL, or 3 s/L, for each sample and 0.0006 f/mL, or 0.6 s/L, for each site. The samples in the study were selected from a pool of 2,000 samples collected by defendants. One hundred samples were selected at random from Texas schools, and a number of other samples were selected on the basis of specific litigation requirements at other schools. In addition, all personal samples and static samples from gymnasiums and from the four Houston schools used in the Constant study (Constant et al. 1983) were selected for analysis. Additional samples were later selected to ensure that there were five indoor and at least one outdoor sample at every site. The sampling strategy was to collect at least one set of dual samples on polycarbonate and cellulose ester filters at high-, moderate-, and low-activity indoor areas, close to where the ACMs were present and in an area with no ACM. A total of 94 outdoor samples and 51 personal samples were analyzed. There are both positive and negative potential biases to the selection of sites.

Table 4-11. Distribution of Building Average Airborne Asbestos Concentrations for Litigation Data by Building Type

Building Category	No. of Buildings	No. of Samples	Min.	10th Percentile	Median	Mean	90th Percentile	Max.	Outdoor
RJ Lee Group[a]									
School and university	171	1008	0	0	0	0.00011	0.00046	0.0017	0.00004
Public and commercial	50	242	0	0	0	0.00006	0.00012	0.00094	0.00012
Residence	10	10	0	0	0	0	0	0	0.00065
Total	231	1260	0	0	0	0.00010	0.00051	0.00206	0.00006
Corn et al. 1991									
Schools	71	328	0	0	0	0.00024	0.00083	0.0023	0
Crump 1990									
Minnesota University buildings	34	170	—	—	—	0.00003	—	—	—
Maryland public buildings	22	91	—	—	—	0.00009	—	—	—

[a] Data provided by RJ Lee Group, Monroeville, PA.

The average indoor concentration of fibers over 5 µm long indoors, across all 71 schools, was 0.00024 f/mL (Table 4-11). This value was significantly higher than the one obtained outdoors, where no long asbestos fibers were detected, and the concentration was less than 0.000003 f/mL. The average level of PCM-equivalent fibers was 0.00017 f/mL (> 0.2 µm width). Although individual results are not given, a summary table (Table 4; Corn et al. 1991) showed that 5 percent of the mean school indoor concentrations exceeded 0.0014 f/mL, with the highest result being 0.0023 f/mL. In terms of all structures, the average for all schools was 18 s/L for chrysotile and 0.66 s/L for amphibole asbestos, compared to 2 s/L for outdoor asbestos. Maximum building averages were 120 s/L for chrysotile and 4.7 s/L for amphiboles. No significant differences were reported between the concentrations detected using personal samplers and those detected using area samplers. No correlation was observed between asbestos concentration in air and type of ACM present, condition of ACM, accessibility of ACM to students, whether or not ACM was covered, air flow, whether or not sweeping was noted, type of school, and year of construction. Also, no correlation with type of asbestos in air and bulk material was found, but there was a correlation between air concentration and the state in which the school was located.

Crump (1990) summarized data collected in 34 Minnesota university buildings (170 samples) and 22 Maryland public buildings (91 samples). No details were provided, except that the arithmetic mean of asbestos fiber concentrations were 0.00003 and 0.00009 f/mL, respectively, for fibers longer than 5 µm (Table 4-11).

4.6.3.2 Review of Unpublished Data

With a view towards augmenting the information on exposure levels in buildings, the Literature Review Panel made an effort to obtain and review unpublished data.

Nonlitigation

A study of U.S. homes with ACM, conducted by the Consumer Product Safety Commission (CPSC 1987), has not been published except as an internal memorandum, but nevertheless provides a valuable data set, and its results have been widely discussed (Table 4-10). The study did not use a random sampling scheme, and sites were chosen on the basis of consumer complaints. The survey was carried out at three locations: San Francisco, Cleveland, and Philadelphia. Fifteen houses were sampled at each of these locations, with one sample collected in close proximity to the asbestos, one sample collected in the main room where there was the highest level of activity, and one sample collected outdoors. Approximately 3,000 liters of air were collected over three eight-hour, or two 12-hour days, with the aim of sampling only during periods of activity. Samples were collected on polycarbonate filters and were analyzed by the Yamate Level II TEM procedure (Yamate et al. 1984). All sizes of asbestos structures and fibers over 5 µm long were evaluated. Much of the asbestos was present in the form of thermal insulation on heating systems in the basements.

Four fibers longer than 5 µm were found in 89 indoor samples in 45 homes. No fibers longer than 5 µm were found in 45 outdoor samples. The average indoor concentration was 0.0001 f/mL. The results for all structures and for fibers over 5 µm long showed that there were no significant differences between samples taken inside or outside the houses, or by the type of ACM present, or by city. Fiber concentrations at only four sites (1 fiber longer than 5 µm at each site) equalled the analytical sensitivity, but this analytical sensitivity represented sample concentrations ranging from 0.001 to 0.004 f/mL, depending on the volume of air sampled.

An unpublished, large data set on ambient levels of asbestos was made available to HEI-AR by McCrone Environmental Services, Inc. (McCrone Environmental Services, unpublished data, 1991) (Table 4-10). These data were not collected for litigation purposes, as far as the Panel is aware. The results from 19 school buildings with ACM (each sampled once per year in 1985, 1986, and 1987), gave a mean of 0.0002 f/mL for fibers over 5 µm long, with the maximum site average of 0.0016 f/mL. Average results for all asbestos structures were 27.7, 2.9, and 2.8 s/L for 1985, 1986, and 1987, respectively. A single office building containing sprayed ACM in various places, including the return-air plenum, as well as thermal system insulation (some of which had up to 40 percent amosite), was sampled quarterly on nine occasions (total of 328 samples) from 1985 to 1988. The building mean for all fibers over 5 µm long was 0.00004 f/mL. The site average for all structures was 1.9 s/L. All sites had O&M programs in place. Full details of the results will be published by the HEI-AR in a supplement to this report.

Table 4-12. Summary of Average Airborne Concentrations in Buildings Sampled for Litigation Purposes[a]

Building Type	No. of Buildings	No. of Samples	(s/L)	(f/mL)	(ng/m^3)	PCME (f/mL)
School	104	672	52.4	0.0001	3.039	0.0001
University	67	336	6.7	0.0001	1.055	0.0001
Commercial	21	130	1.6	< 0.0001	3.908	< 0.0001
Public	29	112	5.4	0.0001	1.392	< 0.0001
Outdoor	—	597	2	0.0001	0.651	< 0.0001
Residential	10	10	4.9	0	0.359	0
Personal	—	66	10	0.0002	1.028	0.0001

[a] Data provided by RJ Lee Group, Monroeville, PA.

Litigation

A large data set was provided to the Panel by RJLee Group, an analytical laboratory based in Monroeville, PA (Table 4-12). The RJLee Group has analyzed approximately 2,000 air samples from 231 U.S. buildings by TEM. The air samples were collected for defendants in preparation for litigation regarding buildings in which asbestos abatement was alleged to be necessary. Typically, five indoor, two outdoor, and one blank sample were analyzed from each building. The following measures of asbestos in air concentrations were considered: total asbestos structures (EPA level II); mass (ng/m^3) for total asbestos structures; structures/mL of 5 µm or longer; and structures/mL of 5 µm or longer with a width of at least 0.25 µm (optical equivalent structures) (see Table 4-12). No analysis of the data was attempted based on product type, age of building, location within building, or other factors.

The data from schools in the RJLee data set included about 70 percent of the samples whose analysis was summarized by Corn and associates (1991). The RJLee Group has also performed the analyses of samples for another recent study, the EPA GSA study (Hatfield et al. 1988; Crump and Farrar 1989; Chesson et al. 1990a); the results of this study are not included in the RJLee data set.

The results of the RJLee Group analyses are presented in Table 4-12. For all indoor air samples, the average was 27 s/L, and 0.0001 f/mL greater than or equal to 5 µm. Ninety-seven percent of all structures found were chrysotile (8,289 chrysotile and 205 amphibole). The average concentration of all structures for indoor samples was significantly higher than for outdoor samples, and airborne asbestos concentrations were significantly greater in schools and universities than in commercial and public buildings (see Table 4-11). The average levels reported in schools and universities, and in public and commercial buildings, were 0.0001 and 0.00006 f/mL greater than 5 µm, and the 90th percentile values were 0.00046 and 0.00012 f/mL, respectively.

As stated above, HEI-AR will publish the data on the 231 buildings analyzed by the RJLee Group in greater detail in a supplement to this report.

4.6.3.3 Evaluation of Possible Biases in the Data

The nonlitigation studies reviewed above in section 4.6.3.1 represent a total of 1,377 samples in 198 different buildings containing ACM. Slightly over half of the buildings (108) are from the United States, with smaller numbers from Canada (26) and the United Kingdom (64). Forty-eight of the buildings are schools, 96 are residences, and 54 are public or commercial buildings.

A key question regarding these data is whether or not, and to what extent, the concentrations measured can be considered representative of U.S. public, commercial and school buildings. Clearly, the buildings sampled to date do not, in any sense, represent a random sample of U.S. public and commercial buildings. Indeed, only 44 of the 198 buildings fall into that category, and 43 of them are GSA buildings from one study. (There are an additional 10 public and commercial buildings from studies in the United Kingdom and Canada.) Although a wider spectrum pf public and commercial buildings have been surveyed in the United Kingdom (for example, factories, shopping centers, offices, laboratories, large apartment blocks and domestic dwellings) the available data from the U.S. is restricted to offices, which are dominated by a single study (Hatfield et al. 1988) and unpublished data in homes (CPSC 1987).

The Panel evaluated the representativeness issue by categorizing each of the studies as either positive, neutral, or negative with respect to several possible selection biases. The potential biases that were considered included reason for building selection, whether an O&M program was established, the level of maintenance activity observed, the types of ACM in the building, the extent of damage to the ACM, the level of activity during sampling, sampling location, and competence of the analytical laboratory. On each of these issues, a study was considered to be positively biased if the study design favored deriving an estimate of airborne exposure above the true mean of the appropriate building population, and negatively biased if the study design favored deriving an estimate of airborne exposure below the true mean. This evaluation was conducted with the authors of some of the studies present (G.J. Burdett, E.J. Chatfield, R.J. Lee, and W.J. Nicholson). The results of this exercise are tabulated in Table 4-13 and can be summarized as follows:

- Friable sprayed surface treatments, as an ACM type, may be over-represented in the available database.

- Samplers tended to be located in direct proximity to ACM, rather than in building areas thought to be most representative of C1 occupant areas.

- Few buildings were sampled in which significantly damaged ACM was present. While damaged ACM was present in 37 buildings in the GSA study, little or no damage was reported in the remaining published studies. Old, poorly maintained buildings are likely to have been under-represented in the available database.

- Nearly all measurements were made under conditions of normal building occupation; however, it is not known to what degree normal levels of building maintenance or custodial activities are represented.

- At least partial O&M programs were in place at some of the GSA buildings and at all of the McCrone school and office buildings.

- With the exception of a few small studies, the buildings investigated were not randomly selected, and it is not known how representative the studied buildings are of the total population of U.S. buildings. The available studies have focused on office buildings, schools, university buildings, and single-family or multiple-unit residences; other building categories (such as shopping centers, theaters, airports, churches, hospitals, factories) are very poorly represented in the available data.

- For the most part, the data represent the results of sampling at one time or over a relatively short period of time, thus, it is not known how well the available database reflects long-term building exposures.

When all of these issues were considered together, some members of the Panel concluded that a net positive bias may exist in the available data, while others concluded that a net negative bias may exist, with respect to all U.S. buildings. It did not appear that the data possess any systematic bias with respect to the buildings sampled.

For the purposes of this report, it was decided to use the data as they are, with a note of caution that it was not possible from the available information to ascertain whether or not the sampled buildings and sampling conditions are truly representative of U.S. public and commercial buildings as a whole. Recognizing the pivotal importance of more information in this area, HEI-AR plans to sponsor research to assess the U.S. population's (C1 occupants') exposure to indoor airborne asbestos (HEI-AR 1990).

Although a similar evaluation was not done for the mass studies that utilized the indirect method, the description in the text suggests that a positive bias may have been present in building selection, the material type studied (friable sprayed asbestos), and the extent of damage. In the Nicholson (Nicholson et al. 1975, 1976) and Sébastien (Sébastien et al. 1979, 1980) studies using the indirect method, the conditions for asbestos release or resuspension would tend to have favored higher airborne concentrations than the conditions encountered in the surveys using direct analysis.

The data from earlier studies may therefore be representative of buildings that were in poor condition and had not been subject to remediation. The increasing awareness among building owners and employees may have resulted in remediation rather than sampling of deteriorated ACM, and such buildings may not be adequately representative in more recent data. One of the objectives of HEI-AR's call for information in October, 1990 was to allow the opportunity for such cases that have been monitored but unpublished to be brought to the attention of the Panel. As yet, however, there is no data to judge the degree to which conditions monitored some 15 years ago are still prevalent today.

Table 4-13. Estimation of Bias in Direct Transmission Electron Microscopy Studies of Airborne Concentrations in Buildings

Study Bias[a]	Building Selection	O&M	Level of Maintenance Activity	Material Type	Extent of Damage	Activity Level During Sampling	Sampling Location	Sample Period	Building Mean[b]	Percent Not Detected[b]	Maximum Single Sample Value[b]
19 Buildings (Canadian) (Pinchin 1982)	Schools random by uninformed customer concern	No	Unknown	Dry sprayed friable fire-proofing	Unknown	Normal daytime occupation	Random with sprayed asbestos	8 hours	0.00042	67	0.003
Bias rating	0	0	0	+	0	0	0				
2 Ontario highrise offices (Chatfield 1986c)	Uninformed concern	No	Yes, indoor renovation, otherwise normal	Dry sprayed friable fire-proofing	Fall-out debris, none to some	1 Building, 2 weekends; 1 building, normal daytime	Random except 1 sample (×2) random	8 hours	0.0034	91	0.042 (in construction area)
Bias rating	0	0	+	+	+	–	0				
2 Ontario colleges (Chatfield 1986c)	Uninformed concern	No	Normal	Dry sprayed friable fire-proofing	None seen	Normal daytime occupation	Random (1 mechanical room)	8 hours	0.0043	57	0.02 (in mechanical room)
Bias rating	0	0	0	+	–	0	0				
3 Ontario Schools (Chatfield 1986c)	Uninformed concern	No	Normal	Dry sprayed friable fire-proofing	None seen	Normal daytime occupation	Random (1 mechanical room)	8 hours	0.0006	86	0.0042
Bias rating	0	0	0	+	–	0	0				
11 Buildings with sprayed/ trowelled ACM (Burdett and Jaffrey 1986)	Research program as available	No	Normal	Dry spray and cementitious spray	Variable	Normal daytime	Bias towards area of maximum damage	6 to 8 hours	0.00040	—	0.012 (darkroom)
Bias rating	0	0	0	+	0	0	0				
24 Buildings with warm-air heaters (Burdett and Jaffrey 1986)	Research report as available	No	Normal (1 building with heater)	Nonspray various	Low	Normal day	Where ACM was present	4 to 8 hours	0.00021	—	—
Bias rating	0	0	0	+	–	0	0				

Table 4-13 (Continued). Estimation of Bias in Direct Transmission Electron Microscopy Studies of Airborne Concentrations in Buildings

Study Bias[a]	Building Selection	O&M	Level of Maintenance Activity	Material Type	Extent of Damage	Activity Level During Sampling	Sampling Location	Sample Period	Building Mean[b]	Percent Not Detected[b]	Maximum Single Sample Value[b]
25 Apartments with amosite board (Gazzi and Crockford 1987)	High activity flats	No	None	Amosite board	None to little	Normal night, normal day	Next to ACM	8 to 16 hours (4 m^3)	0.00030	52	0.0025
Bias rating	0	0	0		0	0	0				
45 Houses with ACM (CPSC 1987)	Consumer complaints	No	Normal housework	Mainly chrysotile paper and some decorative plaster	None to little	Normal	Next to ACM and in high activity area	3 × 8 hours or 2 × 12 hours (3 m^3)	0.00010	96	0.004
Bias rating	0	0	0	–	0	0	0+				
GSA: 37 buildings with damaged ACM, 6 buildings with undamaged ACM (Hatfield et al. 1988)	Random statified by geography and asbestos contents and condition	In process of imple-menting	Normal	TSI and spray	37 damage 6 non-damage	Normal	Next to ACM or in adjacent high activity area	2 × 8 hours (5 m^3)	0.00005	98	0.0037
Bias rating	+	0–	0	+	+	0	0+				
RJ Lee Group litigation data	Presence of ACM-subset chosen by defendant	A few with O&M	Normal	Varied bias to 50% acoustic spray, 50% fire-proofing spray	Variable	Normal	ACM present stratified by activity	2 × 8 hours (2 m^3)	0.0001	70	0.0047
Bias rating	0–	0–	0		0	0	0+				

[a] Bias is either: + towards sampling a high exposure; – towards sampling a low exposure; 0 normal building conditions.

[b] Results for fibers longer than 5 μm (fibers/mL).

4.6.3.4 Discussion and Summary of the Building Air Measurement Data

Data Analysis and Averaging

To summarize a large number of data points, it is usual practice to choose a measure of central tendency (such as the arithmetic mean, geometric mean, median or mode) and then describe the spread of the data about the center using the range (maximum and minimum), percentiles, standard deviation or geometric standard deviation. It is important that the distinction among the different statistics be kept in mind during data analysis and risk assessment.

The available environmental measurements of asbestos are limited by the analytical sensitivity, as in the case of concentrations of asbestos fibers longer than 5 µm (below 0.001 f/mL or 10 s/L). With many measurements at or below the analytical sensitivity and relatively few measurements at higher levels, the data are distributed in a highly skewed fashion. The central tendency of such data is better described by the geometric mean (or median) rather than the arithmetic mean. However, because of the analytical limitations, the medians computed for most groupings of buildings in the present report (Tables 4-14 and 4-15) were zero (that is, more than 50% of individual building means were below the limit of detection).

To avoid the problems related to the analytical sensitivity, the Panel has used, throughout this Report, the arithmetic mean as the measure of central tendency of exposure. It should be noted that with a relatively modest number of samples, the arithmetic mean of a set of building averages is very sensitive to the few high levels measured; thus the arithmetic mean may under- or overestimate the average concentrations experienced by the majority of building occupants.

Because information on concentrations in buildings had limited analytical sensitivity, detailed analyses of variability were not worthwhile. Therefore, by averaging as described above (see also Appendix 1), information is lost on the variability in concentrations within buildings. However, individual samples with particularly high concentrations were investigated and were usually found to be either associated with maintenance activity or taken in unventilated rooms.

The data from the studies discussed in section 4.6.3.1 have been reviewed in Appendix 1 and, in some cases, reanalyzed, to derive average asbestos concentrations in each of the 198 ACM-containing buildings studied. Ranges and means of these building averages for each study are presented in Table 4-10. Where detailed information was available, the arithmetic mean concentration in a given building was computed by dividing the total number of fibers (or structures) detected on filters collected in the building by the total volume of air analyzed in all the samples collected in that building. This approach yielded building average concentrations that had improved analytical sensitivities compared with the individual samples. Where all the data were not presented in the publications, the Panel relied on the averages reported by the authors. For a group of buildings (for example, buildings grouped by study or by building type), the mean was calculated by averaging the building means; any building mean reported as below the analytical sensitivity (that is, where no fibers were detected) was considered to be zero for the purpose of this calculation. Where sufficient data were available, other statistics, such as the 90th percentile, are also reported.

Table 4-14. Distribution of Building Average Airborne Asbestos Concentrations for Nonlitigation Data by Study[a]

Study	No. of Buildings	Building Types[b]	Minimum	10th Percentile	Median	Mean	90th Percentile	Maximum
Burdett and Jaffrey 1986[c]	39	5S,8PC,26 R	0	0	0.0001	0.00026	0.0009	0.0017
Chatfield 1986c	7	5S,2PC	0	0	0.0005	0.00243	0.0080	0.0080
Gazzi and Crockford 1987[c]	25	R	0	0	0	0.00030	0.0008	0.0025
Hatfield et al. 1988; Chesson et al. 1990b; Crump and Farrar 1989	43	PC	0	0	0	0.00005	0.0003	0.0006
Pinchin 1982	19	S	0	0	0	0.00042	0.0020	0.0030
CPSC 1987	45	R	0	0	0	0.00010	0	0.0020
McCrone 1991 (unpublished) schools	19	S	0	0	0.0002	0.00022	0.0005	0.0016
McCrone 1991 (unpublished) office	1	PC	—	—	—	0.00004	—	—

[a] Fibers greater than 5 µm.

[b] S = schools, PC = public and commercial buildings, R = residences.

[c] Only including buildings with asbestos.

Table 4-15. Distribution of Building Average Airborne Asbestos Concentrations for Nonlitigation Data by Building Type[a]

Building Type	No. of Buildings	Minimum	10th Percentile	Median	Mean	90th Percentile	Maximum
School	48	0	0	0	0.00051	0.0016	0.0080
Residence	96	0	0	0	0.00019	0.0005	0.0025
Public and commercial	54	0	0	0	0.00020	0.0004	0.0065
All buildings	198	0	0	0	0.00027	0.0007	0.0080

[a] Fibers greater than 5 µm.

Summary of Data

Summary statistics computed from the 198 ACM-containing buildings are presented in Tables 4-14 and 4-15 and Figures 4-1 and 4-2. The means of the building average concentrations in the various studies range from 0.00004 to 0.00243 f/mL. The 90th percentiles of building averages range from 0 to 0.008 f/mL. Table 4-15 and Figure 4-2 present the data from the same studies with the results combined according to building categories: schools (including a few colleges), residences, and public and commercial buildings. The mean concentrations are 0.00051, 0.00019, and 0.00020 f/mL in schools, residences, and public and commercial buildings, respectively. The 90th percentiles are 0.0016, 0.0005, and 0.0004, respectively. When all data are pooled, this data set represents 1,377 samples in 198 different buildings with ACM. For the pooled data, the mean exposure value is 0.00027 f/mL, with 90th and 95th percentiles of 0.0007 and 0.0014 f/mL.

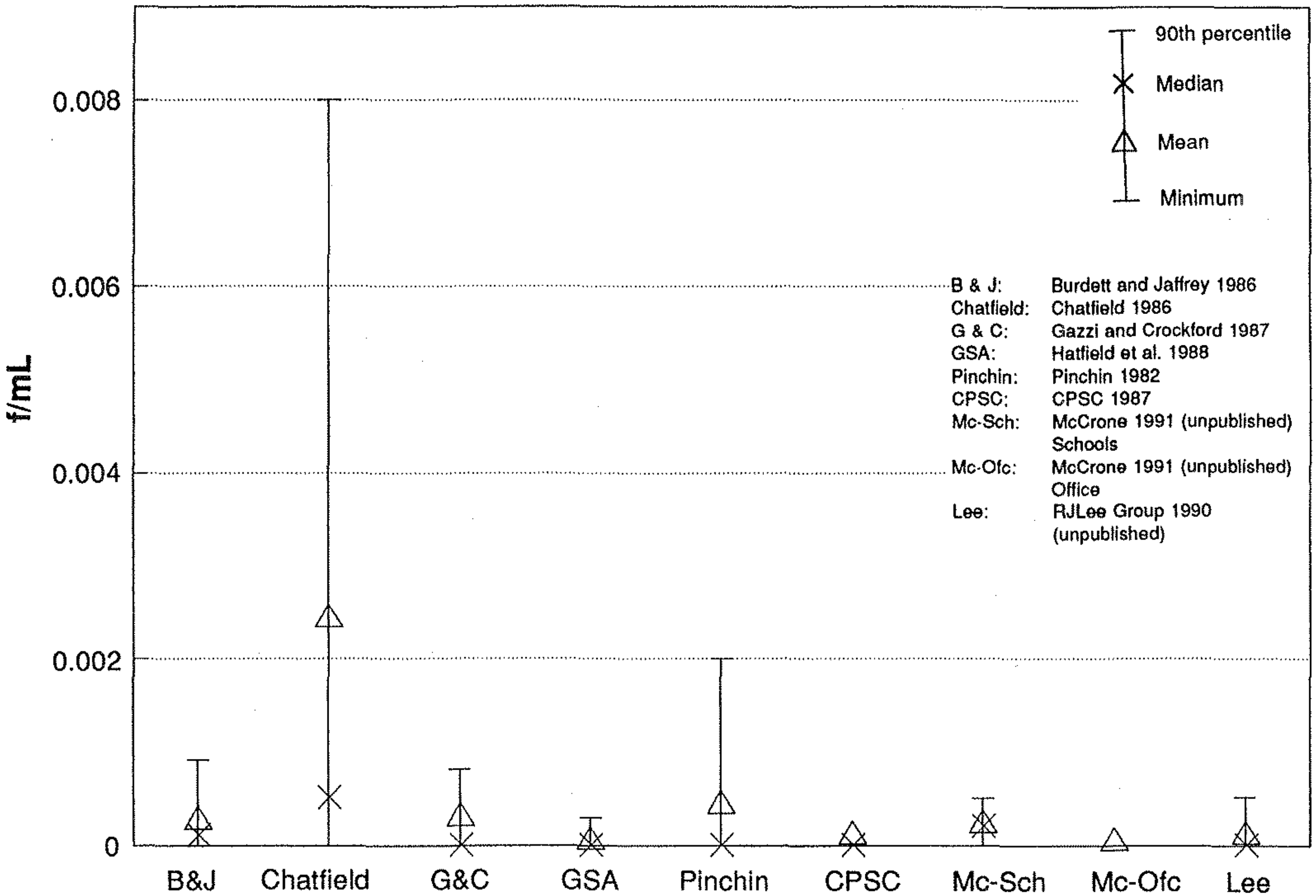
With respect to the public and commercial buildings, the average value is particularly influenced by the GSA building study, since 43 of the 54 buildings are from this study (Hatfield et al. 1988; Crump and Farrar 1989; Chesson et al. 1990b). Hence, the caveats and uncertainties regarding this study (Section 4.6.3.1 and Table 4-10) should be kept in mind when interpreting the data for public and commercial buildings. It should also be noted that the public and commercial building average is strongly influenced by a single observation from the Chatfield (1986c) study. One sample collected in an office building in this study had a value of 0.042 f/mL, the highest among the samples collected in the public and commercial buildings. The author described this sample as having been collected in an area where cable installation was ongoing (Chatfield, personal communication 1991). Had this single sample value been excluded from calculation of the average for all public and commercial buildings, the average value would have been reduced from 0.00020 to 0.00008 f/mL for fibers greater than 5μm.

With respect to the data from schools (including a few colleges), the average value (0.00051 f/mL) is strongly affected by a sample collected in a mechanical room, as described in the original report, but later described by the author as being taken in a janitorial closet (Chatfield 1986c; 1991, personal communication); if this high value (0.02 f/mL) were to be excluded, the average would be reduced to 0.00038 f/mL.

For the litigation data, the mean concentrations range from 0.00003 to 0.00024 f/mL. When the data from the RJLee Group (which include most of the data reported by Corn and associates [1991]) are grouped by building category, the average values for schools and universities, and for public and commercial buildings, are 0.00011 and 0.00006 f/mL, respectively.

When the data for public and commercial buildings in nonlitigation studies are compared with the litigation data from RJLee Group, a four-fold difference is found between the averages (0.00020 f/mL from nonlitigation data, and 0.00006 f/mL from the Lee data). However, if the highest value from the nonlitigation data is excluded from calculation of the average (see above), the average values are not substantially different (0.00008 for nonlitigation data and 0.00006 for litigation data). With respect to schools and universities, the average values are within a factor of three to five: 0.00051 f/mL for nonlitigation data (0.00038 f/mL with the highest value excluded), and 0.00011 f/mL for litigation data). In view of the disparate sources from which these data have been derived, and the fact that most samples yielded counts that were close to the analytical sensitivity, such differences are not likely to be statistically significant.

Figure 4-1. Distribution of Building Average Airborne Concentrations for All Data by Study[a]

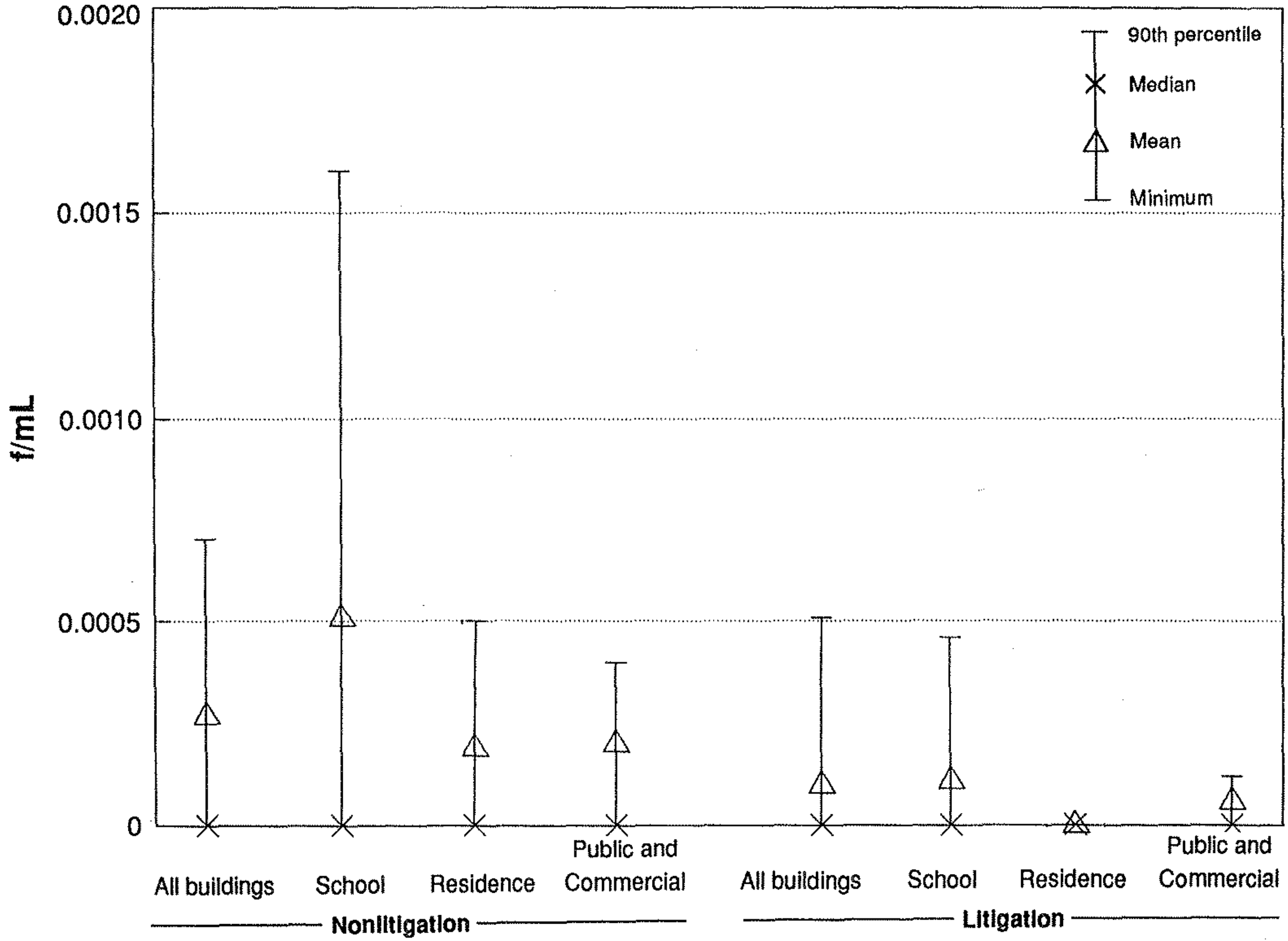


	B&J	Chatfield	G&C	GSA	Pinchin	CPSC	Mc-Sch	Mc-Ofc	Lee
No. of buildings	39	7	25	43	19	45	19	1	231
No. of samples	211	53	25	339	63	89	269	328	1,260

Study

[a] Fibers greater than 5 μm.

Figure 4-2. Distribution of Building Average Airborne Concentrations for all Data by Building Type[a]



	Nonlitigation: All buildings	Nonlitigation: School	Nonlitigation: Residence	Nonlitigation: Public and Commercial	Litigation: All buildings	Litigation: School	Litigation: Residence	Litigation: Public and Commercial
No. of buildings	198	48	96	54	231	171	10	50
No. of Samples	1,377	393	215	769	1,260	1,008	10	242

Building Type

[a] Fibers greater than 5 µm.

Another aspect of the fiber concentration data presented here is the proportion of short and long (> 5 µm) asbestos fibers. The rationale for the Panel's decision to focus on fibers longer than 5 µm is discussed in sections 4.2, 6.3.1, and 6.4. It will be noted from the data presented in Tables 4-10 and Table 4-11 that the concentrations of fibers longer than 5 µm (expressed as f/mL) are less than those of fibers of all lengths (expressed as s/L). Detailed information on distribution of fiber size were not available; such information for longer fibers is necessarily limited because relatively few long fibers have been counted. In samples collected in buildings with ACM, the proportion of concentrations of fibers longer than 5 µm to all fibers varies from a low of 0.2 percent in one of the office buildings (McCrone Environmental Services, unpublished data, 1991) to almost 20 percent in 24 U.K. buildings with warm air heaters (Burdett and Jaffrey 1986); on average, this ratio is about 6 percent across all the studies reviewed in this report.

Additional Considerations in Averaging Methods

Under the assumptions of a linear dose-response model, the average exposure is described by the time-weighted average exposures in various situations which have differing concentrations. Thus, ideally, potential exposure subpopulations, classified by buildings, activities, type and condition of ACM, type and degree of ventilation, and other factors would be identified and sampled within a statistical design. The average for each subcategory would be calculated by summing the volume of air sampled and the fibers counted, and by computing the appropriate ratio. Using the subcategory averages, the overall exposure of an idealized "average" occupant would be estimated by forming the time-weighted average of the average concentration measured for each subpopulation. The available data, however, are far too incomplete to attempt such an analysis.

From the available data, average airborne concentrations can be calculated in several ways:

1. Volume averaging assumes that there is a single universe of air to be sampled within a sampling frame of interest (such as a building or a group of buildings). In this case, the average concentration is computed by summing the total number of fibers counted in all samples and dividing this quantity by the total volume of air sampled. Thus, this method gives more weight to samples collected with large volumes.

2. Sample averaging assumes that each sample is a random, equally representative measure of the true mean in the sampling frame of interest. Here, the average concentration is computed by summing the individual sample concentrations and dividing by the number of samples. An average of this kind gives equal weight to each sample collected. Thus, in computing averages across buildings, sample averaging gives greater weight to those buildings with larger numbers of samples.

3. Building averaging assumes that individual building means represent the appropriate unit of measure. The average concentration in a given category of buildings would be computed by summing the individual building mean concentrations and dividing by the total number of buildings in that category. This method gives equal weight to each building in the computation of group averages; however, it ignores differences in the volume and duration of sampling and the number of samples collected in each building.

4. Study averaging assumes, in considering data reported in different studies, that each study is an equal sampling of a universe of buildings; the exposure average is thus the arithmetic average of the study averages. In giving equal weight to all studies, this procedure ignores any differences between the volumes of air analyzed, the numbers of samples collected, the numbers of buildings surveyed, and the buildings themselves.

The Panel has employed the method of building averaging in computing the overall averages and other descriptive statistics reported in the previous section. Individual building means were treated as the unit of observation from which statistics were computed in the various groups of buildings. (As noted above, the mean concentration in individual buildings has been computed, where possible, as a "volume average;" this yielded building average concentrations that can be thought of as pooled, building-wide samples, and which had improved analytical sensitivities compared with individual samples.) As noted above (section 4.6.3.3), it is not known how representative the concentrations of asbestos measured in any particular building are of concentrations present in U.S. buildings as a whole, nor is it known how representative they are of the exposures of occupants of such buildings. Such knowledge, if available, could guide the choice of appropriate weights to use in estimating average population exposures based on measurements made in specific buildings and situations. However, because such information is not available, it was deemed prudent not to adopt arbitrary weights, such as those provided by sampling volume or frequency, or by specific studies, and instead to allow each building mean to stand on its own with equal weight.

4.6.4 Temporal and Spatial Variations in Exposure Levels

The concept of "peak exposures" has been prominent in discussions of airborne asbestos concentrations in buildings. This concept implies that asbestos concentrations in buildings follow a pattern characterized by infrequent episodic peaks superimposed on generally low background levels. Some have argued that air monitoring inside buildings has little value for estimating exposures of (and hazards to) building occupants because, among other things, small-scale sampling surveys are likely to miss the "peak episodes" (Nicholson 1989; EPA 1985c, 1987). Though they may occur infrequently, it is argued, peak episodes could dominate the average exposures of building occupants. Thus, if sampling surveys miss the episodes, average exposure concentrations would be systematically underestimated. Because this issue has been a topic of major discussion in the development of public policy on asbestos, and was specifically included in the Congressional mandate to HEI-AR, it is important to evaluate the nature of asbestos concentration variations in buildings. Relevant information includes the cause, frequency, and magnitude of peak exposures, and their temporal and spatial patterns.

As discussed in Chapter 6, the biological effects of asbestos depend on inhalation of fibers in the lung. At very high asbestos concentrations, such as those that occurred historically in the asbestos industries, the relation between cumulative retention and exposure concentration may be nonlinear because of the overload of normal lung clearance mechanisms at such very high exposure levels (see section 6.4). However, at concentrations currently observed in buildings, cumulative fiber retention and the associated risk of developing cancer are far removed from the overload effect, and are likely to be linearly related to exposure. This implies that the ideal measure for assessing risk to building occupants would be the long-term average exposure concentration; intermittent peak exposures would be relevant only insofar as they contribute to long-term average exposures. The key question is whether or not typical sampling surveys are likely to estimate, without bias, the full distribution (including the upper tail, or "peaks") of exposure levels in a representative way, or, instead, are likely to systematically undersample peak levels, resulting in underestimates of long-term average exposures.

Here, as elsewhere, it is important to distinguish between the exposure patterns of general building occupants (C1) and those of custodial (C2) and maintenance (C3) occupants. Because their work sometimes involves direct contact with ACM or ACM dust or debris, C2 and C3 occupants are more frequently exposed to elevated asbestos concentrations, or "peaks," in buildings with ACM (Hisanga et al. 1990). The situation for C1 occupants is less clear.

The rationale for the existence of episodic peak concentrations superimposed on generally low background levels of airborne asbestos is based on the assumption that substantial releases of asbestos fibers into the air of buildings occur only intermittently, usually as the result of mechanical disturbance of ACM or its debris, associated with maintenance, renovation, and custodial work. Less predictable are the activities of C1 occupants, who may inadvertently or intentionally disturb ACM or debris.

Once released, asbestos fibers would be expected to remain airborne in a building for a limited time. An exponential decay is normally observed in aerosol particle concentrations, but relatively few measurements have been reported for asbestos aerosols (Moorcroft and Duggan 1984), due in part to the difficulty of obtaining sufficient analytical sensitivity for short-term samples. The decay of aerosol concentrations will be influenced by dilution factors such as room size and air exchange with the outdoors. The spatial dispersion of aerosols following a source release depends on the same factors. Aerosols are much more restricted than gases in their spatial dispersion, due to both lower diffusion coefficients and to gravitational settling to surfaces (described by Stokesian theory).

By monitoring the activities and exposures of C2 and C3 workers, it would be possible to estimate the frequency of potential peak exposures and the duration of the relevant disturbances. The magnitude of the exposure is subject to many variables and must be obtained by air measurements during the disturbance. Unfortunately, monitoring short-term exposure levels of asbestos fibers with adequate analytical sensitivity presents problems.

The limited data available on exposures associated with maintenance activities suggest that the levels are highly variable and, under worst-case conditions, short-term levels approaching those seen in some asbestos industries are possible (data summarized in section 4.7, Airborne Asbestos Levels in Occupational Settings, and Chapter 5). The relative effect of infrequent peak exposures to maintenance personnel in public buildings, as compared to general occupants, can be demonstrated by simple calculation. A maintenance worker who is subject to a single short-term exposure at the OSHA excursion limit of 1 f/mL for 30 minutes would receive an exposure equivalent to about three years of exposure at typical average levels in public and commercial buildings (0.0001 f/mL). Similarly, a single day's work at the current OSHA PEL of 0.2 f/mL would be equivalent to approximately eight years of exposure at typical average levels. These calculations further underline the importance of monitoring maintenance workers and the use of careful work practices when ACM is disturbed.

There are insufficient data to correlate directly the magnitude of the maintenance workers' exposures to the exposures of C1 building occupants. Furthermore, the temporal and spatial patterns of C1 asbestos exposures, and the factors influencing these patterns, have not been systematically studied. However, it may be reasonable to assume that asbestos fiber exposure patterns for C1 occupants are similar to those that have been observed for respirable particulate matter in general. Concentrations of respirable particulate matter in homes and offices usually follow a distribution that is unimodal, with a tail skewed towards higher values. Because such distributions appear to be continuous and unimodal, the definition of peak or episodic concentrations is an arbitrary one. For example, peak levels might be defined as concentrations falling above some percentile (for example, 90th or 99th) of the distribution.

The validity of air monitoring as an exposure (and risk) assessment tool for C1 occupants depends on the extent to which such data provide unbiased estimates of average C1 exposures. This is a statistical/epidemiologic question: that is, are typical air sampling surveys likely to sample the full distribution of exposure levels in a representative way?

The answer to this question has been controversial. Some have argued that short-term air sampling is not likely to reflect actual long-term contamination levels in buildings because building managers are unlikely to schedule maintenance and renovation activities (that might result in release of fibers from ACM) during periods when air sampling is taking place (Nicholson 1990). Others discount such arguments, and suggest that well-designed survey methods can be used to obtain unbiased exposure estimates (Lees 1989) or that the large data base now available is likely to include a representative proportion of data sampled during disturbance episodes (Crump 1990; Corn et al. 1991). While most recent air monitoring studies of ambient levels in buildings (see Table 4-10) have been conducted during periods of normal building activity and occupation, no authors have specifically reported whether or not typical levels of maintenance and renovation took place during sampling. Thus, it is not presently possible to reach firm conclusions on this issue.

Very few studies are available in which repeated measurements have been taken in the absence of abatement work. Two studies in which limited repeat measurements were made at the same site, without concurrent abatement of ACM (Constant et al. 1983; Powers 1989), showed reduced levels on resampling. An unpublished but extensive data set of repeated measurements has been made available to HEI-AR by McCrone Environmental Services, Chicago, Illinois. In that study, TEM measurements were made over nine quarterly periods in a building containing sprayed asbestos in the air ventilation system. The building was subject to an ACM O&M program during the time of sampling. A total of 328 air samples were analyzed in that study by a direct analysis method based on Yamate and colleagues (1984). The range of individual measurements for all asbestos structures was from ND to 88 s/L, with a mean of 1.9 s/L. The range of measurements for asbestos structures over 5 µm long was from ND to 0.0021 f/mL, with a mean of 0.00004 f/mL. The 95th percentile of measured concentrations was below the LOD and the 99th percentile was 0.001 f/mL.

There is a need for more data from well-designed studies on the temporal and spatial distributions of ambient asbestos concentrations in buildings and of personal exposures of C1 occupants. Particular emphasis should be placed on demonstrating the representativeness of the sampling design by defining the sampling frame of interest and by carefully selecting locations and times to be sampled. The HEI-AR plans to sponsor research on the effect of custodial and maintenance activities on the asbestos exposure of C1 occupants (HEI-AR 1990).

4.6.4.1 Evidence for Elevated Concentrations in Nonlitigation Data

In analyzing the data from various studies summarized in Table 4-10, individual samples were found to have varying sample volumes and analytical sensitivities; therefore, a multipoint average has been calculated for each building. This has the advantage of giving better sensitivity and a more reliable representation of the C1 occupant exposure. However, a building average will always underrepresent a single-sample peak value. Ideally, when a high measurement is found, the reason for the high value should be investigated, and, where appropriate and feasible, resampling should be carried out to confirm the measurement.

Many of the measurements were found to be sensitivity-limited (for example, a single fiber longer than 5 µm in the CPSC data accounted for a sample concentration of 0.004 f/mL).

The largest numbers of asbestos fibers longer than 5 µm counted in a single sample were reported by Chatfield (1986c). Eleven fibers were found in a sample taken during installation of computer cables in an office building with sprayed friable ACM in the ceilings, yielding a sample concentration of 0.042 f/mL. Similarly, six fibers were counted in a college mechanical room/closet, giving a sample value of 0.020 f/mL. Both of these values have a significant effect on averages computed across all nonlitigation studies (that is, increasing the school and college building mean from 0.002 to 0.008 f/mL and increasing the public and commercial building mean from 0.00008 to 0.00020 f/mL).

In calculating building averages, it was intended that the data be representative of the C1 occupant exposure under normal building conditions, and there was much deliberation about the drawbacks and merits of excluding potentially nonrepresentative data prior to computing summary statistics. In the final analysis, the Panel decided that all samples reported by the authors in the original publications would be included in the data base from which summary statistics have been computed.

As noted above, the 95th percentile for all 198 building averages is 0.0014 f/mL. Therefore, all buildings with averages above approximately 0.001 f/mL had unusually high values. Where the authors of the original publications noted the potential causes, the high levels were generally due to C2 and C3 activities, or due to samples taken in small, unventilated areas. Data from repeated measurements in the high concentration areas were not available.

4.6.5 Comparison of Mass and Numerical Asbestos Fiber Concentrations

The more recent measurements of asbestos fiber concentrations in both ambient and building atmospheres have been made in terms of numerical asbestos structure counts using direct transfer TEM preparation procedures, and these cannot easily be related to the earlier results specified in terms of mass concentration. Various reports and authors have attempted to compare the early mass measurements with the more recent work, using numerical conversion factors to calculate theoretical fiber concentrations from the mass values (Walton 1982; CPSC 1983; NRC 1984; ORC 1984; Berman and Chatfield 1989; Esmen and Erdal 1990), but they have come up with mass-to-fiber-count conversions usually based on the same industrial or laboratory-derived data (Lynch et al. 1970; Rohl et al. 1976a; Davis et al. 1978; Dement and Harris 1979; Cook and Marklund 1982; Dement et al. 1982). Several reports have made risk estimates based on the mass to PCM equivalent fiber conversion (EPA 1980, 1986a; CPSC 1983; NRC 1984; ORC 1984) and have uniformly specified a value of 1 PCM equivalent fiber count as equivalent to approximately 30,000 ng/m^3. However, the mass measurements in ambient atmospheres do not often include any fibers longer than 5 µm in the actual fiber counts, much less fibers of dimensions such that they would have been optically visible, and it is, therefore, difficult to justify the use of such a conversion process or factor. Indirect methods of sample preparation will give large increases in the number of short fibers of chrysotile, and in samples from buildings, the collection of large matrices of ACM that may dissolve, ash, or break up, makes it impossible to predict any relationship. Therefore, the conversion factors that have been derived, and that were considered during the choice of the value to be used, have ranged from 9.1 PCME f/ng to 770 PCME f/ng (ORC 1984). In view of the extreme range of the conversion factors that have been measured experimentally, the use of a single constant factor is a most unreliable procedure and it cannot be recommended.

In principle, a conversion factor could be calculated for specific sites using the direct-transfer method of preparation, but usually in ambient atmospheres there are too few asbestos fibers in the analyses. Only studies with large data bases, where significant levels of asbestos are found, can be used to estimate an environmental conversion factor from mass concentration to fiber numbers. This was possible for the Corn and colleagues (1991) paper of direct TEM measurements in 71 schools (see Appendix 1), and using these data, a value of 1 f/cc equivalent to 25,300 ng/m^3 was calculated for PCM equivalent fibers, similar to the value (30,000 ng/m^3) used for conversion of the mass concentration data in the National Research Council review (NRC 1984).

Mass concentrations calculated from both direct and indirect methods can be influenced by the presence of a few large fibers or structures. The early mass data were based on methods that comminuted the sample to break up the larger aggregates and produced many more fibers to count, particularly for chrysotile. This had the effect of increasing the sensitivity and precision of the mass analysis, but at the cost of affecting the size distribution. The direct method (except for floor tile) usually has a minimal effect on the size distribution, and is less precise and has a lower analytical sensitivity for mass analysis because much fewer structures are present in the airborne state. Unless significant (over 100) numbers of fibers are counted by either the direct or the indirect method, the mass values have little statistical meaning.

4.6.6 Asbestos Fiber Concentration Measurements in Buildings with Resilient Floor Coverings

There are two categories of resilient floor coverings: sheet material, consisting of a vinyl layer with a chrysotile paper backing, and floor tiles, in which chrysotile is uniformly dispersed throughout the material. Within the floor tile category, the organic binder material may be either asphalt or polyvinyl chloride. Not all of these products contain asbestos; over a period of time the asbestos content of floor tiles has been reduced, and new floor covering materials sold in the United States do not contain intentional additions of asbestos.

The chrysotile paper used as a backing for some types of sheet floor covering is not accessible once the material has been installed, and significant release of airborne fibers can only occur during either installation or removal. In contrast, in asbestos-containing floor tile, the asbestos is uniformly dispersed throughout the thickness, and asbestos-containing particles can be released when the surface is abraded in any way. The asbestos in nearly all floor tiles is chrysotile.

Vinyl-asbestos or asphalt-asbestos floor tile must be considered as a special variety of asbestos-containing material in that, although these materials would be considered nonfriable, the forces that may be exerted on them during normal use are sufficient to cause abrasion and generation of dust if they are not properly maintained. Properly waxed, these floor coverings can be considered to have been encapsulated, and no fiber release can occur as long as the wax coating is maintained. However, buffing, wax stripping, and other abrasive treatments may cause the release of particulate material from the surface of the floor tile.

If the floor tile is of an asbestos-containing variety, the particulate material abraded will contain asbestos fibers; such particulate material presents a unique analytical problem. When air samples containing debris from asbestos-containing floor coverings are prepared for TEM observation, the solvents used in the preparation dissolve the vinyl polymer or asphalt, releasing a great number of asbestos fibers from each particle. Usually, almost all of these fibers are less than 3 µm in length, but some varieties of floor covering contain, and may release, longer fibers. Although the direct-transfer TEM specimen preparation methods are normally considered not to modify the size distribution of the particles or fibers, this is not the case for floor covering debris. A single particle of floor covering debris can result in an extremely complex grouping of asbestos structures on a TEM specimen (Chatfield 1989). Asbestos structure counts made on such TEM specimens are very difficult to interpret, because the TEM specimen preparation itself causes the generation of a large number of asbestos structures from each particle of floor tile debris present on the original filter.

If samples containing floor covering debris are analyzed using indirect TEM specimen preparation techniques incorporating ashing, very high asbestos fiber counts and mass concentrations can be obtained (Sébastien et al. 1982; Dufour 1984). For example, if four 10-µm-diameter particles of typical floor tile material were observed in a 10-grid opening fiber count on a 1,500 liter air sample as collected for an AHERA clearance, the sample would pass the clearance criterion if the particles were unaffected by the preparation. If this sample filter were to be prepared by indirect TEM procedures, such as those used by Sébastien and Dufour, the mass concentration reported would be 2,600 ng/m^3, and the numerical asbestos structure count could amount to 310 f/mL. This calculation assumes that the floor tile contains 15 percent chrysotile, and that all of the chrysotile fibers are approximately 2 µm in length. Dufour (1984) reported airborne chrysotile mass concentrations exceeding 400 ng/m^3 in buildings where the only source of chrysotile appeared to be floor tile. If the original particles remained intact as collected on the sample filter, such an air sample would pass the AHERA 70 s/mm^2 clearance criterion. Clearly, floor tile debris presents special problems of interpretation, since the use of indirect methods, and even partial dissolution of such particles by the solvents used for direct-transfer TEM specimen preparation, can result in high asbestos structure counts not representative of the material as it was airborne.

Table 4-16. Transmission Electron Microscopy Analyses of Personal Samples Collected During Removal of Resilient Floor Coverings[a]

	Asbestos Structures (All Sizes) (s/L)		Asbestos Fibers Longer than 5 µm (f/mL)	
Material	Mean	Range	Mean	Range
Floor tile (25 measurements)	280	15 – 960	0.0095	0 – 0.039
Felt-backed vinyl floor covering (34 measurements)	220	7.9 – 760	0.026	0 – 0.12
Asphalt cut-back	65	7.6 – 180	Below analytical sensitivity	

[a] Source: Environ Corporation (1989, 1990a,b); reprinted with permission.

Three studies, sponsored by the Resilient Floor Covering Institute (RFCI) and provided to the Panel by Environ Corp., Washington DC (Environ 1989, 1990a,b), have investigated the airborne asbestos concentrations generated during removal of asbestos-containing floor covering materials. The 1989 study focused on removal of floor tiles, and showed that, if recommended work practices were followed, floor tiles could be removed without exceeding the OSHA action limit of 0.1 f/mL. It was also concluded that PCM was a poor technique for determination of asbestos exposures arising from the removal of floor tiles.

There was no statistically significant correlation between the the PCM data and the TEM data for fibers longer than 5 µm. In the 1990 work, it was found that, using recommended work practices, removal of resilient sheet vinyl flooring with a felted asbestos backing, as well as removal of asphaltic cut-back adhesive containing asbestos could also be achieved without exceeding the OSHA action limit. Table 4-16 shows the concentrations of all asbestos structures, and the concentrations of asbestos fibers longer than 5 µm (all widths), measured by TEM on personal samples used to monitor the exposures of the removal mechanics. These measurements were all performed using direct-transfer method for TEM specimen preparation. The concentrations of fibers longer than 5 µm by this method would overestimate the exposures in terms of the OSHA regulations, because all fiber widths are included in these measurements, rather than just those thicker than 0.25 µm.

Other studies on floor tile have been reported by MacDonald and coworkers (1988), in which drilling, breaking and other manipulations were performed on floor tile. Airborne asbestos concentrations, measured by PCM, of up to 0.055 f/mL were reported. Burdett and colleagues (1990) conducted a study of residue levels after floor tile had been removed. A concentration of 1.348 asbestos s/mL, measured by TEM, was observed during removal of the tile, although PCM monitoring inside the removal enclosure generally yielded results less than 0.01 f/mL. Aggressive air sampling after the removal was completed, yielded an average asbestos concentration, measured by TEM, of 0.0013 f/mL (fibers longer than 5 µm). As was found in Environ Corporation's work on floor tile removal, the study also showed that TEM and PCM measurements were not correlated.

TEM analyses of samples containing floor tile debris were acknowledged by both the RFCI study and the Burdett study to present problems in fiber counting, because of the compexity of the asbestos structures. This leads to some difficulty in interpretation of numerical asbestos structure concentrations.

If asbestos-containing floor tile is present in a building, its possible effect on any air sampling measurements made in the building should not be ignored. Poorly-maintained floor tile can clearly be a source of asbestos-containing dust, and the work of both Sébastien and Dufour seems to demonstrate that under some circumstances this dust can appear in air samples.

4.7 Airborne Asbestos Levels in Occupational Settings

This section focuses on exposure levels experienced by other groups of building occupants (C2 to C5) who are exposed to asbestos in buildings during the course their occupational activities. Persons in categories C2 and C3 are employed in relatively small numbers in any particular building, but in total, their numbers are substantial, and these groups have a higher potential for exposure than C1 occupants. Such workers are likely to come in contact with or disturb ACM during their normal custodial and maintenance activities and may generate high local concentrations of asbestos. Workers in categories C4 and C5 are generally employed by outside contractors or by city or county government; they may work in a given building for varying periods of time. It should also be kept in mind that there is no uniform definition of workers in each of these categories, and that an overlap between references to, and duties of, each group exist in the literature. For example, a recent report states that Boston school custodians undertook some maintenance and abatement activities (such as "maintenance of boilers" and "patching and/or removing torn insulation on pipes and/or boilers") as a routine part of their employment (Oliver et al. 1991).

4.7.1 Custodial Workers

During their cleaning duties, custodial workers may resuspend fallout debris and settled dust from surfaces on a regular basis and may occasionally disturb the surfaces of ACMs. There are relatively few studies in which exposures of custodial workers have been measured (see also Chapter 5). Lumley and coworkers (1971) reported PCM results which showed that disturbance to fallout debris increased airborne fiber concentrations, and brushing of a friable sprayed crocidolite surface produced an average of 11.9 f/mL. Sawyer (1977) reported average PCM results for dusting (4.0 f/mL), dry sweeping (1.6 f/mL), and cleaning books (15.5 f/mL) in a library contaminated with fallout debris from friable sprayed chrysotile.

Nicholson and associates (1975) reported increased TEM mass concentrations for dry sweeping in a school. Kominsky and colleagues (1990, 1991) studied HEPA vacuuming of contaminated carpets and the changing of filter bags. Burdett (1988) studied the effects of several janitorial functions in assessing the possible effects of aggressive sampling on surface dust in a polluted building, and reported increases up to 100-fold for aggressive, compared to passive, sampling. Corn and associates (1991) reported asbestos levels during periods that included sweeping, but found no statistically significant increase in monitored airborne levels. However, no comprehensive study to measure increased levels of airborne asbestos during janitorial activities was found in the literature.

The case of floor tiles calls for special consideration, and has been discussed separately in section 4.6.6.

4.7.2 Maintenance Workers

This group of workers can have a wide range of intermittent exposures and may be exposed to concentrations that require respiratory protection. Airborne asbestos concentrations during maintenance activities have historically been measured by the PCM to determine compliance with the eight-hour time-weighted average PEL. From 1972 to July 1986, occupational exposures were subject to an OSHA PEL of 2 f/mL and a short-term excursion limit of 10 f/mL. The PEL was reduced to 0.2 f/mL in July 1986, and a further reduction to 0.1 f/mL has been proposed recently. A short-term excursion limit of 1 f/mL measured over 30 minutes, originally introduced in October 1988, remains in effect (Table 4-17). It should be noted that the above regulations apply to airborne asbestos concentrations; where workers use respiratory protection, their exposures may be reduced depending on the efficiency of such equipment.

An estimate of the exposures of maintenance personnel can be made based on such regulations. For instance, as discussed in section 4.6.4, the current maximum short-term excursion limit of 1 f/mL monitored over a 30 minute period (Table 4-17) corresponds to a cumulative exposure of 0.5 f/mL/hour, which is equivalent to two or three times the annual exposure of a C1 occupant would receive in a public building with a background of 0.0001 f/mL (assuming 1,600 to 2,000 hours in buildings per year). Although the level and duration of exposure for each maintenance activity will vary, average estimates of exposure for routine maintenance in commercial and residential buildings have been published by CONSAD (1984, 1985, 1990). CONSAD gives estimates of 130 to 740 × 10^3 for the annual number of workers who are partially exposed; they receive the equivalent of 26 to 40 × 10^3 person-years of exposure at various personal exposure levels depending on the category of work. Using such data, CONSAD has calculated the average exposure of maintenance workers in each work category (Table 4-18). For example, ceiling tile repair or replacement was carried out by up to 38,650 persons with an estimated maximum of

Table 4-17. Regulatory History[a]

Date of OSHA Ruling	PEL[b] (TWA[c])	Peak Exposure	Action Level (TWA)	STEL[d] (30 min)	Comments
May 1971	12.0 f/mL				Initial promulgation
Dec 1971	5.0 f/mL	10 f/mL			Emergency response
June 1972	5.0 f/mL	10 f/ml			Final rule
1976–1986	2.0 f/mL				
June 1986	0.2 f/mL		0.1 f/mL		
1988	0.2 f/mL		0.1 f/mL	1.0 f/mL	
1990	0.1 f/mL			1.0 f/mL	Proposed rule

[a] Source: Federal Register, 29 CFR Parts 1910 and 1926, Vol. 51, No. 119, pp. 22614–22615.

[b] PEL = permissible exposure limit.

[c] TWA = time-weighted average.

[d] STEL = short-term exposure limit.

1067 annual full-time person-years exposure, or an average of 44.17 hours/year/person (assuming 1,600 hours/year). For this activity, OSHA estimated a personal exposure (with respirator usage) of 0.045 f/mL, which is equivalent to an exposure of 1.99 f/mL for one hour, 12.4 times the annual exposure for an arbitrary background of 0.0001 f/mL. In the past, without respirator usage, an exposure of 0.45 f/mL was estimated (CONSAD 1990), a concentration approximately three orders of magnitude above that for C1 building occupants. These estimates support the suggestion that the C2 and C3 workers are the main source and recipients of episodic, peak exposures (see also section 4.6.4, Temporal and Spatial Variations in Exposure Levels). These calculations also suggest that maintenance personnel may experience an annual exposure of about one or two orders of magnitude above that of C1 building occupants. Similar calculation procedures have been used to estimate the effect of poorly controlled remediation work on individual C1 occupant exposures (Burdett 1986c).

Measurements of airborne asbestos concentrations during maintenance activities support the notion that such activities generate elevated fiber levels. For example, Sawyer (1977) reported PCM concentrations between 1.1 and 7.7 f/mL for installation activities at a Yale library with badly damaged friable asbestos, and Hamilton (1980) reported levels of 1 to 5 f/mL for various activities in a ceiling space with sprayed asbestos. Paik and coworkers (1983), in a review of removal and maintenance activities in areas with sprayed ACM, found geometric mean concentrations by PCM of 0.18 f/mL for sheet metal workers, 0.13 f/mL for carpenters and electricians, and 0.03 f/mL for painters. Other data summarized by CONSAD (1984) are shown in Table 4-19. It is apparent that short-term exposures can be very high during work in ceiling spaces containing friable asbestos. CONSAD (1990) published estimated ranges of PCM exposure levels for routine maintenance in public and commercial buildings and for general industry (Table 4-18). These data were not updated from the earlier estimates (CONSAD 1984, 1985), which were derived from various sources, including those above. In addition, CONSAD (1990) reported arithmetic eight-hour TWA values and worker exposures, with assumptions about the efficiency of respirators (Table 4-20).

Table 4-18. Effect of Peak Exposure Levels From Maintenance Activities in Buildings[a]

Type of Maintenance Activity	Maximum Number of Workers Exposed	Estimated Exposure with and without Respirators[b] (f/mL)	Maximum Exposure (person years)	Average Activity Time Per Building[c] (hours)	Ratio of Maintenance: Ambient Exposure with Respirators[d]	Ratio of Maintenance: Ambient Exposure without Respirators[d]
Repair/replace ceiling tiles	38,650	0.045 (0.45)	1,067	2.33	0.66	6.55
Repair adjust HVAC/lighting	60,793	0.006 (0.31)	3,285	7.17	0.27	13.9
Other work above drop ceilings	4,847	0.006 (0.31)	469	1.02	0.04	2.1
Repair boiler	180,984	0.018 (0.18)	1,720	3.75	0.42	4.2
Repair plumbing	180,984	0.011 (0.011)	1,720	3.75	0.26	0.26
Repair drywall	80,231	0.075 (0.75)	5,662	12.36	5.79	57.9
Repair flooring	65,338	0.02 (0.02)	22,437	48.98	6.12	6.12
Repair roofing	127,621	0.12 (0.12)	3,740	8.16	—	—
Total for routine maintenance	739,448	—	40,100	87.6	—	—
New OSHA PEL	—	0.1	—	8	—	5.0
OSHA excursion limit	—	—	—	0.5	—	3.12

[a] Source: CONSAD (1990); reprinted with permission.

[b] Does not include estimates for minor repair but includes reduction due to respirator usage.

[c] Average activity time calculated using maximum in exposure in person years times 1600 hours and divided by the EPA (1988b) estimate of 733,000 public and commercial buildings with friable ACM.

[d] Calculated from estimated exposure with (and without) respirators times average activity time divided by ambient level (1600 hours x 0.0001 f/mL).

Table 4-19. Asbestos Fiber Levels Reported During Maintenance Activities[a]

Description of Study	Number of Measurements	Concentrations (f/mL) Minimum	Maximum	Geometric Mean	Geometric Standard Deviation	Percent Over 2.0 f/mL	Percent Over 0.5 f/ml	Percent Over 0.2 f/mL	Percent Over 0.1 f/mL
Demolition of nonload bearing partitions in office buildings (Clayton Environmental Consultants)									
• Laborer: personal	22	0.15	11	1.6	3.4	45	82	91	100
Routine adjustment of HVAC equipment (above suspended ceiling) by building maintenance personnel (Clayton Environmental Consultants)									
• Personal sample	5	0.04	0.0	0.21	3.0	0	20	40	80
• Area beneath work	4	0.04	0.1	0.06	2.8	0	0	0	25
Removal of drop ceiling tiles by renovation contractor and/or building maintenance personnel (Clayton Environmental Consultants)									
• Personal samples	11	0.02	1.4	0.14	4.6	0	1.8	45	64
• Work area	1	—	1.2	—	—	—	—	—	—
Incidental exposures of HVAC workers while installing, replacing, repairing, or inspecting equipment located near asbestos-containing insulation materials (T. Joel Loving, University of Virginia)									
• HVAC worker: personal sample	14	0.11	6.9	0.61	3.5	14	50	86	100
Wet removal of small sections (typically less than three feet in length) of asbestos insulation from pipes to repair leaks, replace valves, make junctions, etc. (T. Joel Loving, University of Virginia)									
• Pipefitters: personal sample	4	0.03	0.92	0.13	4.5	0	25	25	50
General renovation/remodeling projects in academic/office buildings (T. Joel Loving, University of Virginia)									
• Carpenter: personal sample	5	<0.01	1.2	0.11	6.6	0	20	40	40

[a] Adapted from CONSAD (1984).

Table 4-20. Representative Exposure Levels, Absent Respiratory Protection, by Construction Activity[a]

Construction Activity	Representative TWA Exposure Levels, Absent Respiratory Protection (f/mL)
New construction	
A/C pipe installation	0.02 to 0.06
A/C sheet installation	≤ 0.15
Roofing felt installation	ND[b] to 0.6
Asbestos abatement and demolition	
Removal	< 0.01 to < 8 (pipe insulation) < 0.01 to < 25 (spray-applied)
Encapsulation	0.03 to 0.28
Demolition	< 0.01 to 11
Renovation/remodeling	
Drywall demolition	0.15 to 11
Remove built-up roofing	ND to 0.2
Remove flooring products	0.02 to 0.04
Routine maintenance: commercial/residential	
Remove/repair/replace ceiling tiles	0.02 to 1.4
Repair HVAC or lighting	0.01 to 2.8
Other work above drop ceiling	0.01 to 2.8
Repair boilers	0.04 to 0.53
Repair plumbing	0.04 to < 0.1
Repair roofing	ND to 0.3
Repair drywall	0.02 to 1.4
Repair flooring	0.02 to 0.04
Routine maintenance: general industry	
Gasket removal and installation	< 0.1
Removal/repair of boiler insulation	< 0.01 to 8
Removal/repair of pipe insulation	< 0.01 to < 0.1
Miscellaneous maintenance activities	< 0.01 to 2.8

[a] Source: CONSAD 1990; reprinted with permission.

[b] ND = Not detected.

Pinchin (1982) reported optical and TEM measurements for inspection and maintenance activities. During inspection activities (involving transit ceiling panels and sprayed amosite), TEM measurements were at the level of detection (0.16 f/mL). In a separate building, concentrations during maintenance activity (snap-in ceiling tile and sprayed chrysotile) were as high as 12 f/mL. However, optical measurements did not reflect the TEM results. Breysse and associates (1989) reported 0.12 f/mL for TEM and SEM asbestos levels during the removal of water tanks from a loft space, and levels below the LOD in the bedroom below.

A comprehensive but unpublished data set (Hygienetics Inc., Boston, MA, 1990) on airborne concentrations during various maintenance worker activities was made available to the Panel by Hygienetics Inc., which established and managed an O&M program at a large hospital in the United States from September 1988 to March 1990. The buildings in the hospital contained both asbestos containing pipe insulation and sprayed-on ACM. Air monitoring took place every time a maintenance worker performed a task in an area with ACM; a total of 415 samples were collected during the 107 tasks monitored. Workers wore personal protection during such activities, but the engineering controls used varied according to the activity performed. Both area and personal samples were collected, and all samples were analyzed using PCM. The mean airborne fiber concentrations in this study, regardless of the type of maintenance activity, were 0.1108 f/mL for personal samples, and 0.0196 f/mL for area samples. The 95th percentiles were 0.4176 (personal) and 0.0542 (area) f/mL. Of the 107 occasions on which air monitoring took place, 63 (36 percent) involved miscellaneous repair tasks (repair of plumbing leaks or faulty equipment, ceiling tile replacement, room remodelling, etc.); the mean fiber concentrations for this category of maintenance activity were 0.1272 f/mL (personal) and 0.0112 f/mL (area). For the 25 tasks (23 percent) involving preventive maintenance on an air handling unit, the mean concentrations were 0.0942 f/mL (personal) and 0.0181 f/mL (area). For the 18 tasks (17 percent) involving miscellaneous installation (of such items as new pieces of equipment, pipe lines, etcetera), the mean fiber concentrations were 0.1742 f/mL (personal) and 0.0322 f/mL (area). In addition, 9 (8 percent) of the monitored jobs involved cable pulling, with mean concentrations of 0.0544 f/mL (personal) and 0.0110 f/mL (area). More detailed results will be included in a supplement to this report to be published in the near future.

Some authors have simulated maintenance activities in the laboratory (Lohrer 1979) or on-site to estimate the asbestos concentrations during maintenance activities. Jaffrey and associates (1988) reported TEM average concentrations of 0.031 f/mL for static samples taken while ceiling tiles were removed below a trowelled amosite ceiling, with moderate disturbance of the surface. Recently, Keyes and colleagues (1991) (personal communication) conducted a series of simulated activities in buildings involved in litigation, and provided their data to HEI-AR. During cable installation (involving ceiling tile removal and dropping to the floor, cable pulling, and dry sweeping) in a ceiling space with sprayed friable fireproofing, large increases in levels of asbestos fibers by TEM were reported. Unfortunately, no measurements of fibers longer than 5 µm were reported, and because the filters were too dense for direct analysis, the indirect preparation method was used, which made comparison with other studies difficult. Other studies involved simulation of the impact of athletic activities in a gymnasium with ACM in poor condition and simulation of room cleaning; all resulted in increased levels of asbestos compared to background. The degree to which laboratory and site simulations are representative of worker exposure in the "real world" is often difficult to assess, and further monitoring of routine maintenance activities is urgently required.

4.7.3 Abatement Workers

To ensure that the level of respiratory protection and work practices are adequate, OSHA asbestos regulations for the construction industry (29CFR 1926.58) require that eight-hour TWA exposures to persons inside regulated areas are initially measured on a daily basis at an abatement site. There are exceptions to this requirement, but most projects carried out have some exposure measurements. Unfortunately, these data are not readily available. Before the introduction of dust suppression and negative air filtration, airborne levels at abatement sites were often of the order of 10 to 100 f/mL. OSHA (29CFR 1926) concluded that the use of amended water has been responsible for a reduction of up to 90 percent of airborne levels during abatement (Ewing and Simpson 1985; Sawyer et al. 1985), and this has become a mandatory requirement, except in certain circumstances (29CFR 1926.58). The use of negative pressure containment has increased during recent years, and now forms an integral part of the work practices during abatement. Using modern techniques, most sites can be controlled to give average airborne levels of under 1 f/mL (Piper et al. 1989). These issues are discussed in greater detail in Chapter 5.

4.7.4 Emergency Personnel

No data were found on the exposure concentrations for emergency personnel.

4.7.5 Impact of Respiratory Protective Equipment

In Chapter 5, a number of approaches and methods are discussed which are aimed at reducing the exposure of workers as well as general occupants to airborne asbestos. During the actual performance of work, although work practice is important in determining dust levels in the vicinity of the work site, the exposure of workers depends on respirator use and performance. Respirators have been available for many years, but the level of comfort and protection they afford and their correct usage has often been inadequate. Various designs of respirators (for example, half-face and full-face negative pressure, powered air, and self-contained and supplied air), offering differing levels of protection and comfort, are now available. The integrity of the seal between the respirator and the face is crucial, especially to the performance of negative pressure respirators; special procedures are used to determine the fit of the respirator. However, it is widely acknowledged that in actual use, this fit factor is not reliable because of the difficulty of achieving and maintaining a good seal; both NIOSH and OSHA assess respirator compliance assuming a protection factor of less than or equal to 1/10 of the nominal fit. Both qualitative and quantitative tests have been established to determine and improve the fit (EPA/NIOSH 1986; OSHA 29CFR 1926.58) but these are carried out only periodically, and only for negative pressure respirators. The minimum requirement is that fit factors of a minimum of 100 and 1000 should be obtained for half-face and full-face negative pressure respirators, respectively. Tannahill and colleagues (1990b) recently reported on the performance of three types of negative pressure, full facepiece respirators with a nominal fit factor of 900 when used in an asbestos factory under close supervision. The geometric means and ranges of protection afforded for each respirator, measured by PCM, were: 200 (11 to 2900), 577 (26 to 3493) and 120 (17 to 500) respectively. Only 16, 40, and 0 percent of the measurements, repectively exceeded the nominal fit factor. There are also concerns on the field performance of filter media (Ortiz et al. 1988).

The problems with respirator performance have led the EPA and NIOSH to recommend only the full facepiece, self-contained breathing apparatus that operates in the pressure demand mode, or type C supplied-air respirators with emergency SCBA backup for asbestos abatement workers.

4.7.6 Summary

The routine occupational activities of custodial (C2) and maintenance (C3) workers in buildings with ACM have the potential for bringing them in contact with ACM or dust and debris containing asbestos. The work of abatement workers (C4) brings them in contact with ACM on a regular basis; such workers are likely to be exposed under controlled (containment, appropriate work practices, and respiratory protection) conditions. While no data on the exposure concentrations of emergency personnel (C5) were found in the literature, it would be expected that such workers would come in contact with asbestos in a sporadic fashion and, under certain circumstances, may not be well-protected.

The available data suggest that all workers in buildings (C2 to C5) have a potential for being exposed to asbestos at levels that are higher than those experienced by general building (C1) occupants. However, very limited data are available on exposures of workers during specific work activities. Also, the overall impact of respiratory protective equipment on workers' exposures (to be contrasted with air concentrations) cannot be estimated with certainty. While the available data indicate a potential for exposure of workers, based upon the limited data available, no average estimates of exposures of workers could be derived. There is a great need to obtain more exposure information in these areas. The HEI-AR plans to sponsor research to assess the personal exposures of C2 and C3 workers as a result of routine occupational activities that may disturb ACM, or dust or debris containing asbestos, as well as investigate the frequency of these activities. No study specifically designed to measure TEM airborne asbestos levels during janitorial activity was found in the literature.

4.8 Conclusions

1. An EPA study (1984), based on a small subset of 231 buildings, estimated that 733,000 (± 200,000) of the 3.6 million population of U.S. public and commercial buildings had some type of friable ACM within their structure. However, two recent studies, in New York City and Philadelphia, showed that the extent of the friable ACM in public buildings may be greater than the EPA estimate. When other, nonfriable, ACM is taken into account (for example, floor tile, asbestos cement boards, and pipes and joining compounds), the number will be much greater, although no reliable estimates are known.

2. The New York City study (1988) found that chrysotile was the predominant form of asbestos in buildings, and that amounts of amphibole asbestos were present more often in thermal systems insulation than in other forms of ACM. Also, important findings from this study include the frequent use of friable surfacing in multistoried buildings, and the high proportion of damage to thermal systems insulation (83.1 percent) compared to damaged surface applications (3.3 percent). Many other surveys have been carried out, particularly in schools, but there has been no attempt to correlate these data to give a better estimate of the area and condition of ACMs in buildings.

3. The majority of thermal systems insulation is only accessible to maintenance personnel who, by the nature of their work, create the highest airborne asbestos concentrations; such materials and such workers warrant special focus and consideration.

4. At present, only analytical TEM, with electron diffraction and EDXA capabilities, can give accurate identification of asbestos minerals in air.

5. To a large extent, the purpose and aim of the measurements will determine which method of sample preparation should be used. Both direct and indirect methods of TEM sample preparation will be required in future work to fully understand airborne asbestos concentrations in buildings.

6. Many insights regarding the problem of asbestos in buildings have been gained by researchers. To be representative, measurements of airborne asbestos in buildings should be made during periods of normal occupation and normal activity. While the activities of general building occupants are not very likely to result in elevated concentrations of asbestos, the routine activities of custodians or maintenance workers can result in localized elevations of asbestos concentration.

7. The mass concentration evidence allowed the following conclusions to be drawn:

   - In the United States, evidence suggests that cementitious sprayed insulation and acoustic plaster in buildings under normal repair rarely give rise to airborne concentrations above the outside ambient;

   - Damaged friable sprayed asbestos, particularly with visible debris, has often been associated with elevated airborne levels (above the outside ambient) in occupied buildings;

   - On the other hand, undamaged friable sprayed asbestos in buildings not of recent construction is rarely associated with elevated levels;

   - Accessible ACMs have a high probability of being damaged.

   - The Constant study (Constant et al. 1983) stands out from other mass studies in that the sprayed asbestos was relatively undamaged; however, the airborne levels were consistently high. Although an unknown amount of vandalism appears to have taken place during sample collection, the presence of some other source or mechanism of release cannot be ruled out.

8. The conclusions drawn from the numerical ambient indoor fiber concentration data are:

   - The available data support the hypothesis that in terms of asbestos fibers of all sizes, some buildings exhibit concentrations exceeding those found in the ambient air. For asbestos fibers longer than 5 µm, concentrations inside the buildings cannot easily be discriminated from the range of asbestos fiber concentrations found outside. This inability is largely a consequence of the fact that most of the measurements of fibers longer than 5 µm are below the LOD.

   - In buildings containing ACM and under normal occupation, the building average concentrations of asbestos structures of all sizes ranged up to 202 s/L, and the building average concentrations of asbestos fibers longer than 5 µm ranged up to 0.008 f/mL. These higher concentrations were relatively rare and were often associated with maintenance activities;

   - Average exposures to C1 occupants in public and commercial buildings are on the order of 0.0001 f/mL. Single-sample measurements will rarely exceed 0.001 f/mL if made with the appropriate sensitivity;

- In comparable situations, results from measurements in school buildings show that, on average, there are higher airborne concentrations than found in public buildings. This is probably due, in part, to the much higher levels of activity, which will wear and resuspend ACMs;

- Asbestos fibers longer than 5 µm represent a small proportion of the total number of airborne asbestos fibers;

- The concentration of airborne fibers of all types in a building atmosphere appears to be associated with the presence of occupants and the level of activity.

4.9 Research Needs

There are a number of areas in which research on asbestos in buildings is required. Some of the areas of research need short-term studies, while others fall into the category of long-term research.

1. Further efforts should be made to generate nationally-representative exposure data for the five categories of building occupants identified in this report. HEI-AR has given this question priority, and has taken steps to sponsor studies designed to generate representative data for C1 occupants in the US (HEI-AR 1990).

2. TEM studies of ambient asbestos fiber concentrations and asbestos fiber concentrations in U.S. buildings have concentrated on the measurement of fibers of all sizes. The combination of fiber-counting protocols used and the natural frequency distribution of fiber lengths are such that there is relatively poor statistical precision and inadequate detection levels for the longer fibers, which are biologically more significant. It is recommended that future studies, in addition to measuring the overall fiber size distribution, should also address measurement of the fibers longer than 5 µm by improving the analytical sensitivity for these longer fibers to 0.0001 f/mL for individual samples.

3. In most circumstances envisioned, peak exposures to C1 building occupants are likely to be coincident with janitorial, maintenance or remedial activities (C2, C3 and C4). Therefore, along with the monitoring of the activities of the latter three groups by both time-activity studies and air sampling, air sampling should be conducted during these peak periods and in areas where C1 occupants are present. Although single samples will be constrained by the time for which such activities are performed, analytical sensitivities of 0.001 should be targeted for such measurements.

4. Friable sprayed asbestos coatings and thermal systems insulation are often present in buildings, but in areas that are isolated from direct contact by C1 building occupants. It is recommended that a separate evaluation of the exposures of maintenance workers in these areas be made in order to assess their level of excess risk.

5. Measurements of airborne asbestos concentrations made by the indirect methods of TEM specimen preparation are generally higher than those made by direct methods of TEM specimen preparation, even for fibers longer than 5 µm. There is a need to determine which type of specimen preparation provides the most appropriate index for assessment of risks to building occupants. Accordingly, TEM measurements should be made by both direct and indirect preparation procedures. If possible, reexamination by the indirect TEM specimen procedure of filters remaining from past building surveys would provide useful data in this area.

6. There is a need for an inexpensive quantitative method to determine average airborne concentrations over long periods (several weeks up to one year). These long-term samples could overcome the limitations associated with monitoring exposures by the current methods, and provide better estimates of the average levels of exposure in public buildings. Several types of samples may need to be investigated, for example, low flow-rate or intermittently operated (for example, timer operated or movement actuated). Such a method will provide important evidence of changes taking place in a building, such as possible deterioration of ACM with time, or the effectiveness of an O&M program. Depending on the nature of the samples, indirect TEM specimen preparation may be necessary.

7. The question of whether or not O&M programs are effective in reducing exposures in buildings must be addressed. It is likely that these questions can be answered only by long-term air measurements. The efficacy of the various methods employed under the O&M programs should also be monitored, if such information is not already available from the experience of the abatement industry.

8. It is possible that some of the questions that could be answered by long-term air sampling could also be answered by properly designed experiments to measure dust accumulation on the interior surfaces in buildings. The relationship between appropriately measured asbestos concentrations in surface dust and the airborne asbestos concentrations during normal occupancy should be investigated. An evaluation of the utility of surface dust measurements, particularly in the areas of sampling and interpretation of the results, is needed.

9. The contribution from asbestos-containing resilient flooring products to the building environment during normal occupancy should be assessed. Resilient flooring is a class of asbestos-containing product in buildings that suffers direct impact and abrasion on a daily basis, as well as aggressive treatment on a periodic basis, and further studies on the effects of maintenance activities or lack of maintenance are required. Airborne dust generated from resilient flooring, however, presents difficult analytical problems, and interpretation of both the analytical data and their significance to health deserve further attention.

10. In addition to personal and area monitoring to determine the concentrations of airborne asbestos during maintenance activities, the duration and frequency of such activities should be characterized, so that the overall impact of different combinations of these activities can be evaluated.

11. For measurement of the thoracic component of airborne asbestos fiber dispersions, there is a need for development of sampler inlets with cut-off characteristics matching the ACGIH and ISO specifications for thoracic dust samplers. These inlets must provide uniformity of the dust deposits on the filters to be analyzed and, if not disposable, they must be readily decontaminated after use.

12. If measurement of asbestos by TEM is to become significantly less expensive, there is a need to automate the fiber identification, sizing, and counting process. However, assuming that this is feasible, it is recognized that such a development program probably would be both long-term and expensive.

4.10 References

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5

Remediation of Asbestos-Containing Materials

This chapter discusses the third aspect of the mandate to HEI-AR, namely to "evaluate the effectiveness of remediation strategies in a scientifically meaningful manner" (U.S. House of Representatives 1988). Remediation, in the context of this review, is a set of methods by which asbestos-containing material (ACM) can be dealt within a building. These include methods that leave the material in the building (such as in-place management by an operations and maintenance [O&M] program, enclosure, or encapsulation) and removal.

The effectiveness of remediation strategies can be evaluated only in relation to the goal of these strategies, which is to achieve an overall reduction in the potential for current and future exposures to airborne asbestos due to releases from ACM in a building.

As described in Chapter 4, building occupants can be grouped into three categories: C1, general occupants; C2, custodial workers; and C3, maintenance workers (see section 4.3, Persons Exposed to Asbestos in Buildings). If levels of asbestos exposure (resulting from releases from ACM contained within the building) of one or more of these categories of building occupants are elevated above average C1 exposures, then the goal of remediation is to reduce these exposures to acceptable levels without causing, through disturbance of ACM in the process of remediation, a corresponding increase in exposures of C1, C2, or C3 occupants or of remediation workers. Even if current levels of exposure are not detectably elevated, anticipated future disturbances of ACM (for example, because of renovation, intermittent contact, or unique characteristics of a given building) can be expected to cause elevated levels of asbestos exposure of occupants in the future. In these situations, the goal of remediation is to prevent such future elevations from occurring, again without causing a corresponding increase in exposure of remediation workers or of C1, C2, or C3 occupants.

Thus, for remediation to be effective, the integrated population exposure resulting from the remediation must be less than the integrated exposure if there were no remediation. This chapter approaches the problem of determining the effectiveness of remediation strategies in relation to this specific goal.

The factors influencing steady-state air concentrations of asbestos in buildings can be categorized broadly as sources and sinks. Principal sources of airborne asbestos in a building include direct disturbance of ACM by building occupants, secondary releases from settled asbestos-containing dust and debris, infiltration of asbestos fibers from outdoors, and fallout from damaged or deteriorating ACM (see section 4.5, Mechanisms of Release). The principal sinks by which airborne asbestos is removed from buildings include building ventilation, and deposition of asbestos-containing particulate in dust on interior building surfaces, followed by cleaning activities that remove the settled dust. Existing airborne concentrations in a given building represent an equilibrium of these factors at the time samples are taken. Temporal variations in air concentrations due to factors such as occasional maintenance and renovation work or seasonal patterns in building ventilation may be observed. In particular, renovation can cause extensive disturbance of ACM, resulting in elevated exposures for workers (C3) and adjacent building occupants (C1 and C2). In practice, planned renovation work will be the main factor determining potential future increases in exposures.

Since the primary goal of remediation is to reduce exposures of building occupants, decisions regarding the choice of a particular remediation option should, in principle, be based on an evaluation of existing exposures and the potential for future exposure to building occupants (C1, C2, and C3) and abatement workers (C4) under various remediation options. As discussed in Chapter 4, while exposures of C1 occupants in the majority of buildings are near urban background levels, exposures of building occupants who disturb ACM or ACM dust and debris can be substantially higher. Thus, evaluation of current exposures and the resulting need for remediation to reduce them most often focuses on C2 and C3 workers.

There are two basic options for remediation: (1) The ACM can be maintained in place with an O&M program, or (2) The ACM can be dealt with through direct abatement procedures including encapsulation, enclosure, or removal. These procedures may be applied alone or in combination.

5.1 Review of Methods to Survey ACM in Buildings

The first stage of any remediation plan is to carry out a survey to catalogue the type, quantity, condition, and location of all ACM in the building (EPA 1985a, 1990a; Conservation Foundation 1990; Greenaway 1986). The level of detail of the survey will depend upon the specific information required. Records about ACM in a building are often inadequate or incomplete, so field investigation of some sort is usually required. Samples from building materials must be analyzed for asbestos by a reliable laboratory using recognized techniques such as polarized light microscopy (PLM) and x-ray diffraction (XRD) (see section 4.4.4, Bulk Sampling and Analysis), or else be assumed to contain asbestos. Surveys fall into one of the following categories: visual survey (questionnaire), real property transfer survey, system survey, space-by-space survey, and renovation, repair, or predemolition surveys.

The *visual survey* (questionnaire) makes maximum use of existing knowledge about a building in order to minimize costs. It is aimed at making a general determination of what types of ACM are likely to be present. An individual with detailed knowledge of the facility compares his or her knowledge of the materials found in the building's systems against a list of materials that typically contain asbestos (Conservation Foundation 1990; EPA 1990b; Low and Mealey 1990; Real Estate position 1990). Suspect materials, rather than being tested, are assumed to contain asbestos. This type of survey may require little or no specialized knowledge about asbestos in buildings, and as such may minimize the need for trained consultants. The visual survey may be used as the basis for a more complete survey.

A *real property transfer survey* provides general information about the quantity and extent of friable ACM in a facility. This survey is intended to provide sufficient information to fulfill the legal requirements of real property transfer and to evaluate the likely economic impact of the presence of ACM on the market value of the facility. This survey is often based primarily on information the owner has about the facility. Individual building systems may or may not be identified.

A *system survey* identifies specific building systems (for example, hot- or cold-water pipe insulation or fireproofing) that include ACM. Such systems are catalogued, but their location throughout the facility is not necessarily determined. This type of survey provides the minimum information required to notify workers and contractors of the presence of ACM in the building. To be effective, this notification depends on each person's knowledge of the locations of the identified systems and understanding of the O&M procedures required if he or she comes into contact with ACM.

A *space-by-space survey* is the comprehensive survey envisioned by the Asbestos Hazard Emergency Response Act (AHERA) regulation (EPA 1987) for school facilities. The survey's aim is to document compositional information about the ACM located in a facility on a space-by-space basis. Each building system or product that contains asbestos is identified, its composition including asbestos and other components is determined, and its accessibility, condition, and quantity are catalogued by location. The information provided facilitates the development of comprehensive remediation schemes. To save the cost of sample analysis, an asbestos content may be assumed for nonfriable materials that are unlikely to be broken up and made friable in normal use (such as resilient flooring, plaster, and drywall taping compound).

Renovation, repair, and predemolition surveys provide information about the asbestos content of all building materials that are likely to be disturbed by planned work. Both friable and nonfriable materials are sampled during these surveys, and their asbestos content is determined.

Other procedures listed below are sometimes used to gather extra information about a building. Although such investigations do not generate the kind of information gathered through the approaches described above, they provide additional information that can be helpful in making an assessment of the appropriate remediation techniques required for a given building.

An *air sampling survey* develops information on airborne concentrations of asbestos in the atmosphere of a facility. As discussed in section 4.4.1 (Air Sampling Strategies), depending on the design of the sampling program, an air sampling survey can describe personal occupational exposures, air concentrations under conditions at the specific time of the sampling, or, with sufficient coverage over space and time, the long-term ambient air concentrations representative of C1 exposures. Air sampling may also be used to assess the effectiveness of control procedures. In the absence of other indicators, a comprehensive air sampling survey evaluating exposures of C1, C2, and C3 occupants may show the need for remediation. Care must be taken to accurately determine episodic exposures for all groups.

Surface dust evaluation surveys assess the asbestos content of surface dust and debris. A variety of sampling methods have been used (see section 4.4.3, Surface Dust Sampling and Analysis) to collect samples from carpets, fabrics, and horizontal surfaces such as furniture, floors, and shelves. Results have been reported as the number of asbestos structures per unit surface area, mass per unit surface area, or as a percentage concentration in the dust (usually after indirect sample preparation). The concentrations are usually compared with those obtained from control surfaces. Surface dust evaluation provides information that can be useful in determining the priority for and type of remediation required, and in helping to determine if settled dust should be subject to remediation. Surface sampling can also be used to verify surface cleanliness following a decontamination procedure. A surface dust survey should be accompanied by a thorough visual inspection and PLM analysis of suspect debris. The relationship between asbestos in surface dust and either past or present inhalable airborne asbestos concentrations is difficult to evaluate (see section 4.5.3.1, Resuspension of Surface Dust: Interpretational Considerations). However, dustfall samples can be used to determine the spatial and temporal distribution of current asbestos particle deposition with collecting plates placed in the areas of interest. Analysis of the dust collected after a known period of time can provide information on the sources of release.

5.2 Review of Assessment Methods

Assessment refers to various methods customarily used for determining whether remediation is necessary and, if so, what form of remediation is appropriate and in what priority. The EPA, in its current guidance documents (EPA 1985a, 1990a) and in the final rule promulgated under AHERA, states that an O&M program is always necessary where ACM is found (EPA 1987). It should be noted that AHERA regulations apply only to schools; thus, under AHERA, assessment involves only setting priorities and selecting abatement alternatives (encapsulation, enclosure, and removal). The discussion in this report regards assessment as a selection of all the appropriate remediation alternatives, including O&M.

All of the assessment methods in current use consider the accessibility and condition of the ACM under evaluation. It is reasoned that (1) as accessibility increases, so does the likelihood of disturbance, (2) damage to material provides evidence that it has been disturbed in the past and therefore may be disturbed in the future, and (3) the more damaged or deteriorated a material, the more fragile it becomes and the more likely it is to release fibers and ACM debris if disturbed.

The asbestos type in the ACM is usually considered during assessment. Amphiboles are more difficult to wet, and hence control, and thus may be given a higher priority for remediation. None of the assessment methods specifically considers asbestos type in ranking. However, the matrix stratification method described below considers each ACM type individually, and hence can change priority ranking based on material type.

Figure 5-1. Matrix Table

			ACM Condition			
			Intact (Monitor)	**Minor Damage (Patch)**	**Moderate Damage (Cover)**	**Severe Damage (Remove)**
Accessibility	Unrestricted (Public) Space	**Accessible ACM**	OMP	3	2	1
		Inaccessible ACM	O&M	4	3	2
	Restricted Space	**Accessible ACM**	O&M	5	4	3
		Inaccessible ACM	O&M	6	5	4

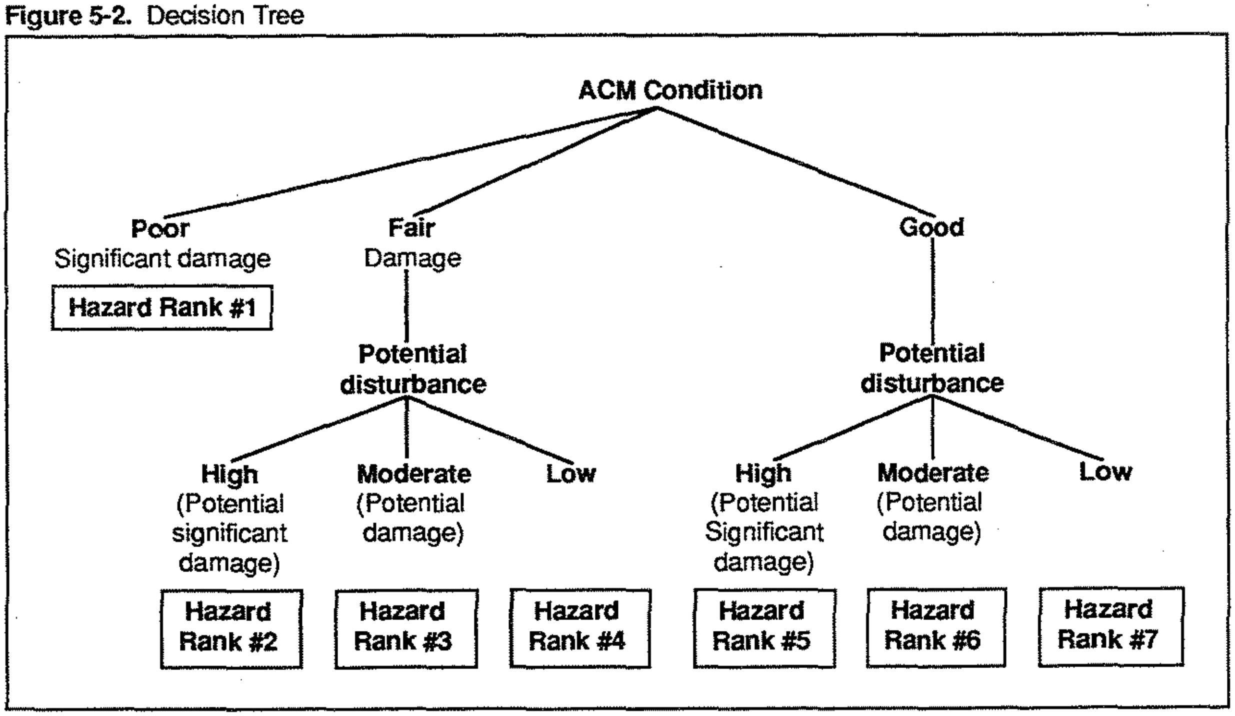
An assessment method for asbestos remediation is illustrated by the above matrix table. ACM accessibility is depicted on one axis and material condition on the other. Accessibility is rated first according to whether access to the space in question is restricted or not, and then whether the material in the space is accessible (can be reached by normal activity in the space). Condition is defined in terms of evident damage, and also by the difficulty of repairing that damage. Response actions range from monitor by an operations and maintenance program (undamaged material) to repair ACM that is slightly or moderately damaged to removal of severly damaged material. Priority for action begins in the upper right hand corner and proceeds diagonally to the lower left.

The following assessment methods have been described in the literature:

The *matrix stratification method* (Sawyer and Morse 1986a; Morse 1988a) considers the accessibility of ACM on one axis, and condition on the other axis, of a four-by-four matrix (Figure 5-1). The space in which the material is found is categorized as either an unrestricted (public) or a restricted space. Materials in the space are then described as accessible or inaccessible. The result is a description of material accessibility broken into four levels. The second axis is used to describe the condition of the material in terms of the work needed to repair the material. The material is either intact (needs no work, therefore only monitoring is indicated), slightly damaged (encapsulant to be applied to holes), moderately damaged (to be covered), or severely damaged (too damaged to repair, therefore to be removed). Considering these factors together provides priorities for remediation activities. For example, material that is highly accessible and badly damaged is given a higher priority for remediation than intact materials in inaccessible locations.

In the *decision-tree method*, branching decisions are based on the condition and potential for disturbance of a material (Keyes et al. 1986; Figure 5-2). The first decision is about the condition of the material, which can be poor (significantly damaged), fair (damaged), or good. If the material is in poor condition it is a priority 1 for remediation. If the material is in fair or good condition, the potential for disturbance is evaluated, taking into consideration the potential for contact, air erosion, and the influence of vibration. Each of these factors can be evaluated as high, moderate, or low. If a material is in fair condition and has a high potential for disturbance, it is priority 2 for remediation, if moderate, priority 3, and if low, priority 4. If a material is in good condition and has a high potential for disturbance, it is priority 5 for remediation, if moderate, priority 6, if low, priority 7. Thus, the decision tree renders seven levels of priority for remediation.

Figure 5-2. Decision Tree



The *algorithm method* (EPA 1979, 1980; Lory et al. 1981; Brandner 1982) assigns a numerical score to each of a number of factors (Figure 5-3). These scores are then combined according to a formula to arrive at a numerical score that establishes priority for each situation. The usual factors considered are condition of the material, water damage, exposed surface area, accessibility, activity and movement, whether there is an open air plenum or direct air stream, friability, and asbestos content.

Figure 5-3. Algorithm

Numerical Exposure Assessment

Factors	Scores			
1. Condition	(0,2,5)			
2. Water damage	(0,1,2)			
3. Exposed surface	(0,1,4)			
4. Accessibility	(0,1,4)			
5. Activity/Movement	(0,1,2)			
6. Air plenum/Air stream	(0,1)		Sum of 1 – 6	
7. Friability	(0,1,2,3)			
8. Percent content	(0,2,3)		Product of 7 and 8	
			Exposure Number	

Additional Comments and/or Illustrations:

Corrective Action:

0 – 12	Deferred action (O&M) Encapsulation
10 – 50	Enclosure
40+	Removal

All of the above assessment methods will result in essentially the same priority ordering of need for remediation if the assessment is performed by one person. The priority order developed by the decision-tree and algorithm methods has been shown to vary significantly across individuals because of the reliance on subjective opinions on the part of the assessor (Patton et al. 1981; Constant et al. 1983). The matrix method is less dependent on subjective determinations and therefore produces more uniform results when a team rather than an individual is involved in the assessment (Sawyer and Morse 1986a). All the assessment methods produce a priority ranking for remediation. The decision-tree and matrix methods also develop direct recommendations for the specific type of remediation needed, while there is no direct relationship between an algorithm score and a particular remediation method. The EPA no longer recommends the use of the algorithm method (EPA 1985a).

5.3 Description of Remediation Methods

For the purpose of this Report, there are two categories of remediation options: (1) an O&M program applied to maintenance, cleaning and renovation activities, and (2) abatement methods including removal of ACM, enclosure of ACM by some rigid, sealed barrier, or encapsulation to embed or coat ACM. These methods may be applied alone or in combination.

5.3.1 Operations and Maintenance

An O&M program is an administrative framework that prescribes the application of specific work procedures to (1) control C2 and C3 worker activities that may disturb ACM, dust, and debris, and (2) respond to any uncontrolled release of material, dust, and debris that does occur. An O&M program is normally applied to cleaning, maintenance, and renovation activities. By controlling the way that these activities are performed, the program prevents or reduces the exposure of workers and prevents the contamination of the building environment by airborne asbestos or asbestos-containing dust and debris. O&M programs also include, where needed, procedures to remove asbestos-containing dust and debris that may be disturbed by C1 occupants or be disturbed in an uncontrolled manner by C2 cleaning personnel or C3 maintenance workers.

Operations and maintenance work procedures were described by Sawyer (1977) in a program in which custodians at the Art and Architecture building at Yale University used wet wiping and high-efficiency particulate air (HEPA) vacuum cleaners to perform normal cleaning and dusting. The principle of using low-volume, high-velocity collection and wet methods for asbestos dust control during cleaning and maintenance activities was initially used in manufacturing industries to control dust, and its application for asbestos control has been described by various authors (Asbestos Research Council 1978; Rajhans and Bragg 1978; Lory 1980). The need for administrative procedures to ensure the use of necessary work practices was first discussed by Sawyer (1984, 1985). The description of these administrative procedures was subsequently refined to focus on either control over areas and systems (Morse and Sawyer 1988) or a permit system (Paull et al. 1986). The EPA described the use of glove bag containment for removal of small areas of ACM (EPA 1983). The use of mini-enclosures for maintenance work was described by OSHA (1986a). The EPA has progressively refined the description of O&M and control procedures in its guidance documents (EPA 1978, 1983, 1985a), and has recently published a guidance document that deals specifically with O&M (EPA 1990) (Green Book). The EPA is in the process of contracting for the development of a companion volume to the Green Book that will contain detailed descriptions of O&M work practices.

5.3.1.1 Basic Components of an Operations and Maintenance Program

The basic components of a successful O&M program are notification, surveillance, controls, work practices, record keeping, and worker protection, training, and oversight (Morse and Sawyer 1979a; EPA 1990a). If an O&M program lacks any of these components, it is likely to fail to control disturbance of the affected ACM.

Notification

Individuals working under an O&M program (C2 and C3 workers) are informed of the type and location of ACM in the facility. This notification is made both to workers employed by the building owner and to outside contractors working in the building.

Building occupants (C1) are notified of the ACM and the nature of the O&M program. O&M procedures include notifications required by regulations such as OSHA hazard communication (1987) (29 CFR 1910.1200) and National Emissions Standards for Hazardous Air Pollutants (NESHAP) material removal (40 CFR, 61 subpart A and M) notifications.

Surveillance

An O&M program includes a plan to observe any changes in the condition of ACM in the building. Surveillance may involve reporting of the condition of ACM observed during routine maintenance, periodic inspections of ACM, and air sampling.

Controls (Policy and Organization)

The owners of a facility initiate an O&M program by formally assigning responsibility to someone who has the necessary authority to implement the program. Building systems and areas of the building where ACM exists are identified and designated as controlled. Existing administrative and management controls used to implement normal operations, maintenance, and renovation are modified to include asbestos O&M procedures. Such modifications can range from the addition of asbestos O&M procedures to normal management controls, to a formal permit system. Administrative procedures are initiated to notify outside contractors of the locations and description of ACM and to ensure that necessary work practices are followed. The O&M program is designed to anticipate the need for periodic abatement projects and to incorporate the necessary administrative steps to ensure that these projects are carried out properly.

Work Practices

Specific work practices are developed that avoid or minimize fiber release during work on ACM. These procedures are used by trained workers for any activity that disturbs ACM. Limits are set on the quantity, type, and location of ACM that a worker with a given level of training and equipment is allowed to disturb.

Record Keeping

All activities of the O&M program are documented. The current location and condition of ACM are tracked. Record keeping required by regulation (for example, OSHA (1980) regulation requirements for records on respiratory protection and medical monitoring) are also included as part of the program.

Worker Protection

An O&M program includes procedures to protect workers and comply with regulations, such as the OSHA regulation (29 CFR 1926.58), that have specific worker protection requirements. Individuals who may disturb asbestos during their work are included in a program of respiratory protection and medical monitoring. Other worker protection measures are provided as necessary, depending on the nature of the work. As required by OSHA, O&M work practices are designed as engineering controls to reduce worker exposure.

Training

The custodial and maintenance staff involved in O&M, as well as the person in charge of implementing the O&M program, are trained. Administrative procedures are instituted to ensure that workers employed by contractors working in the building are also properly trained.

Oversight

The entire program is critically evaluated at periodic intervals. This evaluation considers success of work procedures, effectiveness of administrative controls, adequacy of documentation, compliance with current regulations, level of personnel training, and equipment condition. This audit is carried out by an individual or agency external to the program, from either another division of the organization or an outside consulting firm.

5.3.1.2 Specific Operations and Maintenance Work Procedures

In the context of an asbestos O&M program, any work procedure is a specific series of steps used to accomplish a cleaning or maintenance activity that may disturb ACM. These steps are designed to prevent or reduce exposure of the worker groups (C2 and C3) and contamination of the building environment (and thus exposure of group C1). The OSHA regulation (29 CFR 1926.58) requires that engineering controls be applied to reduce or eliminate exposures of C2 and C3 workers from any activity that could disturb ACM. Initial exposure monitoring is required to determine airborne fiber levels generated by the controlled activity before the work procedure is put into routine use. Based on the measured exposure, respiratory protection must be provided if the PEL or EL is exceeded, or medical monitoring and training if the action level is met. OSHA also requires periodic monitoring to demonstrate that the level of respiratory protection established by initial monitoring continues to be adequate. The evaluation of exposure to C1 occupants during application of work procedures is not directly required by OSHA, but is usually evaluated during design of an O&M program.

Many work procedures used for asbestos control during O&M work originated with local ventilation and dust control measures used in dust-producing manufacturing and milling activities (ACGIH 1986). The use of HEPA-filter devices, wet wiping, and mopping are effective procedures for the cleanup of ACM debris (Sawyer 1977) and for containing the spread of dust. Glove bag containment was added as a control procedure for removal of small quantities of pipe insulation in 1983 (EPA 1983). The widespread use of mini-enclosures as part of O&M procedures began in 1986 after these were described in the revised OSHA construction standard (OSHA 1986a).

Local Collection and Control

Local collection and control of dust and ACM debris (National Institute of Building Sciences [NIBS] 1986; Sawyer 1977) include careful (nondisruptive) work practices used to prevent or minimize material disturbance and hence generation of airborne dust during work on ACM. Wetting is used to suppress airborne dust emissions where disturbance of ACM does occur. Wet cleaning is used to pick up dust. Vacuum cleaners equipped with HEPA filters are used for collection of loose material and to provide localized low-volume, high-velocity ventilation to collect any airborne dust that is generated. The most detailed description of the current practice can be found in the repair and maintenance sections of the 1986 edition of the NIBS Model Guide Specifications, Asbestos Abatement in Buildings (NIBS 1986). These procedures can feasibly be applied to most types of work encountered in cleaning and maintaining buildings, including work in confined and irregularly shaped areas such as spaces above suspended ceilings. (For example, there is no practical way to erect an airtight enclosure in a ceiling plenum with spray-applied fireproofing overhead that is crowded with piping, duct work, and conduit.) The major disadvantage of using these procedures without some sort of enclosure is that failure of the procedure could result in localized contamination.

Localized Containment (Mini-Enclosure)

This type of enclosure is described in the OSHA regulation 1926.58, appendix G. An enclosure large enough for a single person is erected around the area where work is to be performed. Access to this enclosure is usually through a vestibule or changing room. A HEPA-filtered vacuum cleaner is used to maintain the interior of the enclosure at a pressure lower than the surrounding area. The worker inside the mini-enclosure has the same respiratory and other protective equipment and training as an abatement worker. Precautions, such as changing disposal suits, are used to prevent building contamination during worker transit from enclosure to enclosure. Workers decontaminate at the end of the work shift in the same manner as abatement workers. The air enclosed by the mini-enclosure is filtered and interior surfaces of the enclosure are decontaminated prior to dismantling. Enclosures can effectively prevent the spread of dust and debris from operations such as chipping and brushing. However, unless some method is used to ensure that the air and surfaces inside the mini-enclosure remain uncontaminated during the work, the enclosed air and interior surfaces of the enclosure need to be decontaminated before dismantling the enclosure.

Glove Bag Containment

A glove bag is a disposable sack constructed of sheet plastic with inward projecting long-sleeved gloves, and is designed to enclose an object from which ACM is to be removed. The glove bag relies on a seal that is tight enough to prevent the escape of ACM debris and airborne asbestos fibers. The procedures for glove bags are described in Appendix G, "Small Scale Short Duration Work," of the current OSHA regulation (OSHA 1986a). During work, the air inside the glove bag and the interior surfaces of the glove bag are contaminated with asbestos. Consequently, the enclosure is completely exhausted with a HEPA-filtered vacuum cleaner, and the glove bag is disposed of after use rather than reusing it. The potential for leakage makes it prudent for all workers using glove bags to wear respirators.

Current OSHA interpretation of 29 CFR 1926.58 (OSHA 1987; Clark 1989; Cowan 1990; Roberts 1990) allows the use of local collection and control and/or glove bag containment as stand-alone procedures where it is impractical to construct a negative pressure enclosure (such as a mini-enclosure). OSHA requires a negative pressure enclosure for removal, demolition, and renovation operations. The procedures described above can be used alone or in combination. Work performed inside a mini-enclosure can use local collection and control procedures to reduce the need for decontamination and clearance air testing prior to disassembly of the enclosure. Respirators, protective clothing, and provisions for worker decontamination are normally included as a part of all these methods.

5.3.2 Abatement

5.3.2.1 Enclosure

An enclosure seals an ACM behind a permanent barrier that provides sufficient containment to prevent the migration of any airborne asbestos from the enclosure to the building environment (Sawyer and Spooner 1978). An enclosure also limits the possibility of casual disturbances of the ACM. Enclosures are frequently constructed out of gypsum drywall (NIBS 1988a) or other durable materials.

5.3.2.2 Encapsulation

Encapsulation is the treatment of ACM with a material that surrounds or embeds the ACM in an adhesive matrix that either binds the material into a cohesive mass or covers it with a skin, thus preventing the release of fibers. There are three types of encapsulant currently in use. Penetrating encapsulants are designed to completely saturate ACM and bind together all fibers into a cohesive mass. Bridging encapsulants are designed to coat over the ACM with a hard or flexible durable layer. Thermal system encapsulants enclose pipe or equipment insulation with a hard or flexible skin that is frequently reinforced with fabric. Whichever process is used, the material must be inspected regularly for deterioration of the encapsulant, ACM, substrate, or bond between the ACM and substrate.

5.3.2.3 Removal

An asbestos removal project involves the isolation of the work space and removal of ACM by trained, protected workers, followed by cleaning and testing for clearance prior to reoccupancy (Sawyer 1976, 1977). The process as currently implemented is described by the model guide specifications and accompanying study guide developed by the NIBS (Morse 1988a, Morse and Harris 1987). OSHA has specific requirements for the protection of workers during removal.

Work Area Isolation

The asbestos removal work area is isolated from the rest of the building and the outside environment during removal to prevent contamination of other areas. Isolation is accomplished by both a physical separation and an air pressure differential. The physical separation is usually accomplished by the construction of barriers or the augmentation of existing structural barriers. The air pressure in the work area is reduced below that of surrounding areas by exhausting air from the space to the outside through HEPA filters. Pressure differentials on the order of 0.01 to 0.05 inches of H_2O static pressure are common. This arrangement is frequently referred to as a negative pressure enclosure. A failure of the negative pressure enclosure can result in escape of airborne asbestos and exposure of building occupants (group C1).

Worker Training and Protection

The individuals removing asbestos in a contaminated environment are trained in the procedures necessary to do this work safely. Protective clothing and respirators are worn. The regulatory requirements and standards for worker and respiratory protection are comprehensive, and are described as a part of the OSHA regulation for construction workplaces (OSHA 1986a). This regulation is reinforced by specific requirements for respiratory protection (OSHA 1974a), hazard communications (OSHA 1974b, 1987), employee's right to know (OSHA 1980), and general construction safety requirements

(OSHA 1986a). There are also additional standards for respiratory protection (ANSI 1980) and worker protection (ASTM 1982). Some worker groups feel that regulatory requirements are inadequate to protect workers (Sweeney 1989; SEIU 1984, 1990a, 1990b, 1991a, 1991b).

Project Decontamination

Project decontamination (NIBS 1988b) starts by removing and disposing of any internal sheet plastic and drop cloths in the work area. It involves either repeated wet cleaning, or HEPA vacuuming of surfaces to remove settled dust and debris, or both. Frequently, surfaces are sprayed with an asbestos encapsulant to lock down any microscopic asbestos-containing particles that may remain. Ventilation or filtration of air is conducted to remove suspended dust. Inadequate project decontamination can result in high levels of dust in the removal area after reoccupancy, as the result of resuspension of material left behind.

Project Clearance

The last step of removal begins with a visual inspection followed by air testing (NIBS 1988c). These procedures are conducted by someone who represents the owner and is independent of the contractor. After the area has been completely cleaned, it is visually inspected by the owner's representative to determine if it is free of all debris, dust, or residue (ASTM 1990). The work area passes visual inspection only when there is no such material found, regardless of source. If the room was dusty before the start of work, the postabatement cleanings will have rendered it clean. The visual inspection may include the use of wipe samples, dust samples, and various means of disturbance. Only after the area has passed visual inspection are air samples collected and analyzed to determine if airborne fiber levels meet clearance criteria. This procedure is referred to as clearance sampling. EPA guidelines for clearance air sampling after removal of asbestos in buildings were published first in 1979, revised in 1983 (EPA 1983), and again in 1985 (EPA 1985), with further clarification in 1985 (EPA 1985b). The EPA Final Rule and Notice 52 CFR 41821 October 30, 1987, promulgated under AHERA (EPA 1986), gives additional measures for school buildings. These and other publications gave guidance (or a mandatory method) for carrying out clearance sampling and releasing the contractor from further cleaning of the work area. The current guidance for public buildings is that clearance air monitoring involves aggressive sampling with at least five samples collected. For phase contrast microscopy (PCM) clearance, all sample concentrations should be less than 0.01 fibers per milliliter (f/mL). Transmission electron microscopy (TEM), however, is the method of choice (Amick and Karaffa 1986; Karaffa et al. 1986a; Cain et al. 1987); five more samples collected outside each homogeneous work area should be analyzed, and the average work area concentration should be subject to a Student's t test to determine that levels are not statistically different inside and outside the work area. The EPA Final Rule and Notice to AHERA mandated the use of TEM clearance procedures for removals in schools involving more than 160 linear feet of pipe insulation or more than 360 square feet of surface area (effective from 1990). Clearance was based on at least five work-area samples with an average of less than 70 asbestos structures per square millimeter (s/mm^2) or a z test based on at least five work area and five outside samples. There were a number of problems with the clearance testing criteria from these documents (for example, the definition of a homogeneous work area, whether "outside" means "outdoors" or "adjacent to the work area," the effect of variance on the t test, and the assumed variance for the z test). A number of the statistical problems have been resolved in later EPA documents (Chesson 1989), and a revised final rule has been in preparation for some time.

Table 5-1. Effectiveness of Operations and Maintenance Cleaning Procedures in Reducing Current Levels of Asbestos in Air and Dust

Data Source		Level Before Cleaning	Level After Cleaning	Reference
Air levels after a fire HEPA vacuuming and wet wiping	*Pooled mean (TEM)*	14.5 s/L	2.3 s/L	ENTEK 1988
	No. of samples	35	125	
	Range	ND – 266.8 s/L	ND – 41 s/L	
Dust levels after a fire HEPA vacuuming, wet wiping and rubber sponge wiping	*Arithmetic mean (TEM)*	1,120,181 ng/cm^2	3.24 ng/cm^2	ENTEK 1988 – 1989
	No. of samples	137	18	
	Range	0 – 1,471,670 ng/cm^2	0 – 46 ng/cm^2	
Dust levels in furniture contaminated by a fire HEPA vacuuming and wet wiping	*Arithmetic mean (TEM)*	53,248 ng/cm^2	17.18 ng/cm^2	ENTEK 1988 – 1989
	No. of samples	184	108	
	Range	0 – 2,602,766 ng/cm^2	0 – 1,566 ng/cm^2	
Dust levels after an uncontrolled VAT removal HEPA vacuuming and wet wiping	*Arithmetic mean (TEM)*	380,475 s/cm^2	197 s/cm^2	ENTEK 1987
	No. of samples	12	25	
	Range	244 – 2,096,173 s/cm^2	0 – 2,828 s/cm^2	
Dust levels in carpet artificially contaminated with chrysotile HEPA-filtered hot water extraction Low contamination	*Geometric mean*	62 million s/ft^2	18 million s/ft^2	Kominsky et al. 1989
	No. of samples	6	6	
	95% confidence limit	39 – 101 million s/ft^2	8 – 43 million s/ft^2	
Dust levels in carpet artificially contaminated with chrysotile HEPA-filtered hot water extraction High contamination	*Geometric mean*	589 million s/ft^2	196 million s/ft^2	Kominsky et al. 1989
	No. of samples	6	6	
	95% confidence limit	397 – 873 million s/ft^2	85 – 449 million s/ft^2	
Dust levels in carpet artificially contaminated with chrysotile Dry HEPA vacuuming Low contamination	*Geometric mean*	47 million s/ft^2	56 million s/ft^2	Kominsky et al. 1989
	No. of samples	6	6	
	95% confidence limit	37 – 59 million s/ft^2	38 – 83 million s/ft^2	
Dust levels in carpet artificially contaminated with chrysotile Dry HEPA vacuuming High contamination	*Geometric mean*	535 million s/ft^2	447 million s/ft^2	Kominsky et al. 1989
	No. of samples	6	6	
	95% confidence limit	356 – 803 million s/ft^2	240 – 832 million s/ft^2	

5.4 Effectiveness of Remediation Methods

The effectiveness of remediation processes can be evaluated by considering the following in combination: (1) the ability of a remediation process to reduce the potential for future exposures; (2) the increase in exposure experienced by any exposure group as the result of remediation; (3) any reduction in current airborne asbestos levels as the result of the remediation. To be effective, the integrated exposures of C1, C2, C3, and C4 workers resulting from the remediation must be less than the integrated exposures of C1, C2, and C3 workers if there were no remediation. If sufficient data were available, the relative effectiveness of remediation options could be compared by considering the integrated exposure resulting from each. In addition, for removal, the safety of replacement materials and the possible exposure impacts of relocating ACM to landfills need to be considered.

5.4.1 Operations and Maintenance

To evaluate the effectiveness of O&M programs, it is necessary to consider the administrative procedures used to implement the program as well as the work procedures used to reduce exposures.

5.4.1.1 Administrative Procedures

The success of O&M programs depends, in part, on the effectiveness of their administrative procedures. A successful O&M program requires a workable administrative framework that reliably causes asbestos control procedures to be applied to any activity that may contact ACM. Existing administrative systems that control in-house workers or outside contractors performing cleaning, maintenance, and renovation work must be modified. The administrative framework must operate as long as there is ACM in the building and, for long-term effectiveness, the procedures need to be a part of the routine functioning of the building's management.

To date, the asbestos control industry has focused on work procedures and paid little attention to the necessity of developing administrative systems to effect asbestos O&M programs. Training courses and certification programs for designing asbestos control procedures are available. However, there are no courses or certification programs available at this time that teach the application of management systems to asbestos O&M programs. The EPA has recently provided general guidance on the development of O&M programs (EPA 1990b). That document is an introduction to the topic and is a necessary first step in developing a national skill base for the design of O&M programs.

5.4.1.2 Work Procedures

The available data show that O&M cleaning procedures using such methods as wet cleaning and HEPA-filtered vacuum cleaners can be effective in reducing asbestos levels in the air and in dust and debris. Table 5-1 shows that O&M cleaning procedures were successful in reducing air levels from 14.5 to 2.3 structures per liter (s/L), dust levels on surfaces from 1,120,181 to 3.24 nanograms per square centimeter (ng/cm^2), and dust levels on furniture from 53,248 to 17.18 ng/cm^2 in a building contaminated by a fire (Entek 1988, unpublished). Asbestos surface dust levels were reduced by wet cleaning from 380,475 to 197 ng/cm^2 in a building contaminated by an uncontrolled vinyl asbestos tile (VAT) removal (Entek Environmental Services, Troy, NY 1987; unpublished data). A study of asbestos contamination in carpeting showed that HEPA-filtered hot-water extraction reduced levels of carpet contamination, but dry HEPA vacuuming did not produce a statistically significant reduction in asbestos levels. Both wet and dry cleaning methods resulted in elevated airborne asbestos levels during the cleaning operations (Kominsky et al. 1989). Steam cleaning of fabric seats in an auditorium contaminated with acoustic plaster from the ceiling gave reductions on the order of 10 to 84 percent, but produced measurable increases in airborne concentrations during simulations in an enclosure (Nysewander and Rhodes 1990).

There are no data that directly compare airborne levels generated by uncontrolled work procedures to those generated during the application of O&M procedures to the same activities. However, data have been collected on asbestos concentrations (measured by PCM) during a variety of maintenance and cleaning activities performed with and without O&M work procedures. The methods of collection, location of samplers relative to the work, sampling rate, sensitivity of measurement, number of samples, and method of calculating means (arithmetic or geometric) vary widely among these data sets, thus preventing meaningful direct comparison. However, inspection of the data reveals differences of up to several orders of magnitude between similar types of work performed with and without O&M procedures. These data, displayed in Table 5-2, report fiber levels measured by PCM (fibers longer than 5 µm with diameters large enough to be detected by an optical microscope). They show that the use of O&M procedures can result in concentrations that are less than those that have been measured in the absence of O&M procedures. Dry removal of pipe insulation has resulted in airborne levels of 4.1 f/mL (Sawyer 1979a), as compared with 0.02 f/mL for careful wet removal (Entek 1990, unpublished data). Glove bag containment has resulted in levels of 0.02 f/mL (Kominsky and Freyburg 1989a; Hygienetics, Boston, MA 1990; unpublished data). Dry removal of chrysotile-containing dry-spray surface treatments (fireproofing) has resulted in levels of 74.36 f/mL (Sawyer 1976), compared to 0.1138 f/mL during removal of similar material using O&M procedures for installation of sprinkler systems (Entek 1986). Uncontrolled removal of ceiling tiles with sprayed ACM fireproofing above the tiles resulted in 5.45 f/mL (Hamilton 1980) and 0.15 f/mL (CONSAD 1984), as opposed to 0.0085 f/mL when O&M procedures were used (Entek 1987). Inspection work above ceilings without control procedures resulted in levels of 1.3 f/mL (Hamilton 1980) and 0.61 f/mL (CONSAD 1984), as opposed to 0.02 f/mL with O&M procedures (Entek 1987). Cable pulling above ceilings where there is spray fireproofing has resulted in levels of 0.93 f/mL (Hamilton 1980) and 1.1 f/mL (the weighted average is 0.59 f/mL) (Environmental Sciences 1990) when no controls are used, and 0.05 f/mL when O&M procedures are used (Hygienetics 1990). Although no studies are available where airborne levels generated by uncontrolled work procedures were compared directly to levels generated with O&M procedures, these data suggest that O&M procedures can reduce exposures to the fiber levels measured by PCM experienced by C3 maintenance workers during normal maintenance activities. No TEM data are available in the literature on the ability of O&M procedures to reduce asbestos levels generated by maintenance work.

Exposures to C2 (custodial) workers cleaning buildings with asbestos contamination have been measured by PCM at 1.6 f/mL for dry sweeping versus 0.2 f/mL for wet cleaning, and 4.0 f/mL for dry dusting versus 0.3 f/mL for wet wiping and 0.4 f/mL for HEPA vacuuming (Sawyer 1977). Experiments using TEM analysis to determine levels generated during use of HEPA-filtered vacuum cleaners for dry vacuuming and wet extraction (Kominsky and Freyburg 1989b) resulted in levels of 157.7 to 163.9 s/L for hot-water extraction and 224.8 to 253.1 s/L for dry HEPA vacuuming, with the preponderance of fibers too short to be counted by PCM (Table 5-3). PCM equivalent counts were too low to measure. Experiments have shown that, in the past, HEPA vacuums may not successfully filter out all asbestos from air passing through them (Wilson 1975; Daniels

Table 5-2. Phase-Contrast Microscopy Airborne Levels Produced During Activities that Disturb Asbestos-Containing Materials

Type of Remediation		Airborne Levels (PCM) (f/mL)	Control Method	Reference
Dry removal of pipe insulation	*Arithmetic mean*	4.1	None	Sawyer 1987
	No. of samples	Unknown		
	Range	1.8 – 5.8		
Removal of pipe insulation	*Mean*	0.05	Pacification: • wetting and abatement procedures	Piper et al. 1989
	No. of samples	1649		
	Range	SD = 0.10		
Removal of pipe insulation	*Geometric mean*	0.09	Pacification: • wet removal	CONSAD 1984
	No. of samples	11		
	Range	< 0.01 – 0.57		
Removal of pipe insulation	*Pooled mean*	0.02	Pacification: • wetting with amended water • careful removal	ENTEK 1990
	No. of samples	38		
	Range	0 – 0.0212		
Wet removal of small sections of pipe insulation	*Geometric mean*	0.13	Pacification: • wet removal	CONSAD 1984
	No. of samples	4		
	Range	0.03 – 0.92		
Removal of insulation from pipes and boilers	*Geometric mean*	0.46	Pacification: • wet removal	CONSAD 1984
	No. of samples	57		
	Range	< 0.01 – 8.0		
Removal of pipe Insulation	*Geometric mean*	0.30	Pacification: • wet removal	CONSAD 1984
	No. of samples	5		
	Range	0.03 – 2.6		
Removal of boiler insulation	*Geometric mean*	1.8		CONSAD 1984
	No. of samples	7		
	Range	0.20 – 4.4		
Glove bag removal of pipe insulation	*Mean*	0.0217	Containment: • glove bag	Hygienetics 1990
	No. of samples	20		
	Range	0.003 – 0.100		

Table 5-2 (Continued). Phase-Contrast Microscopy Airborne Levels Produced During Activities that Disturb Asbestos-Containing Materials

Type of Remediation		Airborne Levels (PCM) (f/mL)	Control Method	Reference
Glove bag removal of pipe insulation	*Mean*	0.0246	Containment: • glove bag	Kominsky and Freyburg 1989
	No. of samples	10		
	Range	0 – 0.0194		
Glove bag removal of pipe insulation	*Mean*	0.04	Containment: • glove bag	Piper et al. 1989
	No. of samples	434		
	Range	SD = 0.13		
Dry removal of fireproofing	*Arithmetic mean*	74.36	None	Sawyer 1976, 1977
	No. of samples	6		
	Range	SD = 28.57		
Dry removal of fireproofing	*Geometric mean*	4.5	None	CONSAD 1984
	No. of samples	71		
	Range	0.07 – 48		
Dry removal of fireproofing	*Geometric mean*	16.4	None	Paik et al. 1983
	No. of samples	79		
	SD	3.16		
Removal of fireproofing	*Geometric mean*	0.5	Pacification: • wet removal	Paik et al. 1983
	No. of samples	15		
	SD	2.0		
Removal of sprayed on insulation material	*Geometric mean*	0.23	Pacification: • wet removal	CONSAD 1984
	No. of samples	110		
	Range	0.01 – 24		
Removal of acoustical insulation or fireproofing	*Geometric mean*	1.1	Pacification: • wet removal	CONSAD 1984
	No. of samples	255		
	Range	< 0.01 – 170		
Removal of small area of fireproofing for installation of sprinkler system (personal samples)	*Mean*	0.1138	Pacification: • LVHV collection with HEPA vacuum • misting	ENTEK 1986
	No. of samples	22		
	Range	0.013 – 0.46		

Table 5-2 (Continued). Phase-Contrast Microscopy Airborne Levels Produced During Activities that Disturb Asbestos-Containing Materials

Type of Remediation		Airborne Levels (PCM) (f/mL)	Control Method	Reference
Lifting out tiles with asbestos containing debris on top	*Arithmetic mean*	5.45	None	Hamilton 1980
	No. of samples	2		
	Range	SD = 0.07		
Removal of drop ceiling tiles by renovation contractor and/or building maintenance personnel	*Geometric mean*	0.14	None	CONSAD 1984
	No. of samples	11		
	Range	0.02 – 1.4		
Lifting out tiles with asbestos containing debris on top	*Arithmetic mean*	0.0085	Pacification: • LVHV collection with HEPA vacuum	ENTEK 1987
	No. of samples	11		
	Range	0 – 0.01		
Worker checking ventilation above ceilings with sprayed fireproofing	*Arithmetic mean*	1.3	None	Hamilton 1980
	No. of samples	4		
	Range	SD = 1.1		
Incidental exposures of HVAC workers while installing, replacing, repairing, or inspecting equipment near asbestos containing insulation materials	*Geometric mean*	0.61	None	CONSAD 1984
	No. of samples	14		
	Range	0.11 – 6.9		
Routine ajustment of HVAC equipment above suspended ceiling	*Geometric mean*	0.21		CONSAD 1884
	No. of samples	5		
	Range	0.04 – 0.9		
Inspecting above ceilings with sprayed fireproofing	*Arithmetic mean*	0.02	Pacification: • LVHV collection with HEPA vacuum	ENTEK 1987
	No. of samples	11		
	Range	0 – 0.09		

Table 5-2 (Continued). Phase-Contrast Microscopy Airborne Levels Produced During Activities that Disturb Asbestos-Containing Materials

Type of Remediation		Airborne Levels (PCM) (f/mL)	Control Method	Reference
Cable pulling area above ceiling with sprayed fireproofing	*Arithmetic mean*	0.93	None	Hamilton 1980
	No. of samples	4		
	Range	SD = 0.78		
Cable pulling above a ceiling with sprayed fireproofing (personal samples)	*Arithmetic mean*	1.1	None	Environmental Sciences
	No. of samples	13		
	Range	0.07 – 10.27		
Cable pulling area above ceiling with sprayed fireproofing (area samples)	*Arithmetic mean*	0.01	Pacification: • varies	Hygienetics 1990
	No. samples	20		
	Range	0.004 – 0.04		
Cable pulling above a ceiling with sprayed fireproofing (personal samples)	*Arithmetic mean*	0.05	Pacification: • varies	Hygienetics 1990
	No. of samples	9		
	Range	0.024 – 0.1		
Fire-alarm testing (personal samples)	*Arithmetic mean*	0.17		Hygienetics 1990
	No. of samples	4		
	Range	0.084 – 0.27		
Relamping of light fixtures (personal samples)	*Arithmetic mean*	0.047		Hygienetics 1990
	No. of samples	9		
	Range	0.02 – 0.09		
Sweeping of fireproofing debris: Dry sweeping	*Arithmetic mean*	1.6	None	Sawyer 1976
	No. of samples	5		
	SD	0.7		
Sweeping of fireproofing debris	*Arithmetic mean*	0.2	Pacification: • wet wiping	Sawyer 1976
	No. of samples	4		
	SD	Unknown		
Cleaning fireproofing off books: Dry method	*Arithmetic mean*	4.0	None	Sawyer 1976
	No. of samples	6		
	SD	1.3		

Table 5-2 (Continued). Phase-Contrast Microscopy Airborne Levels Produced During Activities that Disturb Asbestos-Containing Materials

Type of Remediation		Airborne Levels (PCM) (f/mL)	Control Method	Reference
Cleaning fireproofing off books	*Arithmetic mean*	0.3	Pacification: • wet wiping	Sawyer 1976
	No. of samples	4		
	SD	Unknown		
Cleaning fireproofing off books	*Arithmetic mean*	0.4	Pacification: • HEPA vacuuming	Sawyer 1976
	No. of samples	8		
	SD	Unknown		
Asbestos abatement at various sites: Dry Removal	*Mean*	0.015	Containment: • asbestos abatement procedures	Piper et al. 1989
	No. of samples	11		
	Range	SD = 0.039		
Asbestos abatement at various sites	*Mean*	0.023	Pacification: • wet removal with regular water	Piper et al. 1989
	No. of samples	6		
	Range	SD = 0.54		
Asbestos abatement at various sites	*Mean*	0.05	Pacification: • wet removal with amended water	Piper et al. 1989
	No. of samples	2034		
	Range	SD = 0.11		
Asbestos abatement at various sites	*Mean*	0.9	Pacification: • wet removal with amended water	Ewing 1983
	No. of samples			
	Range			
Asbestos abatement at various sites Dry removal	*Mean*	17.1	Containment: • asbestos abatement procedures	Ewing 1983
	No. of samples			
	Range			
Asbestos abatement at various sites	*Mean*	0.18	Pacification: • wet removal with amended water	Piper et al. 1989
	No. of samples	1541		
	Range			

1977; Johnston and Clapp 1980, 1985; Karaffa et al. 1987; Wilmoth et al. 1988). There are no equivalent data for current models of HEPA vacuums.

The work targeted for O&M procedures will occur during the normal operation of a building whether controls are in place or not. The initiation of an O&M program is likely to reduce future exposures of C2 and C3 workers by applying controls to work that would otherwise occur in an uncontrolled manner. It is unlikely that potential future exposures of abatement workers (C4) and emergency personnel (C5) would be changed substantially by an O&M program. Although no data are available on this topic, one would expect that C1 occupants would have much less opportunity to be exposed to elevated levels of asbestos if an O&M program is in place.

Table 5-3. Airborne Levels by Transmission Electron Microscopy Produced During Cleaning of Carpets Contaminated with Asbestos-Containing Materials[a]

Type of Remediation		Airborne Levels Before Cleaning TEM (s/L)	Airborne Levels During Cleaning TEM (s/L)	Percent too Short to be Counted by PCM Sampling	Control Method
Carpet cleaning: Highly contaminated carpet	*Arithmetic mean*	76.1	157.7	99.4	HEPA-filtered hot water extraction
	No. of Samples	12	12		
	SD	47.1	69		
Carpet cleaning: Low contaminated carpet	*Arithmetic mean*	67.3	163.9	99.7	HEPA-filtered hot water extraction
	No. of Samples	9	9		
	SD	87.4	91.1		
Carpet cleaning: Highly contaminated carpet	*Arithmetic mean*	142.4	224.8	99.6	Dry HEPA vacuumed
	No. of samples	12	12		
	SD	123.5	149.9		
Carpet cleaning: Low contaminated carpet	*Arithmetic mean*	57.1	253.1	99.7	Dry HEPA vacuumed
	No. of samples	9	9		
	SD	31.5	166.5		

[a] Source: Kominsky and associates (1989).

5.4.1.3 Local Collection and Control

Procedures such as wetting, and local exhaust and collection using HEPA-filtered vacuum cleaners, are standard methods for reducing levels of airborne asbestos during abatement and have a proven record of reducing personal exposures of workers. Reducing dust emissions at the source is the most effective way of preventing the spread of airborne asbestos beyond the point of generation, thus preventing exposures to general building occupants (group C1). Low-volume, high-velocity collection is a standard and well-tested method of controlling exposures in industrial hygiene practice (Rajhans and Bragg 1978; ACGIH 1986). Studies by NIOSH indicate the effectiveness of local area ventilation in controlling exposures during extremely dusty operations, such as opening bags of asbestos (Cooper 1984; Heitbrink 1984). As noted, the data in Table 5-2 show that wet cleaning methods and HEPA-filtered vacuum cleaners can reduce exposure of custodial workers (group C2).

5.4.1.4 Localized Containment (Mini-Enclosures)

The Panel had access to only one source of information on the effectiveness of mini-enclosures (Entek 1985, 1990, unpublished). The data in Table 5-4 show that mini-enclosures can effectively contain elevated airborne asbestos concentrations. Two separate data sets show airborne fiber levels measured by PCM inside mini-enclosures during removal of fireproofing to be 0.16 f/mL compared to 0.0221 f/mL outside containment (Entek 1985), and 0.1105 f/mL inside mini-enclosures compared to 0.0078 f/mL outside containment (Entek 1990). However, the mini-enclosures in this case were decontaminated and tested by visual inspection, followed by AHERA-type TEM clearance sampling. This type of testing is too time-consuming and expensive to be practical for O&M procedures, and alternative procedures that minimize releases are required. There are no studies on the effect that disassembly of mini-enclosures without decontamination and clearance would have on bystander exposure. The use of mini-enclosures without local collection and control is likely to increase exposures of maintenance workers (C3) inside the enclosure, and of general building occupants (C1) at disassembly. Exposures of abatement workers (C4) and emergency personnel (C5) are not likely to be affected by the use of mini-enclosures. Exposure of cleaners (C2) is likely to be lessened by the reduction in the release of dust and debris from the site of the maintenance activity.

Table 5-4. Mini-Enclosure Effectiveness: Air Levels Measured by Phase-Contrast Microscopy Inside and Outside of Enclosure During Asbestos Removal Work

Data Source		Inside Containment (f/mL)	Outside Containment (f/mL)	Reference
Mini enclosure removal of fireproofing	*Arithmetic mean*	0.1105	0.0078	ENTEK 1990
	No. of samples	12	12	
	Range	0.0435 – 0.3509	0 – 0.0489	
Mini enclosure removal of fireproofing	*Arithmetic mean*	0.16	0.0221	ENTEK 1985
	No. of samples	16	14	
	Range	ND[a] – 0.51	ND – 0.07	

[a] ND = not detected.

5.4.1.5 Glove Bag Containment

Glove bags are an important and useful method for carrying out small-scale O&M activities, as they reduce airborne levels and prevent the spread of much of the asbestos debris to make cleanup considerably easier. TEM levels of 60 s/L (Kominsky and Freyburg 1989a) and PCM levels of 0.02 f/mL (Hygienetics, Boston, MA 1990; unpublished data) with glove bag use are much lower than the 4.1 f/mL measured during dry removal of pipe (see Table 5-5; Sawyer 1979a,b). The available data indicate that levels produced during glove bag work can be equivalent to 0.02 f/mL (Entek 1991), or may be lower than

0.13 f/mL (CONSAD 1984), levels produced during careful wet removal without enclosure. There are insufficient data to determine whether or not glove bags reduce airborne levels

Table 5-5. Perimeter Levels at Glove Bags

Remediation Method		Level Outdoors[a]	Level Before Work[a]	Level During Work[a]	Analysis Method	Reference
O&M	*Arithmetic mean*	4	24.6	60	TEM AHERA	Kominsky and Freyburg 1989
	No. of samples	5	10	8		
	SD	4	19.4	29.5		
O&M	*Geometric mean*	NA	NA	0.13	PCM	CONSAD 1984
	No. of samples			4		
	SD			4.5		
Large-scale TSI[b] removal	*Arithmetic mean*	6	77	630	TEM EPA	Hollett et al. 1987c
	No. of samples	2	6	10		
	Range	—	—	230 – 1,500		
Large-scale TSI removal	*Arithmetic mean*	6	85	1,620	TEM EPA	Hollett et al. 1987a
	No. of samples	4	6	12		
	Range	—	—	463 – 2,514		
Large-scale TSI removal	*Arithmetic mean*	0.001	0.0025	0.155	PCM	Hollett et al. 1987b
	No. of samples	4	12	8		
	Range	—	—	0.001 – 0.458		
Large-scale TSI removal	*Arithmetic mean*	0.001	0.0014	0.002	PCM	Hollett et al. 1987d
	No. of samples	4	14	8		
	Range	—	—	0.001 – 0.004		

[a] Units for transmission electron microscopy levels are in s/L; phase-contrast microscopy levels are in f/mL.

[b] TSI = thermal system insulation.

below those attainable by wetting and careful work practices. There are limited studies that suggest that glove bags used for O&M may not completely contain fiber releases. In a recent study, airborne asbestos levels increased from 24.6 s/L before work began to 60 s/L during the work in the vicinity of the glove bag (Kominsky and Freyburg 1989a) (Table 5-5). This change was not statistically significant, however. Another study reported difficulty in sealing glove bags sufficiently to prevent leakage, because of the pressure fluctuations that occur during their use (Hollett 1989). There are no TEM data, obtained during uncontrolled pipe insulation removal, available for comparison. Though limited, the data suggest that the glove bag may be more suited to enclosure of debris and reduction of exposure than to complete isolation of ACM dust. Although capable of reducing emissions, the airborne exposures near glove bag work areas may be sufficiently high to merit precautionary measures for workers, such as respiratory protection, disposable clothing, and showering. Measures may also be necessary to guard against contamination of the building environment, such as performing the work when the building is unoccupied to avoid bystander exposure, shutting down air-handling equipment, establishing controlled access at the worksite, and decontamination (wet wipe and HEPA vacuum) of the site at completion of work. Such precautions are normal in the asbestos control industry (NIBS 1988d). The extent of the extra precautions necessary will vary with the complexity, frequency, and size of the removal. At least one company has produced a glove bag that is intended to operate under negative pressure (Greenfeld 1989; McMillan 1989), which has been approved by OSHA as negative pressure enclosure (Greenfeld 1989; McMillan 1989). The use of glove bags will not have an effect on exposure of the C4 and C5 exposure groups. Exposure of custodial workers (C2) is likely to be diminished by the reduction in the release of dust and debris from the site of the maintenance activity.

Appendix G to the OSHA regulation (29 CFR 1926.58) describes glove bag and mini-enclosure containment as appropriate O&M procedures, but fails to adequately describe local collection and control. This has led to O&M programs that rely on containment without careful work procedures and local collection. Neither containment method is effective as a stand-alone procedure. The proper design of control programs using effective procedures needs to be described more fully at the national level.

5.4.2 Abatement

Abatement procedures include enclosure, encapsulation, and removal.

5.4.2.1 Enclosure

One study was found with limited data on airborne asbestos levels before and after enclosure. Sébastien and associates (1980) reported a substantial reduction in asbestos levels in a highly polluted building (A) in a study of buildings in Paris; the levels at specific sites fell from 751 ng/m^3 to 1 ng/m^3 and 518 ng/m^3 to 1 ng/m^3. A metal lathe and plaster were used to enclose the ACM, followed by cleanup to remove dust and debris.

The NIBS specification describes three levels of worker protection and work area isolation for the installation of gypsum drywall asbestos enclosures (NIBS 1988a). If the drywall is to be attached directly to an ACM, the project is treated similarly to an asbestos removal project. If the work involves infrequent and localized attachment to the ACM, it is treated as an O&M project. If no contact with an ACM is involved, the project is not treated as an asbestos project, except for notification and prophylactic use of respirators and other personal protection equipment. There are no data to support this breakdown, but it is logical in conception. Enclosures that are fabricated from hard, durable materials such as drywall, metal, or masonry should provide a high level of assurance against future exposures from accidental disturbance. Entry into an enclosure for maintenance or other work must be treated as an O&M procedure.

5.4.2.2 Encapsulation

Encapsulation of ACM has been described as sealants applied to ACM surface treatments such as acoustical plasters or fireproofing (Sébastien 1977, 1980; Sawyer and Spooner 1978). A number of problems with this method of remediation are discussed in these reports: high airborne fiber levels during application, potential failure due to damage if the encapsulated surface is accessible to occupants, dependence on the integrity of the treated material and its bond to its substrate, and possible compromise in fire safety. The reports concluded that encapsulation could work to reduce fallout from an ACM if it was in good condition and was out of reach of occupants. Sébastien and coworkers (1980) briefly discussed the difficulties and poor performance of a polyvinyl encapsulant. Lory and Hienzsch (1983) described penetrating and bridging encapsulants and cataloged a number of practical difficulties with selection and installation. This study recommended the use of a field test to evaluate an encapsulant prior to use.

Table 5-6. Airborne Asbestos Mass Concentrations with Encapsulation

Data Source	Type		Before (ng/m^3)	During (ng/m^3) Perimeter	During (ng/m^3) Inside Work Area	Clearance (ng/m^3)	Post Occupancy (ng/m^3)
Chesson et al. 1986[a]	Unpainted ceilings	*Mean*	18.53	0.953	—	0.11	1.91
		No. of samples	9	6	—	10	9
		Range	0.7 – 111	0.2 – 3.3	—	0 – 0.3	0.2 – 4.5
Mirick et al. 1987[b]	First field trial	*Mean*	1.31	207	1273	2.48	4.95
		No. of samples	2	3	6	4	2
		Range	0.62 – 2.0	2.4 – 600	500 – 3300	ND – 7.1	4 – 5.9
Mirick et al. 1987	Second field trial	*Mean*	0.21	—	1703	1.45	—
		No. of samples	2	—	8	2	—
		Range	0.17 – 0.25	—	ND – 4200	1.2 – 1.7	—

[a] Authors ascribe reduced concentrations at clearance and postoccupancy to clean up work performed as part of the work rather than to encapsulation.

[b] Authors ascribe reduced concentrations at clearance to a reduction of activity during sampling. Increases after occupancy were ascribed to increase in activity, restart of HVAC equipment, and contamination from adjacent areas.

Two large studies were conducted for the EPA by Battelle Laboratories to evaluate latex paint (Chesson et al. 1986) and a large number of commercial preparations marketed as encapsulants (Mirick et al. 1987). These studies produced data on airborne levels before, during, and after encapsulation work (Table 5-6). The data show a reduction in airborne asbestos concentrations after the encapsulation, but both studies ascribe this change to other causes (cleaning or a reduction in activity during the sampling). Average airborne levels of 0.022 f/mL experienced by C4 workers applying encapsulant, as reported by OSHA (1990), are equal to or slightly higher than those experienced by removal workers (Table 5-7). This is consistent with earlier observations made by Sawyer (1978) and Lory and Heinzsch (1983). These data suggest that the exposure of abatement workers (group C4) and building occupants (group C1) during the encapsulation of surface treatments may be similar to that during removal, and probably exceeds exposure during O&M. Workers applying encapsulant may be exposed to volatile solvents in a manner similar to exposures experienced by painters. Encapsulated surfaces may remain fragile and subject to damage; thus there will be little, if any, reduction in the potential for future exposure to any maintenance workers (C3) or occupants (C1) who may directly impact the surface. However, a reduction in the dust and debris would be expected to reduce the exposures of C1 occupants, custodians (C2), and maintenance workers (C3).

One goal of the Mirick and associates (1987) study was to determine the acceptability of commercially marketed encapsulants. The encapsulants were evaluated on cohesion and adhesion strength, impact resistance, and adverse affects on fire safety properties. Out of 100 encapsulants tested, only 11 were found to be acceptable and 23 marginally acceptable. A number of practical problems were noted in the study, including incompatibility of materials leading to incomplete penetration or bonding to ACM, fallout or delamination during application due to softening of ACM and weight of the encapsulant, increased difficulty with removal of encapsulated ACM at the time of demolition or renovation, and adverse effects on fire safety properties of the encapsulated material. The encapsulants were tested on sprayed mineral wool that did not contain asbestos. As such, these tests may not be representative of different types of ACM. The results of the Battelle Laboratories tests need to be evaluated for each material for which an encapsulant is being considered.

As noted above, application of encapsulants can have an adverse effect on fire safety of a structure. When applied to fireproofing, a penetrating encapsulant might affect its fire protection rating. Application of an encapsulant adds a combustible material where there was none before. This may violate flame-spread, fuel-contributed, smoke-generated, or other fire-related requirements of the applicable building code and create a safety hazard. Encapsulants may form a membrane of combustible material over ACM, saturate ACM with combustible material, or form a thick layer of plastic foam covered with gypsum-filled polyester (Maloney 1988) to cover ACM. The effect of adding combustible material to a building on building code compliance and fire safety should be evaluated on a case-by-case basis.

At this time, there are no industry standards for determining the suitability of an encapsulant for a particular application or for evaluating the adequacy of an encapsulation job (NIBS 1988a). This makes it difficult to predict the suitability of a particular encapsulant in a given situation, particularly for asbestos-containing surface treatments. Successful application requires compatibility between the encapsulant and the surface to which it is applied, and a high level of cohesiveness within the material and between the material and its substrate. A higher and more uniform level of worker skill is required in encapsulation (where repair of a deficient application may not be possible) than in other abatement methods where deficiencies in the work can be detected by a supervisor and corrected. Test patches are frequently used to determine suitability and effectiveness; however, this determination is largely subjective. There are several field tests available to help evaluate the success of an encapsulation (ASTM Specification for Encapsulants for Friable Asbestos-Containing Building Materials, Proposed Specification P-189). However, these tests are useful only after completion of the work, when repair is difficult or impossible.

Table 5-7. Projected Exposure Levels Resulting from the Use of Respiratory Protection

Description of Work	Area Samples (f/mL)	Personal Samples (f/mL)	Projected Personal Levels with Half-Face Respirator (protection factor = 10)	Levels with Powered Air Purifying Respirator (PAPR) (protection factor = 50)	Reference
Abatement: Removal of surface treatment	0.16	1.1	0.1100	0.0220	CONSAD 1984
Abatement: Removal of surface treatment	0.29	0.23	0.0230	0.0046	CONSAD 1984
Abatement: Removal of boiler insulation	0.5	1.8	0.1800	0.0360	CONSAD 1984
Abatement: Removal of insulation	0.17	0.46	0.0460	0.0092	CONSAD 1984
Abatement: Removal of pipe insulation	0.09	0.30	0.0050	0.0010	CONSAD 1984
Abatement: Encapsulation of surface treatment	0.09	0.17	0.0170	0.0034	CONSAD 1984
Removal of drop ceiling	1.2	0.14	0.0140	0.0028	CONSAD 1984
Sheet metal/HVAC worker	0.02	0.14	0.0140	0.0028	CONSAD 1984
General laborer	0.06	0.14	0.0140	0.0028	CONSAD 1984
HVAC work	0.06	0.21	0.0210	0.0042	CONSAD 1984
O&M: Preventive maintenance on AHU	0.02	0.09	0.0095	0.0019	Hygienetics 1990
O&M: Miscellaneous repair	0.011	0.13	0.0130	0.0026	Hygienetics 1990
O&M: Miscellaneous installation	0.032	0.17	0.0170	0.0034	Hygienetics 1990
O&M: Cleaning debris	0.011	0.20	0.0200	0.0040	Hygienetics 1990
O&M: Generator test	0.004	0.084	0.0084	0.0017	Hygienetics 1990
Cable pulling area above ceiling with sprayed fireproofing (PCM)	0.01	0.05	0.0050	0.0010	Hygienetics 1990

Table 5-7 (Continued). Projected Exposure Levels Resulting from the Use of Respiratory Protection

Description of Work	Area Samples (f/mL)	Personal Samples (f/mL)	Projected Personal Levels with Half-Face Respirator (protection factor = 10)	Levels with Powered Air Purifying Respirator (PAPR) (protection factor = 50)	Reference
Renovation: Carpenter	NA	0.13	0.0130	0.0026	Paik et al. 1983
Renovation: Electrician	NA	0.13	0.0130	0.0026	Paik et al. 1983
Renovation: Sheet metal worker	NA	0.19	0.0190	0.0038	Paik et al. 1983
Renovation: Painter	NA	0.08	0.0080	0.0016	Paik et al. 1983
Renovation: Sprinkler work	0.0018	0.1138	0.0114	0.0023	ENTEK 1987
Removal of pipe insulation		0.02	0.0020	0.0004	ENTEK 1990
Glove bag removal of pipe insulation	0.02	0.14	0.0140	0.0028	Hygienetics 1990
Glove bag removal of pipe insulation		0.0246	0.0025	0.0005	Kominsky and Freyburg 1989

The lack of a history of successful projects and of standards caused NIBS (NIBS 1986; Morse 1988b) to adapt several specification methods. One of these methods allowed the project designer to transfer responsibility for success of the encapsulation to the manufacturer of the encapsulant. It was felt that this may overcome the reluctance of asbestos project designers to use new products.

EPA guidance concerning encapsulation (Sawyer and Spooner 1978; EPA 1983, 1985a) has focused on surface treatments, but has not dealt with the use of encapsulants on thermal system insulation. Encapsulants, particularly bridging encapsulants and nonorganic piping coatings and cements used as encapsulants, have indeed been used successfully in repairing thermal system insulation (Morse 1988c).

5.4.2.3 Removal

In evaluating the effectiveness of removal, it is important to consider the reasons for which removal might be performed. Removal of entire installations of ACM is generally conducted to support renovation or demolition work (for example, the removal of fireproofing as part of a renovation). In conjunction with a well-controlled asbestos removal project, the levels of asbestos in the air and in dust produced by demolition are much lower than those generated by uncontrolled demolition (Tables 5-2 and 5-7); however, it does not necessarily follow that the postabatement levels are satisfactorily low.

Removal of accessible, damaged portions of an asbestos-containing building system is conducted to eliminate the potential for uncontrolled disturbance of such ACM. Such activity can involve the removal of small portions of an asbestos-containing installation (for example, damaged pipe insulation in corridors), or a complete system (for example, damaged and accessible friable acoustical plaster ceilings).

Asbestos removal may also be conducted to remove the source of a continuing supply of asbestos-containing visible debris, or to reduce elevated airborne asbestos levels. The data in Table 5-1 show that O&M procedures, which are essentially the same as decontamination procedures used at the end of asbestos removal projects (Morse 1988d), can reduce levels of asbestos in the air and dust.

To determine the effectiveness of removal as a remediation measure, one must consider exposure increases that may result from the removal process, taking into consideration the efficacy of current practice, available technology, and project clearance methods.

Airborne Asbestos Concentrations Measured Before, During, and After Removal

Studies in which measurements have been taken before, during, and after removal have produced mixed results (from the data reviewed here in Tables 5-8 through 5-12). Out of 31 projects in which clearance levels were reported, 16 reported that levels decreased or remained the same, and 15 reported increased levels. In 23 of the 31 projects, postabatement levels were given; in 10 cases the levels decreased or did not change, and in 13 cases the levels increased. In 18 projects, perimeter samples were presented; in 12 instances levels increased, and in 6 they decreased. The differences observed in the studies seem to be produced by site-specific factors, so that it is difficult to draw any generalized conclusions. In addition, the rate of development of asbestos control techniques during the last few years has been rapid. Much of the data that were available for review by the Panel reflect superseded technology and methods. The statistical significance of any observed differences is difficult to assess because of the low counts observed before, during, and after removal. Direct comparison between studies is also difficult, as they each involved different site conditions, sampling procedures, and analysis methods.

Review of Results Using Transmission Electron Microscopy (Direct Preparation). Table 5-8 presents data from studies of asbestos removal projects that used direct preparation TEM; the reported results are presented in units of structures per (s/L) to keep it consistent with the convention adapted in Section 4.2. The data show airborne asbestos concentrations for perimeter samples during abatement, aggressive sampling during postabatement, and nonaggressive sampling during postabatement, as they each relate to preabatement concentrations.

The use of glove bags for containment (as an alternative to negative pressure work-area enclosure) in large-scale removal of pipe insulation was studied in four schools (Hollett et al. 1987a,b,c,d) (Table 5-8). In each school, asbestos-containing pipe insulation in several contiguous spaces was completely removed by relocating glove bags down the pipe, and a sufficient amount of material was removed to require NESHAP notification (more than 240 linear feet). (This procedure differs from the customary O&M practice, in which a glove bag is sealed in one location, is used to remove a small quantity of material to permit maintenance work, and is not relocated.) In two schools, nonaggressive TEM samples were collected before and after abatement. Postabatement levels were reported to be significantly higher than preabatement levels (85 s/L preabatement and 259 s/L postabatement at Washburn Elementary; 77 s/L preabatement and 265 s/L postabatement at Bloom Middle School). These results were attributed to leakage from the bags during use

Table 5-8. Air Sampling Before, During, and After Abatement Measured by Directly Prepared Transmission Electron Microscopy (s/L)

Building	Activity		Outside	Before	During Perimeter	Postabatement Aggressive	Postabatement Nonaggressive	Reference	TEM Method
Washburn Elementary School	Glove bag removal	*Mean*	6	85	1,620	282	259	Hollet et al. 1987a	Yamate Level I
		No.	4	6	12	6	6		
		Range	—	—	463 – 2,514	—	—		
Bloom Middle School	Glove bag removal	*Mean*	6	77	630	409	148	Hollett et al. 1987c	Yamate Level I
		No.	2	6	10	6	6		
		Range	—	0 – 89	230 – 1,500	—	—		
Columbus East High School, 1984 (Auditorium): Phase I	Removal of fire proofing	*Mean*	15	167		45.3[a]	13	Karaffa et al. 1986	Yamate Level II
		No.	10	3		3	3		
		Range	6 – 60	135 – 222		—	—		
Columbus East High School, 1984: Phase I	Removal of fire proofing	*Mean*	15	167		725	64	Karaffa et al. 1986	Yamate Level II
		No.	10	3		20	26		
		Range	6 – 60	135 – 222		—	6 – 800		
Columbus East High School, 1985: Phase II	Removal of fire proofing	*Mean*	2.3	0.3	NA	252.6	225.6	Karaffa et al. 1989	Prep: NIOSH 7402 Counting: Yamate Level II
		No.	10	18		18	18		
		Range	0 – 7	0 – 6		0 – 1,520	0 – 820		
Columbus East High School, 1988: Revisited	Removal of fire proofing	*Mean*	0	—			0.33	Powers et al. 1989	Prep: AHERA Counting: Yamate Level II
		No.	5	—			15		
		Range	0 – 0	—			—		

Table 5-8 (Continued). Air Sampling Before, During, and After Abatement Measured by Directly Prepared Transmission Electron Microscopy (s/L)

Building	Activity		Outside	Before	During Perimeter	Postabatement Aggressive	Postabatement Nonaggressive	Reference	TEM Method
High School 2	Removal of acoustical plaster	*Mean*	0	11		16.2	5.8	Karaffa et al. 1989	Prep: NIOSH 7402 Counting: Yamate Level II
		No.	4	12		12	12		
		Range	0 – 0	0 – 60		0 – 70	0 – 30		
University building: Site 1	Removal of fire proofing	*Mean*	4.8[b]	9.1[c]	8.9	5.6	5.7[d]	Kominsky et al. 1989	Yamate Level II
		No.	11	10	31	5	5		
		SD	—	5.3	9.8	3.9	4.6		
University building: Site 2	Removal of fire proofing	*Mean*	0.8[b]	36.7[c]	30.4	308.2	241[d]	Kominsky et al. 1989	Yamate Level II
		No.	10	5	31	5	7		
		SD	—	73.9	45.9	176.7	149.5		
University building: Site 3	Removal of fire proofing	*Mean*	0[b]	0.1[c]	12.9	2.3	2.8[d]	Kominsky et al. 1989	Yamate Level II
		No.	6	8	49	7	2		
		Range	0 – 0	SD = 0	SD = 27	SD = 1.9	SD = 3.9		
Corvallis Environmental Research Lab, 1984: Phase I	Removal of surface treatment (amosite 80%)	*Mean*	6	15[e]	—	37[f]	10[e]	Karaffa et al. 1986	Yamate Level II
		No.	2	3	—	9	9		
		Range	5.5 – 15	11 – 24	—	—	< 5 – 28		
Corvallis Environmental Research Lab: Phase II 1986 – 1987	Removal of surface treatment (amosite 80%)	*Mean*	3.6	3.6[e]	—	19[g]	3.4[g]	Karaffa et al. 1988	Yamate Level II
		No.	5	5	—	10	10		
		Range	0.8 – 6.4	1.6 – 5	—	6.2 – 43.1	0.5 – 9.4		

Table 5-8 (Continued). Air Sampling Before, During, and After Abatement Measured by Directly Prepared Transmission Electron Microscopy (s/L)

Building	Activity		Outside	Before	During Perimeter	Postabatement Aggressive	Postabatement Nonaggressive	Reference	TEM Method
Office building 1	Removal of wet-spray fire proofing	*Mean*	0	1.45	4.6	1.7[h]	4.1	Entek 1988, 1990	Prep AHERA Counting Yamate Level II
		No.	3	35	38	384	15		
		Range	0 – 0	ND – 266.8					
Office building 2	Removal of dry-spray fire proofing	*Mean*		4	4.6	4.8[h]		Entek 1987, 1991	Prep AHERA Counting Yamate Level II
		No.		20	25	250			
		Range		0 – 55					
Office building 3	Dry removal of amosite fire proofing	*Mean*	0.9	0		2.7[h]	2.5	Entek 1989, 1990	Prep AHERA Counting Yamate Level II
		No.	5	5		5	9		
		Range		0 – 0					

[a] A garage door was opened during sampling. This may have reduced levels during aggressive testing.

[b] Samples collected before, during, and after abatement.

[c] Perimeter samples before abatement: Site 1 = 5.2 s/L, Site 2 = 3 s/L, Site 3 = 0.8 s/L.

[d] Samples collected after abatement inside the building at the perimeter of the work area.

[e] Postabatement samples collected in areas of the building with no ACM.

[f] Samples collected after two of three spaces abated had been reoccupied.

[g] Samples collected after abated spaces had been reoccupied.

[h] Aggressive clearance samples collected per AHERA requirements. Clearance was based on Yamate Level II counting rules.

and to the practice of relocating the bag down the pipe. Upon analysis of samples collected in the same schools by PCM (see Table 5-9), the asbestos levels were reported not to change appreciably (1.5 s/L preabatement and 1.5 s/L postabatement at Washburn Elementary; 4 s/L preabatement and 4.8 s/L postabatement at Bloom Middle School). Both schools would have failed aggressive PCM or TEM clearance requirements. (Workers in three of the four schools had exposures above the OSHA permissible exposure limit (PEL); the time-weighted average for all four sites was 300 s/L, with the highest short-term exposure of 9,000 s/L.) Much of the difficulty in using the glove bags for large-scale abatement work is the need to traverse along the pipe and replace the bags and seals at regular intervals. The principal conclusion of the studies was that the three types of glove bags used in these studies did not completely contain the asbestos being removed.

The EPA monitored airborne asbestos levels by TEM before and after removal of sprayed fireproofing containing 30 to 60 percent chrysotile from Columbus East High School in Columbus, Ohio (Table 5-8). Removal took place in phases during the summers of 1984, 1985, and 1987. Phase 1 removal was carried out using practices recommended by the EPA and Association of the Wall/Ceiling Industries (AWCI 1981). In 1984 (Karaffa et al. 1986b), airborne asbestos levels were measured before and after removal in one portion (the auditorium) of this multipart project and were found to be lower after removal (13 s/L) than before (167 s/L). Postabatement samples in all areas of the project were lower (64 s/L) than preabatement samples in the auditorium. Both the auditorium and the entire project would have failed aggressive PCM or TEM clearance testing. Phase 2 removal in 1985 (Karaffa et al. 1989) was conducted in accordance with practices recommended by the EPA at the time (EPA 1983). Prior to the phase 2 study, the six work areas had aggressive clearance levels of less than 0.01 f/mL by PCM. Four of the six areas would have failed an aggressive AHERA TEM clearance test. Levels after abatement (225 s/L) were higher than those before (0.3 s/L) (see Table 5-8). Columbia East High School was revisited in 1988, one to four years after abatement (Powers 1989), and two-day samples were collected outdoors and in areas previously abated. Yamate level II direct TEM analysis was carried out and arithmetic means of five samples each on three floors were 0.5, 0.2, and 0.3 s/L, with an overall mean of 0.33 s/L. No ambient asbestos was detected. The inside levels were not found to be statistically different from outside samples.

The EPA sampled airborne asbestos levels before and after removal of acoustical plaster with a 10 percent chrysotile content from ceilings in an unnamed high school. This study was included in the same report as Columbus East High School phase 2 (Karaffa et al. 1989). The removal project was conducted in accordance with practices the EPA was recommending at the time (EPA 1983). Prior to the study, the four work areas at this school had aggressive clearance levels less than 0.01 f/mL by PCM. One of the four areas would have failed an aggressive AHERA TEM clearance test. Levels before abatement (11 s/L) were higher than those after (6 s/L), although the study did not find this difference to be statistically significant (see Table 5-8).

A study performed for the EPA (Kominsky and Powers 1988; Kominsky et al. 1985a, 1989f, 1990) summarized data from removal conducted according to EPA Purple Book guidance (EPA 1985a) of asbestos-containing fireproofing in three university buildings (Table 5-8). Negative-pressure air filtration systems were used at all three sites, with extensive cleaning and lockdown of the asbestos debris. At site 1, the authors found no statistically significant difference between samples collected inside the work area before and after abatement. At the other two sites, the postabatement levels inside the work areas exceeded preabatement levels (36.7 s/L preabatement and 308.2 s/L postabatement at site 2; 0.1 preabatement and 2.3 postabatement at site 3). The study suggested that the differences noted at sites 2 and 3 might be due to aggressive sampling methods used for postabatement samples compared to static sampling for preabatement samples. However, at both sites 2 and 3, nonaggressive perimeter levels during and after removal exceeded preabatement levels, indicating a possible failure in the work-area containment. All three sites would pass the AHERA *z* test clearance if compared to these elevated perimeter levels. Sites 1 and 3 would also pass if comparison was made to outdoor levels, but site 2 would fail if compared to outdoor levels (Kominsky et al. 1990a). Perimeter samples after abatement at site 2 (241 s/L) were approximately 80 times higher than preabatement levels (36.7 s/L) (Karaffa et al. 1986a, 1988). All three sites would pass aggressive PCM clearance testing (Table 5-9). The study concluded that the perimeter of site 2 had been contaminated by a failure of the work-area enclosure, and that clearance testing that allowed comparison to this contaminated area would allow a contaminated work area to be reoccupied. A sampling strategy that monitored the contamination level outside the abatement area was recommended.

An amosite-containing surface treatment was removed from parts of the EPA Corvallis Environmental Research Laboratory in Corvallis, Oregon, in a two-phase project in 1984, and 1986 to 1987 (Karaffa et al. 1988). The EPA monitored asbestos levels after abatement work had been completed. No preabatement samples were collected. Table 5-8 presents data on airborne asbestos levels in this building as measured by direct preparation TEM. At the completion of phase 1, concentrations measured in the abatement area after reoccupancy (10 s/L) were lower than areas of the building with no ACM (15 s/L), but higher than outdoor levels (6 s/L). After phase 2, sample concentrations in the abatement area (3.45 s/L) were lower than concentrations in areas of the building with no ACM (36 s/L), and slightly lower than outdoor levels (3.6 s/L). The precision of the TEM analysis in phase 2 was questioned because a blind recount analysis of 12 of the samples produced results that were higher than those of the first analysis. Aggressive and nonaggressive samples were collected after occupancy for both phases. Aggressive samples from inside asbestos work areas would have failed *z* test clearance requirements when compared to outdoor samples. PCM samples collected at the end of phase 1 (Table 5-9) would not have passed an aggressive clearance test, and were all lower than the TEM samples (Karaffa et al. 1986a).

The EPA study evaluation of asbestos abatement techniques, Phase 3: Removal (Tuckfiled et al. 1988), used mass measurements to evaluate removal techniques. This study is discussed in the section of mass measurements. Amick and colleagues (1986) reported further results and statistical analysis from two schools with 10 removal sites that were part of the EPA Phase 3: Removal study. Samples were prepared by the NIOSH 7402 method and analyzed by the EPA draft interim protocol (Yamate et al. 1984). The effects of aggressive and static clearance sampling were evaluated, but, prior to any TEM sampling, all sites were passed at a 0.01 f/mL level by aggressive sampling and conventional PCM counting. In school 1, sprayed fireproofing containing 30 to 60 percent chrysotile was removed, and a total of 99 samples were analyzed (16 outdoor, 13 field blanks, and 70 indoor samples from six removal sites). Measured levels by both passive and static sampling were higher at all six sites after removal, but due to the high variability in concentrations were not statistically significantly higher before removal than after. The levels were, however, significantly higher in indoor than in outdoor samples after removal, but not before removal, showing that airborne levels had increased. A *z* test was applied to the results: four out of the six aggressive clearances failed and five of the static clearances failed. School 2 had spray-applied acoustical plaster containing 10 percent chrysotile removed from four sites. Airborne concentrations were low, and no statistically significant differences were found. Only one site failed the *z* test during aggressive sampling. The results indicated that the effect of asbestos removal on indoor air quality are unpredictable.

Table 5-9. Air Sampling Before, During, and After Abatement Measured by Phase-Contrast Microscopy

Building	Activity		Outside (f/mL)	Before (f/mL)	During Perimeter (f/mL)	Postabatement Aggressive (f/mL)	Postabatement Nonaggressive (f/mL)	Reference	Method
Washburn Elementary School	Glove bag removal	*Mean*	0.001	0.0015	0.11	0.02	0.0016	Hollet et al. 1987a	f/cc PCM P&CAM 239
		No.	8	12	12	14	14		
		Range	0.001 – 0.001	—	0 – 0.43	—	—		
Bloom Middle School	Glove bag removal	*Mean*	0.0002	0.004	0.052	0.0244	0.0048	Hollett et al. 1987c	f/cc PCM P&CAM 239
		No.	8	12	10	13	13		
		Range	0.001 – 0.003	—	0.043 – 0.096	—	—		
Sands Elementary School	Glove bag removal	*Mean*	0.001	0.0025	0.155	0.0096	0.001	Hollet et al. 1987b	f/cc PCM P&CAM 239
		No.	6	12	8	14	16		
		Range	0.001 – 0.001	—	0.001 – 0.458	—	—		
Winton Place Elementary School	Glove bag removal	*Mean*	0.001	0.0014	0.002	0.0022	0.0011	Hollett et al. 1987d	f/cc PCM P&CAM 239
		No.	6	14	8	14	14		
		Range	0.001 – 0.001	—	0.001 – 0.004	—	—		
Columbus East High School, 1984	Removal of Surface treatment	*Mean*	0.002	0.014	—	0.027	0.008	Karaffa et al. 1986	f/cc PCM P&CAM 239
		No.	10	2	—	14	20		
		Range	0.001 – 0.005	0.014 – 0.014	—	—	0.002 – 0.01		
Corvallis Environmental Research Lab, 1984: Phase I	Removal of surface treatment	*Mean*	0.002	< 0.002[a]	—	0.021	0.003	Karaffa et al. 1986	f/cc PCM P&CAM 239
		No.	5	7	—	9	9		
		Range	0.001 – 0.002	< 0.002 – 0.005	—	0.002 – 0.057	0.005 – 0.018		

Table 5-9 (Continued). Air Sampling Before, During, and After Abatement Measured by Phase-Contrast Microscopy

Building	Activity		Outside (f/mL)	Before (f/mL)	During Perimeter (f/mL)	Postabatement Aggressive (f/mL)	Postabatement Nonaggressive (f/mL)	Reference	Method
University building: Site 1	Removal of fire proofing	*Mean*	0.007[b]	0[c]	0.0023	0.0015	0.0022[d]	Kominsky et al. 1988	f/cc PCM NIOSH 7400 A Rules
		No.	3	10	31	5	5		
		Range	SD = 0.0006	SD = 0	SD = 0.0019	SD = 0.0010	SD = 0.0011		
University building: Site 2	Removal of fire proofing	*Mean*	0.0012[b]	0.0012[c]	0.0015	0.0024	0.0027[d]	Kominsky et al. 1988	f/cc PCM NIOSH 7400 A Rules
		No.	5	5	31	5	7		
		Range	SD = 0.0004	SD = 0.0004	SD = 0.0014	SD = 0.0011	SD = 0.0025		
University building: Site 3	Removal of fire proofing	*Mean*	0.0020[b]	0.0020[c]	0.0106	0.0080	0.0074[d]	Kominsky et al. 1988	f/cc PCM NIOSH 7400 A Rules
		No.	3	8	61	7	5		
		Range	SD = 0.0017	SD = 0.0011	SD = 0.0133	SD = 0.0031	SD = 0.0068		
Various abatement sites	Various	*Mean*	—	0.02	0.04	—	—	Piper et al. 1989	Varies
		No.	—	511	901	—	—		
		Range	—	—	—	—	—		

[a] These samples are postabatement samples collected in areas of the building with no ACM.

[b] Samples collected before abatement.

[c] Work-area samples and perimeter samples before abatement are: Site 1 = 0.0003 f/mL, Site 2 = 0.0014 f/mL, Site 3 = 0.0040 f/mL.

[d] Samples collected inside the building at the perimeter of the work area.

TEM measurements of fibers longer than 5 µm before, during, and after asbestos removal at six sites (Burdett et al. 1989) are summarized in Table 5-10. The results show a pattern of increased levels after abatement, with levels declining through time unless renovation and increased disturbance were present. At college phase 1, postabatement levels of 0.065 f/mL reduced to 0.008 f/mL in 26 weeks, and to 0.0004 f/mL at reoccupancy 35 weeks after abatement. College phase 2 showed a similar reduction through time after abatement, with an initial concentration of 0.0034 f/mL declining to 0.001 f/mL in 9 weeks and to 0.0004 f/mL in 18 weeks. The number of the abated areas returned to the low preabatement levels monitored in the buildings. TEM measurements of all asbestos structures also showed increased levels. Similar increases have also been reported by Walvszewski and Paulsson (1988). Measurements by TEM that consider asbestos fibers or structures of all sizes have reported increased levels after removal at sites in the United Kingdom (Burdett et al. 1988) and Sweden (Waluszewski and Paulsson 1988).

Table 5-10. Air Sampling Before, During, and After Abatement for Fibers Longer than 5 µm[a,b]

Type of Building	No. of Samples	Outdoor (f/mL)	Before (f/mL)	During[c] (f/mL)	After (f/mL)	Reoccupation (f/mL)
College: Phase I	48	0.00015	0.0002	0.29	0.065	0.0004
College: Phase II	43	0.00015	0.0002	—	0.0034	0.0004
Laboratory	58	< 0.001	< 0.0001	0.080/ 0.003	0.014	—
School 1	20		0.002	—	—	0.0008
Factory (test 1)		< 0.003	—	5.3/0.3	—	—
Factory (test 2)		< 0.0003	—	9/0.16	—	—

[a] Source: Burdett and associates (1989).

[b] Concentration measured by TEM

[c] Perimeter.

Levels Determined Using Phase Contrast Microscopy. Table 5-9 presents data from studies of asbestos removal projects that used PCM and reported results in terms of fibers per milliliter (f/mL). Phase contrast microscopy does not distinguish between asbestos and other fibers, and cannot detect fibers less than 0.2 µm diameter (see Chapter 4). (For most of these projects, the results of TEM analysis using the direct preparation method are reported in Table 5-8.) Analysis using the PCM is frequently used to monitor airborne fiber levels inside and outside of asbestos work areas during the course of abatement.

Perimeter levels were reported to be higher than preabatement levels in all eight projects for which this information was reported. These results correspond well to the increases measured by TEM and reported in Table 5-8. Postabatement aggressive samples also showed a trend toward levels elevated above preabatement levels (eight projects showed increases, one project a decrease). Postabatement nonaggressive samples showed no clear pattern in relation to preabatement samples (five projects showed increases, one did not change, and three showed decreases).

Although PCM results of fiber counts outside the enclosure are difficult to interpret if raised levels are found, they are informative of the levels generated in the work area. Two studies in particular have measured levels inside the work area. Piper and colleagues (1989) collated data from 4,538 individual air-monitoring measurements from a number of sources. The purpose of the study was to evaluate asbestos levels in active abatement projects, but the data were mostly taken during small residential removal projects (70 percent), with ACM in the form of friable thermal systems insulation, and from projects that the authors considered to be well-run. Of the 218 personal samples taken during active abatement, the mean fiber concentration was 0.27 f/mL, with the 95th percentile at 0.82 f/mL. The mean concentration for 1,541 area samples inside the containment area was 0.18 f/mL, with the 95th percentile of 0.56 f/mL, and the mean concentration for perimeter samples outside the containment area was 0.04 f/mL for 901 samples. Background concentrations prior to the removal were 0.02 f/mL, based on 511 samples (see Table 5-9). When the data were plotted by year, a progressive decrease was seen in the reported fiber concentrations from 0.94 f/mL in 1981 to 0.03 f/mL in 1988, possibly reflecting the improvement in abatement methods. A small upward trend was found in 1989. Bailey and coworkers (1988) investigated airborne concentrations to which inspectors might be subject when carrying out visual inspection at abatement sites in the United Kingdom. Results obtained over the duration of the visual inspection showed that, of the 100 personal samples collected, 51 were less than 0.01 f/mL, and 12 were less than 0.1 f/mL. As sampling times varied from 5 to 194 minutes, the sensitivity of the PCM analysis was limited and may have overestimated the exposure.

Levels Determined Using Transmission Electron Microscopy (Mass Measurements). Tables 5-11 and 5-12 present data from studies of asbestos removal projects that used indirect preparation TEM and reported results in terms of mass concentration in nanograms per cubic meter (ng/m^3).

Sébastien and colleagues (1980) found increased levels in two buildings where dry removal followed by wet cleaning was used. A study of three schools by Bozzelli and Russell (1982) found significant reductions (50 to 90 percent) in airborne levels one week after removal. This study was limited to nine samples, two before removal and one after in each school, and all but the first two samples were taken while the building was unoccupied. The authors suspected the samples may have been tampered with, as fiber agglomerates of some 200 µm diameter were found. Also, no details of sample preparation were given.

Removal was the focus of two EPA studies known as phase 1 (Chesson et al. 1985) and phase 3 (Tuckfield et al. 1988). In phase 1, four U.S. schools were monitored before, during, immediately after, and five months after removal, with the first and last monitoring taking place during normal occupation (Chesson et al. 1985). Each sample was run for five days and controls were collected both in rooms not containing asbestos and outdoors. The mass concentration remained low both before and after removal (less than 6 ng/m^3) but increased during removal (to 140 ng/m^3 at one school, where a negative air system was not used). The phase 3 study sampled 39 sites in six schools (28 with ACM on the ceiling and walls, 6 indoor sites without asbestos, and 5 outdoor sites) (Tuckfield et al. 1988). The same time sequence for sampling as in the phase 1 study was used. The concentrations during and immediately after the removal were lower, but the levels after reoccupation were the same or slightly higher, than before the removal (pooled average increased from 22.2 to 28.7 ng/m^3). However, as the control samples also increased (14.9 to 26.8 ng/m^3), there appears to be some evidence either that the pollution was disseminated throughout the school, increasing exposures of C1 occupants, or that some other source of asbestos was present. No information on the removal procedures used was given in this study.

Pinchin (1982) gave mass results which showed that four out of five removal sites monitored gave increases after removal (Table 5-12). Pinchin (1982) also gave TEM numerical fiber concentrations from eight Canadian removal sites. Concentrations of all fibers increased at seven out of eight sites after removal.

Table 5-11. Air Sampling Before, During, and After Abatement for All Fibers[a]

Type of Building	No. of Samples (Sites)	Outdoor Range[b]	Before[b]	During[b,c]	After[b]	Reoccupation[b]	Reference
School 1	(3)	0.2 – 4	0.1	12	0.1	0.2	Chesson et al. 1985
School 2	(8)	0 – 0.1	0.3	8.1	0.1	0	
School 3	(3)	0 – 0.3	0.3	15.4	0.3	0.3	
School 4	(3)	0.1 – 0.6	0.4	140.0	0	0.3	
School 1	7	0.1 – 0.9	13.3	0.3	0.2	65.9	Tuckfield et al. 1988
School 2	2	—	51.4	—	—	44.2	
School 3	5	0 – 8.2	18.1	13.7	0.1	15.9	
School 4	4	0 – 0.4	38.4	1.6	5.5	21.3	
School 5	3	0 – 1.2	53.8	6.5	1.0	57.2	
School 6	5	0 – 1.6	15.0	1.2	2.4	8.7	
Building T	3(1)	—	1	—	68/100	—	Sébastien et al. 1980
Building H	2(1)	—	5	—	130	—	
School 1	3(1)	—	5.2/9.2	—	2.3	—	Bozzelli and Russell 1982
School 2	3(1)	—	24.9/29.7	—	2.9	—	
School 3	3(1)	—	38.9/37.7	—	4.9	—	

[a] Mass concentration measured by TEM: all fibers (ng/m^3).

[b] Geometric mean.

[c] Perimeter.

Table 5-12. Air Monitoring Results from Canadian Removal Projects[a]

Project Number	Before Start of Project					During Work Outside Area	After Contract Completion				
	Optical Microscopy Fibers	Transmission Electron Microscopy				Optical Microscopy Fibers	Optical Microscopy Fibers	Transmission Electron Microscopy			
		Total Asbestos Fibers		Asbestos Fibers > 5 µm				Total Asbestos Fibers		Asbestos Fibers > 5 µm	
	(f/mL)	(s/L)	(ng/m³)	(f/mL)	(ng/m³)	(f/mL)	(f/mL)	(s/L)	(ng/m³)	(f/mL)	(ng/m³)
1	0.024	40	2.345	< 0.005	—		0.06	56	0.20	< 0.004	—
	0.020	10	0.092	< 0.005	—		0.04	62	2.05	< 0.004	—
		11	0.044	< 0.005	—		0.01	52	2.00	< 0.005	—
		47	0.330	< 0.005	—		0.17		0.40	< 0.004	—
Average:	0.022	27	0.703	< 0.005		(b)	0.07	57	1.16	< 0.004	—
2	< 0.1	24	4.53	0.003	1.4		0.1	27	154.2	0.002	120.0
	< 0.1	17	2.05	0.002	1.6		0.1	59	64.2	0.008	53.1
	< 0.1	19	3.14	0.004	1.8		0.1	75	177.3	0.013	148.0
		5	1.01	0.002	1.0						
Average:	< 0.1	16	2.68	0.003	1.5	0.2[c]	0.1	54	131.9	0.008	107.0
3	< 0.1	16	2.520	< 0.002	—		0.1	28	16.5	0.002	14.0
	< 0.1	11	1.405	0.002	0.1		< 0.1	36	97.3	0.007	92.0
	< 0.1	17	1.305	0.002	0.1		< 0.1	14	60.3	0.007	60.0
Average:	< 0.1	15	1.743	0.001	0.1	0.69[d]	< 0.1	26	58.0	0.005	55.3
4	< 0.1	10	1.109	0.004	0.68		< 0.1	8	2.68	0.002	2.5
	< 0.1	9	4.309	0.002	2.06		< 0.1	11	0.40	< 0.003	—
	< 0.1	50	4.600	0.003	1.00			10	0.25	< 0.003	—
Average:	< 0.1	23	3.339	0.003	1.25	2.21[e]	< 0.1	10	1.11	0.001	0.8

Table 5-12 (Continued). Air Monitoring Results from Canadian Removal Projects[a]

Project Number	Before Start of Project					During Work Outside Area	After Contract Completion				
	Optical Microscopy Fibers (f/mL)	Transmission Electron Microscopy: Total Asbestos Fibers (s/L)	Transmission Electron Microscopy: Total Asbestos Fibers (ng/m^3)	Transmission Electron Microscopy: Asbestos Fibers > 5 µm (f/mL)	Transmission Electron Microscopy: Asbestos Fibers > 5 µm (ng/m^{3}0	Optical Microscopy Fibers (f/mL)	Optical Microscopy Fibers (f/mL)	Transmission Electron Microscopy: Total Asbestos Fibers (s/L)	Transmission Electron Microscopy: Total Asbestos Fibers (ng/m^3)	Transmission Electron Microscopy: Asbestos Fibers > 5 µm (f/mL)	Transmission Electron Microscopy: Asbestos Fibers > 5 µm (ng/m^3)
5	0.001	77	(f)	0.004	(f)		0.100	140	(f)	0.004	(f)
	0.004	20	(f)	< 0.001	—		0.007	720	(f)	0.080	(f)
	0.004	13	(d)	0.002	(f)		0.011	740	(f)	< 0.001	—
Average:	0.003	37		0.002		0.02[g]	0.039	530		0.028	
6	0.004	15	(f)	0.001	(f)		0.028	100	(f)	< 0.001	—
	0.003	14	(f)	< 0.001	—		0.019	48	(f)	< 0.001	—
	0.004	7	(f)	0.001	(f)		0.019	210	(f)	0.005	(f)
Average:	0.004	12		0.001		0.009[h]	0.022	119		0.002	
7	< 0.001	13	(f)	< 0.001	(f)		0.002	40	(f)	< 0.001	—
	0.003	12	(f)	< 0.001	(f)		0.003	498	(f)	0.034	(f)
	0.002	24	(f)	< 0.001	(f)		0.004	8	(f)	0.003	(f)
Average:	0.002	16		< 0.001		0.009[i]	0.003	182		0.012	
8a	0.04	(f)	(f)	0.004	(f)	0.08	0.00	(f)	(f)	0.01	(f)
	0.02					0.3	0.02				
Average:	0.03			0.004		0.19	0.01			0.01	
8b	< 0.01	19	0.13	< 0.004	—	0.04		172	1301.1	0.024	1200.0
						0.09		340	22.9	< 0.006	—
Average:	< 0.01	19	0.13	< 0.004	—	0.07	0.03[j]	256	662.0	0.012	600.0

Table 5-12 (Continued). Air Monitoring Results from Removal Projects[a]

Source: Pinchin (1982); reprinted with permission.

[a] All results from area samples. Phase-contrast microscopy (PCM) results measured by NIOSH Method P and CAM 239. Individual results and averages are reported.

[b] No samples taken.

[c] Average of six measurements ranging from less than 0.1 to 0.4 fibers/mL.

[d] Average of nine measurements ranging from less than 0.1 to 2.8 fibers/mL.

[e] Average of seven measurements ranging from 0.1 to 8.7 fibers/mL.

[f] Figure not reported.

[g] Average of seven measurements ranging from 0.006 to 0.039 fibers/mL.

[h] Average of eight measurements ranging from 0.006 to 0.013 fibers/mL.

[i] Average of 12 measurements ranging from 0.002 to 0.16 fibers/mL.

[j] Average of five measurements ranging from 0.01 to 0.09 fibers/mL.

Clearance of Abatement Projects

Upon failure of visual inspection, asbestos-containing dust and debris can be left in the work area after abatement has been completed (Abstracts from NIOSH; Brownlee et al. 1988; Kominsky 1989b; Kominsky et al. 1989d, 1991). Such failure can lead to increased postabatement levels because of reentrainment of such dust and debris.

Brownlee and colleagues (1988) and Kominsky and associates (1989c) published a study of 79 New Jersey schools in which extensive visual clearance examination and aggressive clearance sampling were conducted after removal. A total of 598 samples were collected on Nucleopore filters and analyzed by TEM using the Draft Interim EPA method (Yamate et al. 1984). Only 25 samples (4.2 percent) exceeded the clearance concentration of 0.01 s/L, and the authors stated that they "unequivocally demonstrated that postabatement air concentrations of 0.01 s/L can be achieved." This study concluded that a thorough visual inspection strongly influences passing a transmission electron microscopy (TEM) clearance test.

The introduction of AHERA (EPA 1987), and of state regulations for training and licensing, has also improved the performance of abatement, with a relatively high number of passes for removals using the method set out in the EPA Final Rule and Notice (52 CFR 41826, October 30, 1987). Burdett and colleagues (1989) reported results from an industry-wide questionnaire on abatement and found that approximately 90 percent of AHERA-type abatements passed the first time. Kominsky and coworkers (1989a, 1991) reported a study of 20 final clearance sites in New Jersey schools that were subject to AHERA regulatory requirements. Inspectors from the State of New Jersey observed pressure differential equipment and arrangement, final cleaning, visual inspections, and clearance sampling procedures. In 15 of the 20 schools, an additional detailed visual inspection(s) was performed by the state inspector. Clearance was to have been done in accordance with AHERA requirements. A variety of ACMs was removed: 13 sites had surfacing material, 8 had thermal systems insulation, 3 involved both surfacing treatment and thermal system insulation, and 2 had ceiling tile. Eleven abatement contractors performed the work and five analytical laboratories reported results. Not one of the 20 sites observed had fully complied with AHERA clearance. At 14 of the sites the recommended aggressive sampling protocol with the leaf blower was not used, and at 12 sites a stationary fan was not used to maintain constant air movement during clearance sampling. Thorough visual inspection was carried out at all sites, with two visual inspections and one recleaning required at 18 sites by the on-site industrial hygienist, and seven repeat visual inspections and six recleanings required by the New Jersey inspectors. Only 6.7 percent of sites that had been visually cleared by the on-site project monitor passed the additional visual inspection by the state inspectors. Of the 20 sites, 18 were cleared by the EPA Final Rule, with 15 (83 percent) passing on the first attempt.

Sensitivity of AHERA Clearance Requirements

The AHERA clearance standard (EPA 1987) is not designed to detect the low background levels of asbestos typically found in buildings (see Chapter 4). Therefore, the clearance standard does not detect either a decrease or an increase in asbestos levels caused by removal. Table 5-13 gives the levels at which an asbestos abatement project can be cleared for reoccupancy according to requirements of the AHERA regulation. The AHERA clearance protocol specifies counting all structures longer than 0.5 µm using the direct TEM sample preparation method, and presumes a filter background contamination level of 70 s/mm^2 as a threshold that must be exceeded in order for a sample to be distinguishable from background. The lan‹uage of the regulation indicates that the decision to use this level is "based in part on ›son statistics which indicate that four structures must be counted on a filter before the fiber count is statistically distinguishable from the count for one structure.... Four structures per 10 grid openings correspond to approximately 70 s/mm^2."

Table 5-13. Maximum Airborne Clearance Levels Using Various Clearance Criteria[a]

	Volume of Each Sample (L)	Cleared with Zero Structures (Result s/L)	Cleared with Four Structures Per Fifty Openings (< 14 s/mm^2) (Result s/L)	Cleared with Four Structures in Ten Grid Openings (< 70 s/mm^2) (Result s/L)[b]	Cleared with Revised Z-test (Result s/L)[c]	Cleared with Z-test (Result s/L)[d]
Maximum mean asbestos concentration in work area (s/L)	560	NA[e]	NA[e]	NA[e]	6	113.8
	1,200	0	4	22.6	6	58.7
	3,800	0	1.4	7	6	18.9

[a] Data from ENTEK.

[b] Level at which the AHERA regulation allows clearance without comparison to outside samples.

[c] The EPA now recommends the use of 2.5 (half the analytical sensitivity) as the value to use for the Z-test when zero structures are counted on the filter. These results assume the outside samples are clean.

[d] AHERA regulation using Z-test to compare levels inside work area to those outside. Assumes outside samples are clean. Detection limit for Z-test is based on the background filter levels at 70 s/mm^2.

[e] The AHERA regulation does not allow clearance to be based on inside samples alone unless the sample volume for each sample is 1,200 liters or greater.

The regulation allows an asbestos work area to be cleared without comparison to outside samples if the number of asbestos structures counted is below this filter background level. This makes the clearance level dependent on the volume of air filtered. If the minimum sample volume allowed by the regulation for this clearance criterion (1,200 L) is collected, the clearance level will be 22.6 s/L; if the maximum allowed volume (3,800 L) is collected, the clearance level is reduced to 7 s/L.

If the fiber count exceeds 70 s/mm^2, the work area samples must be compared to samples from outside the work area using a z test. If the outside samples are zero, the regulation requires that the "detection limit" for the analysis be used as the comparison concentration, although the regulation never defines the "detection limit." If the filter background level is used as the detection limit, the concentrations that will clear can range from a low of 18.9 s/L for the maximum sample volume allowed (3,800 L) to a high of 113.8 s/L at the lowest sample volume allowed by the regulation (560 L).

Several alternative schemes have been used in the asbestos control industry in an attempt to achieve a lower clearance level without changing the sampling requirements of the AHERA regulation. The EPA now recommends that a value of 2.5 s/L (one-half the analytical sensitivity) be used for the z test for samples with asbestos structure counts of zero (Chesson 1989). Table 5-13 displays the clearance levels that result from the use of various criteria: (1) the Chesson revision to the z test (6 s/L), (2) a limit of no more than four structures on a total of five pooled samples (4 to 1.4 s/L), and (3) a limit of no structures at all. Table 5-14 presents data on 186 work areas for well-controlled asbestos removal projects cleared by the AHERA protocol. Of these work areas, clearance occurred in 41 percent with no structures found in the clearance samples, 79 percent with up to four structures in five pooled samples, and 96 percent with up to four structures in one sample (70 s/mm^2). This suggests that lower clearance levels could be achieved without a large impact on the cost of abatement projects. Table 5-15 presents data on the actual clearance concentrations measured for 169 of the abatement projects in Table 5-14.

The technology exists to attain any desired clearance level within the abatement area. The data in Tables 5-14 and 5-15 suggest that, for well-controlled abatement projects, clearance levels comparable to building background levels can be achieved using current practices. Building clearance mechanisms (ventilation and cleaning) may be sufficient to return postabatement concentrations from the AHERA level to preabatement levels, but there are no data on the effectiveness or speed of this process. Postabatement levels (that is, after building reoccupation) are likely to depend both on the clearance level achieved and on the ability of work practices to contain the work area during the abatement. Sampling conducted after reoccupation as a routine quality assurance check on the abatement process would help to ensure that levels were actually reduced, or at least not increased, by the removal.

Exposure to Workers

The data in Table 5-7 show that, during remediation, the exposure of workers (group C4) can be higher than that for O&M workers and for workers involved in general building maintenance (C2 and C3). Labor groups (SEIU 1984, 1990a, 1990b, 1991a, 1991b) feel that OSHA requirements for respirators and protective equipment are inadequate, and result in unnecessary exposure of abatement and other workers. Workers engaged in abatement work will inevitably experience exposures that exceed that of building occupants. This may occur because of an inadequate level of protective equipment or equipment failure. Table 5-7 also shows that, for well-run removal projects, worker exposures can be reduced to levels equivalent to those found during O&M.

Exposures of groups C1, C2, and C3 can result from failures of work-area isolation measures as well as from inadequate clearance criteria before reoccupancy of the removal site. The data in Tables 5-8, 5-11 and 5-12 on levels outside of, but adjacent to, asbestos removal project areas show an increase in airborne asbestos levels in 12 out of 18 projects monitored. This suggests that for the majority of projects reported in the literature, there is a leakage of airborne asbestos across the containment barriers. This can be explained by the number of faults observed by NIOSH inspections of abatement projects (Table 5-16). Out of 26 removal projects inspected, minor faults were observed in 9 projects and major faults in 5 projects. These faults were observed on the day of inspection, and may represent a continuing problem with the project or an incident that occurred only on the day of inspection. During the time of these inspections (1982 to 1985), one could expect a 35 percent chance of a major fault occurring that could contaminate a building outside of the removal site, and a 54 percent chance that some kind of fault would occur. These are sufficiently high probabilities to account for the elevated levels observed outside removal sites. It is possible that the quality of removal work has improved since that time as the result of the publication of the NIBS specification (NIBS 1986, revised 1988), the establishment, under AHERA, of training requirements for those designing and executing

Table 5-14. Projects Cleared at Various Clearance Levels Using Transmission Electron Microscopy Analysis Required by the AHERA Regulations[a]

Material Type	Cleared with Zero Structures		Cleared with Four Structures per Fifty Grid Openings (< 14 s/mm²)		Cleared with Four Structures in Ten Grid Openings (< 70 s/mm²)[b]		Cleared with *Z*-test[c]		Total Cleared		Number Failed	Total Projects
	No. of Projects	Percent	No. of Projects	Cumulative Percent	No. of Projects	Cumulative Percent	No. of Projects	Cumulative Percent	No. of Projects	Percent		
Amosite surface treatment	4	31	7	85	1	92	1	100	13	81	3	16
Chrysotile surface treatment	52	42	47	79	24	98	2	100	125	91	13	138
Thermal insulation	6	32	7	68	4	89	2	100	19	100	0	19
Vinyl asbestos tile	4	57	2	86	0	86	1	100	7	88	1	8
Ceiling tile	3	60	2	100	0	100	0	100	5	100	0	5
Total	69	41	65	79	29	96	6	100	169	91	17	186

[a] Data from ENTEK.

[b] Level at which the AHERA regulation allows clearance without comparison to outside samples.

[c] AHERA regulation clearance using *Z*-test to compare levels inside work area to those outside.

Table 5-15. Airborne Asbestos Concentrations at Various Clearance Levels Calculated by Pooling TEM Clearance Samples for 169 Abatement Projects

Material Type	Number of Projects		Cleared with Zero Structures (s/L)	Cleared with Four Structures per Fifty Grid Openings (< 14 s/mm²) (s/L)	Cleared with Four Structures in Ten Grid Openings (< 70 s/mm²)[a] (s/L)	Cleared with Z-test[b] (s/L)	Reference
Amosite surface treatment	13	*Pooled mean*	0	2	8.7	19.6	ENTEK 1988 – 1990
		Range	—	—	—	—	
		No. of samples	20	45	5	5	
Chrysotile surface treatment	125	*Pooled mean*	0	1.8	8.7	19.6	ENTEK 1988 – 1990
		Range	—	—	—	—	
		No. of samples	215	222	119	10	
Thermal insulation	19	*Pooled mean*	0	4.1	9.7	39.1	ENTEK 1988 – 1990
		Range	—	—	—	—	
		No. of samples	26	35	15	10	
Vinyl asbestos tile	7	*Pooled mean*	0	2.3	None	None	ENTEK 1988 – 1990
		Range	—	—			
		No. of samples	20	3			
Ceiling tile	5	*Pooled mean*	0	0.9	None	None	ENTEK 1988 – 1990
		Range	—	—			
		No. of samples	15	10			

[a] Level at which the AHERA regulation allows clearance without comparison to outside samples.

[b] AHERA regulation clearance using Z-test to compare levels inside work area to those outside.

Table 5-16. Summary of Observations from NIOSH Inspections of Work Sites

Remediation Method	No. of Projects (Reports)	No. of Fault Free Projects	No. of Minor Faults[a]	No. of Major Faults[b]
Removal	26	12	9	5
Encapsulation	1	1	0	0
Enclosure	0	0	0	0
Glove bag	4	3	1	0
O&M	5	5	0	0
Local exhaust ventilation	8	6	2	0
Total	44	27	12	5

[a] A minor fault is any reported fault that is not major; included are: High fiber levels in work area, inadequate wetting, and plastic failure not in work-area isolation.

[b] A major fault is one that could expose a worker or contaminate adjacent areas of the building; included are nonuse of respirators, failure of negative-air machines, fallen work-area isolation barriers (critical barriers), failed visual inspection after removal of containment measures, and high airborne-fiber levels outside of containment.

abatement projects in schools (1987), and changes in the OSHA regulation. One study seems to indicate an improvement in air levels during abatement (Piper et al. 1989); however, there are insufficient data to determine if a trend exists. High levels outside of abatement areas were found as late as 1987 in abatement projects conducted in accordance with the EPA Purple Book (EPA 1985a) (see Tables 5-8 through 5-12). Many difficulties and faults in abatement and project clearance procedures were found in a study of 20 asbestos abatement projects in New Jersey schools that occurred as late as the summer of 1988 (Kominsky et al. 1988). The task of containing an asbestos abatement area becomes more difficult in high-rise and occupied buildings; hence such abatement projects are more prone to failure (Morse and Harris 1987; Heneveld and Tumulty 1988; Spicer 1990; Tuckey 1990).

The Use of Glove Bags

Glove bags have been used as a stand-alone procedure for removal of asbestos-containing pipe insulation. As discussed earlier, the data in Tables 5-5, 5-8, and 5-9 indicate that use of glove bags in this manner results in increased airborne asbestos levels during and after abatement (Hollet 1987a,b,c,d). The tendency of glove bags to leak has caused the OSHA to require negative pressure enclosures around abatement projects that use glove bags (McMillan 1989). This action by OSHA has resulted in the development of arrangements that allow the interior of the bag to be maintained at a pressure lower than the surrounding area, using interior bracing and a HEPA-filtered vacuum cleaner. It is clear from the data reviewed here that glove bags should never be used as a stand-alone abatement isolation procedure for long pipe runs. Their use should be restricted to small-scale, short-duration O&M operations where a bag is used without being moved.

Other Concerns

Asbestos removal projects will prevent future exposures, to the extent that the removal is complete or untreated areas are clearly identified. Some ACM is left behind by most removal projects, particularly in projects involving removal of spray fireproofing. It is not unusual for asbestos enclosures to be installed in areas that are too confined to permit careful removal and thorough inspection. Fireproofing and pipe insulation are frequently left in place when their access would require demolition of major structural assemblies, such as walls. There is no uniform practice concerning identification and notification about remnants of ACM left behind by removal projects. Unless there is adequate notification, uncontrolled disturbance of the materials left in place, usually by maintenance or renovation workers (C3) could occur.

Using an asbestos encapsulant as a "lock-back" to seal any residue that may remain at the end of a removal project is a standard practice in the asbestos control industry. However, this may cause failure of the bond and other compatibility problems with replacement materials, which can be dangerous when the replacement material is fireproofing.

During removal projects, the area in which the work is to occur must be isolated from other portions of the building. In buildings occupied during the removal, there can be difficulties maintaining access to fire exits. The temporary structures used to isolate the work area and construct decontamination units may be constructed of combustible materials such as plywood and sheet plastic, creating a fire hazard in a building. This becomes a more serious problem if the ACM being removed is a fireproofing that provides fire protection for the building.

Continuous on-site project monitoring independent of the contractor has been recommended as an important part of an abatement project (Morse and Harris 1987; EPA 1985a, 1990). Project monitoring requires proficiency in abatement procedures, contract administration, and air monitoring (NIBS 1986, 1988). There is currently no certification or definition of the project monitor in any federal regulation. A number of states have added this discipline and defined qualifications and training requirements (for example, Florida, New Jersey). In some instances, the lack of a national definition has led to difficulties. For example, New York State Department of Labor Industrial Code Rule 56 separates the project-monitoring and air-monitoring functions and requires them to be independent of one another. This regulation requires that air monitoring be conducted, but does not require continuous project monitoring. The result is a doubling of project-monitoring costs (monitor and air sampler are two independent parties), or the outright elimination of the critical project-monitoring function.

Asbestos-containing or contaminated materials that are removed must be disposed of, generally in a landfill. EPA NESHAP regulations (1990a) require leak-tight containers for waste and disposal of material in landfills. There may be a risk of exposure for transporters and landfill personnel if containers are broken by handling (handling at landfills is usually accomplished with bulldozers or other large earth-moving equipment). There is a risk that waste in lanfills may be uncovered at some point, during later use of the site. When a landfill has been filled to its capacity, it is frequently used for some other purpose. Such use could involve excavation for the purpose of developing the land or for building construction. Responsibility for waste in landfills remains with the generator of the waste, the building owner. In response to this concern, some waste disposal firms are offering indemnification to building owners against any claims that may arise due to disposal in a controlled hazardous-waste landfill. Another alternative is the conversion of asbestos-

Table 5-17. Relative Effect of Remediation by Exposure Group[a]

Remediation Action	C1 Building Occupants	C2 Custodial Workers	C3 Maintenance Workers	C4 Removal Workers	C5 Emergency Personnel	Total All Workers[b]	Total Building Occupants[b] (Except C5)
O&M	(–)[c]	(–)	(–)	(0)	(0)	–3	–3
Removal	(–),(0),(+)	(–),(0),(+)	(–),(0),(+)	(+)	(–),(0)	–3 to +4	–2 to +4
Enclosure	(0),(+)	(–)	(–)	(+)	(0)	–1 to 0	–1 to 0
Encapsulation	(0),(+)	(–)	(0)	(+)	(0)	0 to +1	0 to +1
No action	(0)	(0)	(0)	(0)	(0)	0	0

[a] Increase or decrease of current and future exposure as the result of remediation. No attempt has been made to weight change by level of exposure or size of affected population.

[b] When computing total, (–) and (+) values cancel each other out.

[c] (–) = decrease in exposure; (0) = no change in exposure; (+) = increase in exposure.

containing waste into amorphous glass (a nonasbestos material) by vitrification (Roberts 1989, 1991; Farmer 1987b, c, d; Reilly 1991; NESHAP 1990b).

The AHERA regulation required that each state develop training and certification programs for inspectors, management planners, asbestos abatement designers, workers, and supervisors that were at least as stringent as the AHERA model. All states complied with this mandate, and a number of states have developed other requirements that exceeded the AHERA requirement. AHERA applies only to schools, but in some states the AHERA certifications are required for any asbestos-related work. As a result, training and experience requirements are not uniform from state to state. There is a lack of reciprocity between the states, making the development of a national cadre of well-trained and experienced designers, workers, and supervisors more difficult. The National Asbestos Council established a committee to develop a plan for reciprocity between states and, working with the EPA, has developed a reciprocity process and standardized national examination patterned after the National Council of Architectural Registration Boards (NCARB). The process is gradually winning support from some states. For the program to take effect, each state must individually agree to participate.

5.5 Summary

A survey to locate ACM and an assessment to determine the necessary and appropriate remediation options is a necessary first step.

There are two basic options for remediation: (1) ACM can be maintained in place with an O&M program. (2) ACM can be handled through direct abatement procedures including encapsulation, enclosure, and removal. These procedures may be applied alone or in combination.

The basic components of an O&M program are notification, surveillance, controls, work practices, record-keeping, worker protection, training, and oversight.

Encapsulation is the process of treating ACM with a material that surrounds or embeds the ACM in an adhesive matrix. This matrix either binds the material into a cohesive mass, or covers it with a skin, thus preventing the release of fibers.

Enclosure is the process of sealing an ACM behind a permanent barrier that prevents the migration of any airborne asbestos from the enclosure to the building environment.

Asbestos removal involves the isolation of a space and removal of ACM by trained, protected workers, followed by cleaning and testing for clearance before reoccupancy.

There are insufficient data to allow clear evaluations of the effectiveness of each remediation method. The conclusions that can be reached from the available data are summarized in Table 5-17, which presents the relative increase or decrease in exposure (without weighting for severity of exposure or number of individuals exposed) resulting from each remediation alternative, for each exposure group.

Operations and maintenance programs can decrease exposures for building occupants (C1), custodial workers (C2), and maintenance workers (C3), and they do not affect exposure to removal workers (C4) or emergency personnel (C5). Unless the administration of an O&M program is adequate, it is possible that the application of O&M work procedures will be incomplete or will fall into disuse through time. O&M does not remove the potential hazard from accessible, damaged material that may be contacted in an uncontrolled fashion by building occupants.

Installation of enclosures may either maintain existing levels or cause an increase or decrease in exposures to building occupants (C1). Enclosures can reduce the potential for episodic exposures to building occupants (C1) that result from contact with accessible, friable, damaged ACM. Enclosures can reduce the possibility of dust and debris and hence exposure to custodial workers (C2). Enclosures may protect ACM from damage by incidental contact by maintenance workers (C3) and hence reduce exposures, unless a maintenance activity requires penetration of the enclosure. In this instance, O&M procedures would be necessary to avoid increased exposures. Installation of enclosures can result in exposures of abatement workers (C4) that range up to those experienced by removal workers. Enclosures will have no effect on exposures of emergency personnel (C5).

Encapsulation of surface treatments can generate airborne asbestos levels similar to those encountered during removal of ACM, and may cause an increase, decrease or no change in exposures to building occupants (C1). Encapsulated surface treatments are not sufficiently durable to reduce potential for episodic exposures to building workers (C1) or maintenance workers (C3) resulting from impact on accessible, friable, damaged ACM. Encapsulation can reduce the possibility of fallout, and hence the resultant exposure of maintenance workers (C3), cleaning personnel (C2) and building occupants (C1). Workers installing encapsulants (C4) to friable surface treatments are likely to experience asbestos exposures equal to or greater than those of removal workers, and may also be exposed to organic vapors. Encapsulation will have no effect on exposures of emergency personnel (C5), although it may increase the risk from fire for a building and its occupants. There are practical problems with the application of encapsulants to surface treatments. Encapsulation is, however, an effective means of repairing thermal system insulation or patching small areas of damage in surface treatments.

Removal can either increase or decrease ambient exposures to building occupants (C1). Removal can reduce the potential for episodic exposures to building occupants (C1) from contact with accessible, friable, damaged ACM. Removal can reduce exposure of custodial workers (C2) and maintenance workers (C3) if all ACM is removed or remaining ACM is protected by an O&M program. An improper removal that leaves behind asbestos-containing dust or debris could increase exposures of these groups. Increased airborne fiber levels will be generated during any sort of abatement procedure (encapsulation, enclosure, or removal), generating a potential for exposure of abatement workers (C4). Removal can reduce exposure to emergency personnel (C5) unless a fire occurs during the course of asbestos abatement, or improper abatement has left behind dust and debris that could be distributed by the fire.

Clearance testing methods in current use are not sufficiently sensitive to measure the low background levels typically found in buildings (see Chapter 4), but modifications to the current method could produce greater sensitivity. Glove bags do not completely contain airborne asbestos if used for large-scale removal projects in which the bag is relocated. Continuous on-site project monitoring independent of the contractor helps to prevent problems. Waste in landfills could be a future source of exposure.

If all increases and decreases in exposure are added, without attempting any weighting for severity of exposure or number of individuals exposed, a score related to cumulative exposure for all worker groups can be obtained for each remediation alternative (Table 5-17). Operations and maintenance scores a cumulative reduction of 3, removal ranges from a reduction of 3 to an increase of 4, enclosure ranges from no change to a reduction of 1, and encapsulation ranges from no change to an increase of 1. In theory, it should be possible to add information on the numerical change in exposures and size of the affected population and calculate the cumulative change due to each remediation method in terms of person • fiber concentration • years of exposure. This would enable a more meaningful ranking.

The trade unions and other worker groups feel that the current OSHA standard does not adequately protect workers who contact or disturb ACM. These groups feel that a building inspection rule, more stringent respiratory protection, worker protection, and training requirements are necessary (SEIU 1984, 1990a, 1990b, 1991a, 1991b).

It is unlikely that the application of a single remediation method will be the most effective alternative for any given situation. A more comprehensive view of asbestos control, using each remediation method where it is most appropriate, provides greater overall effectiveness (and cost-efficiency). It is possible that all four remediation methods will be used in a single building. For example, fireproofing above ceilings may be controlled by an O&M program, piping in the boiler may be encapsulated, surface treatments accessible in stairways may be enclosed, and damaged accessible pipe insulation in corridors may be removed.

There is a lack of reciprocity in regulations among the states, making the development of a national cadre of well-trained and experienced designers, workers, and supervisors more difficult.

The literature indicates that any time there is a disturbance of an ACM, there is a possibility that the control procedures will fail and that asbestos will be released into the air. The vagaries of human attention to detail and the inevitable occasional triumph of chaos over human planning and organization makes such releases inevitable. The impact of a release on the individuals immediately involved can be ameliorated by protective clothing, respirators, training, and work procedures. The potential impact on the building environment and general building occupants will depend in large part on the scale of the material disturbance, so that the risk due to large-scale remediation such as encapsulation, enclosure, or removal, exceeds that of the smaller disturbances during O&M.

This seems to argue for the implementation of O&M rather than any other form of remediation. However, O&M alone is frequently not possible for a number of reasons. Accessibility and condition of some or all of the ACM may dictate removal to prevent recurring episodic disturbance of the material. At some point in the history of any building, large-scale renovation or demolition will require that removal be undertaken. Renovation and removal normally occur in a cycle that is determined by the life of active building systems (heating, ventilation, and air-conditioning; plumbing; electrical), the life of interior finishes, and technological innovations leading to more efficient building systems. For public and commercial buildings, this cycle typically has a duration of 20 to 40 years, so that many buildings with ACM, constructed during the building boom between 1950 and 1970, are affected at present.

5.6 Research Needs

1. Further study is necessary to characterize O&M procedures and identify those that are effective.

2. The significance of asbestos in settled dust and its relevance to assessing the effectiveness of O&M procedures needs to be ascertained.

3. Currently, there are no well-defined tests of the effectiveness of encapsulation as a remediation measure. The development of performance indices and acceptance criteria are necessary to enable the evaluation and acceptance of encapsulation work. These measures need to be suitable for field application by the designer or evaluator of the remediation.

4. The current clearance testing methods should be evaluated to see if they are able to detect postoccupancy levels that are equal to or less than preabatement levels or outdoor ambient levels. If current methods are insufficiently sensitive to accomplish this, then new methods should be developed.

5. Clearance procedures and air sampling techniques for small remediation projects (such as mini-enclosures) need to be developed that can be implemented on-site, have an immediate turnaround, and reliably ensure that postremediation levels do not exceed previous levels. This may involve the comparison of test methods (visual inspection, PCM, or Fibrous Aerosol Monitor [FAM]) to TEM sampling for specific materials and activities.

6. There is no guidance generally available on design and execution of asbestos abatement projects in high-rise and other complex structures or industrial sites, such as exists in EPA documents for simpler structures. The ability of current abatement practice to control asbestos removal projects on complex projects should be evaluated, and a publicly accessible record of successful control methods should be developed.

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