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Project Summary

Assessment of Assay Methods for Evaluating Asbestos Abatement Technology

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Two analytical methods and two sampling schemes were evaluated for their effectiveness in a project to remove air-entrainable asbestos from Columbus East High School in Columbus, Indiana. The two analytical methods were phase contrast microscopy (PCM) and transmission electron microscopy (TEM). The sampling schemes included a static method and an aggressive one using a leaf blower.

The study results indicated that the building abatement did meet the PCM specifications in effect at the time, allowing acceptance of the work and reoccupancy. However, the TEM results revealed airborne asbestos concentrations averaging four times outdoor levels with peak values near 1 million asbestos structures/m³. Aggressive sampling amplified the significance of the situation, producing average airborne asbestos concentrations that were 50 times the outdoor levels, with peak concentrations near 1.5 million asbestos structures/m³ of air.

As a result of this study, TEM coupled with aggressive sampling is the currently recommended method of choice for post-abatement clearance.

This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The Technical Assistance Program of the Office of Pesticides and Toxic Substances of the U.S. Environmental Protection Agency (EPA) provides guidance and information on the identification of asbestos-containing materials in buildings and on the correction of potential asbestos hazards. Four EPA Guidance Documents contain much of the technical information about asbestos in nonindustrial settings.[1,2,3,4] These documents describe how to establish an asbestos identification and control program, provide background information and direction to school officials and building owners on exposure assessment, and develop and implement an asbestos abatement program. The most recent asbestos guidance from EPA not only emphasizes recent experience and new information on asbestos control *but also introduces and discusses criteria* for developing an appropriate asbestos control plan.

Considerable scientific uncertainty still surrounds the effectiveness of specific abatement actions in reducing the risk of exposure to airborne asbestos. One critical concern among those responsible for asbestos abatement is how clean the contractor leaves a building (or building area) after removing the asbestos material or after completing work that could have disturbed an asbestos-containing material (e.g., encapsulation, enclosure, or special maintenance operations). The two criteria recommended by the EPA guidance (1983)[3] that was in effect at the outset of this study were visual inspection of the worksite and air monitoring after completion of the project. Visual inspection should detect incomplete removal, damage caused by abatement activity, and (most important) the presence of debris or dust left by inadequate cleanup of the work area. Air monitoring by the membrane filter collection technique and phase-contrast microscopic (PCM) analysis are recommended to supplement the visual inspection and to determine whether elevated levels of airborne fibers generated during the removal process have been sufficiently reduced. This currently recommended optical microscopic technique is one of two methods specified by the National Institute for Occupational Safety and Health (NIOSH) to determine airborne fiber concentrations; it is used by the Occupational Safety and Health Administration (OSHA) to measure total airborne fibers in occupational environments.

The EPA-recommended air-monitoring methodology for determining abatement completion (NIOSH Method No. P&CAM 239) was as follows:

> Air sampling should begin after the project has been completed and all surfaces in the abatement site have been cleaned, perferably within 48 hours after abatement work is finished. A minimum of three air monitors per worksite and at least one per room is recommended. Air is drawn through a membrane filter for about 8 hours at a flow rate of approximately 2 liters per minute. A total air volume of approximately 1,000 liters collected at the specified flow rate should be sampled. After the sampling, a section of the filter is mounted on a microscope slide and treated to form a transparent, optically homogeneous gel. The fibers are sized and counted by using a phase-contrast microscope at 400 to 450X magnification. For counting purposes, a fiber is defined as a particle with a physical dimension longer than 5 micrometers and a length-to-diameter ratio of 3 to 1 or greater.[3]

This method is intended to give an index of the airborne concentration of fibers of specified dimensions in an atmosphere known or suspected to contain asbestos; it is not designed to count fibers less than 5 μm long or to differentiate asbestos fibers from other fibrous particulates.

The most significant limitation of the PCM method compared with transmission electron microscopy (TEM) and scanning electron microscopy (SEM) is that PCM is limited in the detection of fine particles (i.e., those with submicron diameters or lengths less than 5 μm) that may be toxicologically significant. For example, in glove-box tests of simulated industrial mechanical operations on asbestos-containing products (drilling, sawing, and sanding), the PCM method counted fewer than 1 percent of the fibers counted by TEM.[5] Although conditions of this glove-box study were obviously different from asbestos abatement activities, some concern existed about the relative merits and capabilities of the different analytical methods used to determine representative fiber concentrations. Another study estimated that small asbestos fibers (i.e., fibers less than 0.2 μm wide and 5 μm long that are not detected by the PCM method) were present at 50 to 100 times the concentration of the larger, optically visible fibers.[6]

Study Objective

The objective of this research project was to identify and quantify the fine fraction of airborne asbestos fibers present in building atmospheres after an asbestos remedial activity. The project focused on the adequacy of EPA's previously recommended PCM method of analysis and sample collection technique. The PCM method was compared with TEM methods, and the feasibility of an alternative aggressive sampling technique was investigated. The results of this study established the advantages and limitations of applying PCM and TEM analytical methods, both separately and in conjunction with an aggressive sampling technique, to the evaluation of air quality following asbestos abatement.

This project was conducted during the postabatement phase of asbestos removal. Reliable methods of air sampling and analysis permit the use of monitoring results to be included in evaluating the efficacy of asbestos abatement methods and in developing better technical guidance for abatement contractors, building owners, and other parties directly responsible for remedial asbestos programs.

Active or recently completed abatement sites were selected for monitoring because they provided an excellent opportunity to collect real world data, and because the monitoring tasks could be arranged with minimum lead time and coordination.

The conditions in a work area while the final air samples are collected can influence the results of a postabatement assessment. After an abatement action, the air is usually sampled while the area is sealed off, before ventilation is restored, and after at least a 24-hr settling period following the final wet cleaning. Consequently, this monitoring technique may fail to detect residual fibers that have settled on horizontal surfaces during this static condition or that were missed by the cleaning.

Residual asbestos fibers constitute a potential exposure hazard because they could be reentrained later, when the air in the area is agitated by personnel traffic, air flow from ventilation systems, and custodial activities. Thus for more accurate characterization of postabatement fiber concentrations, the work area should experience appreciable air movement to simulate actual use conditions during air monitoring.

The introduction of air turbulence into the work area during the collection of stationary air samples is termed "agressive sampling." This method entails the creation of air movement by the use of blowers, fans, brooms, or compressed air streams to entrain any particulate matter that may be present. The advantages of the aggressive sampling technique over the static (or nonaggressive) sampling are that the former reflects worst-case conditions and that the testing requires a relatively short period. The disadvantages are that this technique is not readily standardized or reproducible, nor does it reflect normal exposure levels to occupants. As with the static sampling method, no criteria have been established to define an acceptable or safe level of fibers in a nonoccupational environment. The research on fiber concentration levels using the PCM and TEM methods is continuing so that the before-, during-, and after-abatement criteria can be developed within the next 2 years.

Project Description

Site Selection

Air monitoring was conducted at two selected sites from which friable asbestos building materials had been removed: Site 1, Columbus East High School, Columbus, Indiana; and Site 2, the U.S. EPA Environmental Research Laboratory in Corvallis, Oregon.

This report describes only the results of the air monitoring survey conducted at Site 1. The monitoring data from Site 2 and the significance of these data are the subject of a separate report. These selected sites met the following criteria:

- The abatement plan involved the removal of friable, spray-applied, asbestos-containing material.
- The contractors carried out the work area preparation, removal, and decontamination in accordance with EPA-recommended specifications and requirements.[1]
- Multiple work areas containing homogeneous asbestos material were available for monitoring.
- The building owner and abatement contractor agreed to cooperate with EPA and to provide access to selected areas of the building.

Abatement Program

A multiphase asbestos abatement and renovation program was conceived and implemented. The first abatement phase was conducted during the summer of 1984 and included the following areas:

Academic Building:
- Third floor - all rooms
- North and south large-group instructional rooms (sidewall enclosures)
- Mechanical penthouses
- Stairwells and elevator shafts
- Industrial arts
- TV studio/publications
- Music rooms
- Auditorium

Gymnasium:
- Storage rooms
- Mechanical room
- Concessions
- Restrooms

Sources of friable, asbestos-containing fireproofing were controlled by removing the material or by placing it in airtight enclosures in areas where complete removal and replacement were not feasible. Decisions regarding the most appropriate control method for each Phase I subspace were based on EPA-recommended assessment factors for evaluating the potential for fiber release.[3]

Asbestos-containing fireproofing insulation had been spray-applied to steel beams and columns on the first, second, and third floors and in mechanical areas. The range of asbestos concentration for this moderately friable material was 30 to 60 percent chrysotile asbestos, based on an analysis of 17 representative bulk samples by polarized-light microscopy and dispersion staining.[7] Throughout these areas, there was a considerable amount of overspray on sections of the corrugated steel deck pan between the treated beams. The treated beams were largely concealed by a suspended lay-in or interlocking steel panel ceiling, but in some areas, the construction design rendered the fireproofed beams visible and exposed.

The structural beams on the lower level had also been sprayed with friable material, but it contained no asbestos. Many of these beams had been enclosed by drywall and therefore were not visible. Other beams on the lower level were concealed above suspended ceilings, and still others were exposed (visible).

Asbestos-containing fireproofing was also found in the gymnasium on the ceiling above the mezzanine level and in the mechanical equipment and storage rooms. The spray-applied material on beams above the suspended ceiling on the lower level of the gymnasium contained mostly fibrous glass and no asebestos fibers.

Procedures

The procedures followed for the removal and enclosure of the asbestos-containing fireproofing at Site 1 were consistent with those described in the EPA guidance documents, and they complied with EPA and OSHA asbestos regulations. Detailed specifications describing the scope of work, the work sequence, and specific performance criteria for the abatement contractor were prepared by the project team and distributed as part of the bid package. The technical job specifications for the removal and enclosure of the asbestos-containing fireproofing were based on the *Guide Specifications for the Abatement of Asbestos Releases From Spray- or Trowel-Applied Materials in Buildings and Other Structures*, published by the Foundation of the Wall and Ceiling Industry.[8]

An industrial hygiene technician was onsite throughout the entire abatement project. The field technician was under the direct supervision of a certified industrial hygienist, who made weekly inspections of the job site and was available for consultation. The first phase of the asbestos abatement program began on May 30 and was completed (excluding final renovation items) by August 11, 1984. The second phase of the abatement program was completed during the summer months of 1985, and the third phase will be completed during the summer of 1986.

Abatement Activities

The abatement activities were performed in three distinct stages: preparation, removal, and decontamination. Each of the building areas included in Phase I were isolated as separate abatement work areas. Some work areas comprised multiple rooms (e.g., the third-floor classroom area and the music area), and some consisted of a single room (e.g., the penthouses, storage rooms, and the TV studio). Each work area was prepared by turning off the ventilation and electrical systems; sealing off all air ducts and openings; covering the floors, walls, and immovable objects with plastic sheeting; installing high-efficiency-particulate-air- (HEPA-) filtered exhaust units; and constructing worker decontamination facilities. Suspended ceilings and carpeting were removed and disposed of as contaminated waste, or they were cleaned and disposed of by conventional means. Workers wearing full protective equipment and approved air-purifying respirators removed the fireproofing by first wetting it with an amended water solution and then scraping it off. The asbestos-containing debris was placed in double 6-mil plastic bags and disposed of at a local EPA-approved sanitary landfill. All substrate materials from which asbestos was removed were wire-brushed and wet-wiped repeatedly to remove as much of the fireproofing material as possible. A dry removal method that did not use the amended water solution was used in the TV studio room to prevent damage to the acoustical panels and electronic equipment in this area.

All stripped or potentially contaminated surfaces were sprayed with an approved asbestos sealant to bond any residual fibers to the substrate. The work area was decontaminated by removing all loose debris, removing the plastic sheeting from the walls and floors, and repeatedly wet-wiping or mopping the walls and floors. When the work area had passed a thorough visual inspection and air monitoring showed that the fiber concentrations were less than 0.05 fiber/cm^3 (the clearance level of the contractor's specifications), the barriers and HEPA-filtered exhaust units were removed, and the area was opened for occupancy by other tradesman responsible for various components of the renovation, for example, fireproofers, painters, electricians, plasterers, and heating, ventilating, and air conditioning (HVAC) installers.

Monitoring Approach

Samples for subsequent PCM and TEM analysis were collected from two or three representative locations within each designated work area after completion of all abatement activities but before any application of replacement fibrous material (e.g., nonasbestos fireproofing). Plastic sheeting on walls and floors had been removed, the substrate had been sprayed with a sealant, and HEPA-filtered exhaust units had been removed. Air sampling was not conducted until the abatement area had passed a rigorous visual inspection by the onsite industrial hygienist and architect. In each designated work area, first static and then aggressive sampling techniques were used. To summarize briefly, filter holders containing either 0.8-μm Millipore mixed-cellulose ester filters (PCM) or 0.4-μm Nuclepore polycarbonate filters (TEM) were positioned (1.4 to 1.7 m) 4.5 to 5.5 ft above the floor at arbitrary locations. Battery-powered sampling pumps were used to draw air through the filters. The constant-flow pumps were calibrated to 2 to 3 L/m and were operated for 6 to 8 hr/test, depending on the contractor's schedule. Samples were collected from several indoor work areas and at outdoor locations during each monitoring period.

In addition to the postabatement monitoring, limited preabatement monitoring was conducted in an area of the auditorium to take advantage of the one opportunity available for preabatement monitoring in the abatement program schedule. Two PCM and two TEM preabatement samples were obtained and analyzed.

Upon completion of each monitoring survey, samples were submitted to the appropriate laboratory for preparation or analysis. The Nuclepore filters were hand-carried to EPA for carbon coating before they were transported to the laboratory for TEM analysis.

Methods of Air Sampling and Analysis

Overview of Sampling Strategy

Samples designated for PCM and TEM analysis were collected with both aggressive and static methods in seven different work areas. Samples were also collected from the surrounding environment outside the building. Each work area consisted of a specific room or rooms and adjacent hallways, closets, or other spaces that were treated as a separate component of the total abatement project. The building areas sampled included the auditorium, gymnasium, industrial arts rooms, music rooms, projection booth, TV studio, and elevators. These sampling locations were not selected as part of a study design; selection was dictated by the contractor's abatement sequence and schedule. After completion of abatement efforts in the individual work areas, representative PCM and TEM samples were collected. All outdoor air samples were collected in the parking lot adjacent to the school building, except for one that was collected on the roof of the building.

All postabatement air samples were collected while the work area was still isolated (i.e., containment barriers were in place) but after (1) the substrate had been sprayed with a sealant, (2) the plastic sheeting covering the walls and floor had been removed, and (3) all surfaces had been wet-wiped. Because of timing, limited preabatement monitoring in one area of the auditorium was conducted before any abatement activity in the auditorium. Insofar as possible, outdoor and indoor air sampling was conducted concurrently, but inclement weather or equipment availability sometimes made this impossible.

Whenever possible, side-by-side samples (one PCM and one TEM) were collected in each work area under static and aggressive sampling conditions. Accessibility restrictions prevented aggressive sampling in some areas. As each building area became available, sampling was performed in the following sequence. Samples designated for both PCM and TEM analysis were collected under nonaggressive conditions approximately 1 to 24 hr following a satisfactory visual inspection of the of work area by the architect and onsite industrial hygienist, depending on the contractor's schedule for final cleaning. Immediately afterward or on the following day, samples for PCM and TEM analysis were again collected, this time under aggressive conditions (i.e., turbulent air movement). Placement of the sampling equipment within each work area was the same during both static and aggressive sampling. The number of samples per work area was not specified by study design, but efforts were made to collect at least two of each type of sample within each work area.

Sampling Equipment

Samples for PCM analysis were collected on 37-mm Millipore, Type AA, mixed-cellulose ester membrane filters (0.8-μm pore size). The filters were preassembled in three-stage polystyrene cassettes by the manufacturer. Samples for TEM analysis were collected on 37-mm Nuclepore polycarbonate membrane filters (0.4 μm pore size). The polycarbonate membrane filter was supported within a three-stage polystyrene cassette by means of a support pad and backup filter (mixed-cellulose ester membrane, 5-μm pore size). Each sample cassette was sealed with a cellulose shrink band to prevent air from entering the sides of the unit during sampling.

Battery-operated personal sampling pumps equipped with rotameters and/or constant-flow controls were used to draw air through the sample filters. All sampling pumps were calibrated with a soap-film flowmeter before and after sample collection. The rotameter setting of each calibrated sampling pump was noted to provide a visual indication of proper pump functioning, and the settings were checked periodically throughout the sampling period.

Sample Collection and Handling

Samples designated for both PCM and TEM analysis were collected at a known flow rate of approximately 2 to 3 L/min (LPM). Sampling duration was 6 to 8 hr. The average sample volume per filter was 1,200 L.

All samples were collected open-faced (i.e., with the face cap of the cassette device removed) to expose the maximum effective surface area of the filter. During sampling, the face caps were carefully stored in clean, resealable, plastic bags. The filter cassettes were positioned at breathing zone height (1.4 to 1.7 m, or 4.5 to 5.5 ft above the floor) and were supported by taping the end of the sampling hose to the wall or clipping it to an adjustable tripod. The sample cassettes were also positioned so that the membrane filters were angled approximately 45 degrees toward the floor.

At the end of the sampling period, each filter cassette was turned upright (i.e., the filter plane was parallel to the floor), the sampling pump was turned off, the face cap of the three-stage filter cassette was repositioned tightly on the cassette, the cassette was disconnected from the sampling hose, a plastic plug was inserted into the cassette outlet, and the cassette was placed face-up in a box for transport. All PCM and TEM filter samples were maintained in this upright position from the time of collection until they were carbon-coated or analyzed by the appropriate laboratory.

The PCM analysis equipment was available at the Columbus East site, and a portion of the PCM samples (final clearance samples collected under static conditions) were analyzed onsite shortly after completion of sampling. Rapid reporting of these sample results was essential so that the building areas could be released to the contractor for additional nonabatement work and renovation. The remaining PCM filters were hand-carried to the laboratory, where they were subsequently analyzed.

The TEM samples were submitted to the EPA Project Officer (or his representative) and hand-carried to EPA in Cincinnati, where they were carbon-coated. The TEM samples were then either shipped by overnight courier or hand-carried to the laboratory for analysis.

Static Sampling

Samples for PCM and TEM analysis were collected under static conditions for comparison with similar samples collected under aggressive conditions. The sampling condition was considered static when air movement in the work area was negligible and/or minimized to the greatest possible extent. Under this condition, asbestos fibers (or any other particulate matter) will settle out if given sufficient time. Any work area, no matter how contaminated, can be totally "clean" as defined by PCM as long as enough time is allowed to elapse before static sampling. The probability of reentrainment of these asbestos fibers is much lower under static conditions than under conditions of typical building use (aggressive sampling conditions). In this study, static sampling conditions existed when the work area was sealed off, all ventilation was shut off, and personnel access was prohibited. These are the typical conditions under which air monitoring is conducted at a work site following asbestos removal and decontamination.

Aggressive Sampling

Samples for PCM and TEM analysis were also collected under agressive sampling conditions. Aggressive conditions were created by introducing air turbulence into the sampling area by intermittent use of a hand-held electric blower. The air movement created was much greater than would exist under conditions of normal building use. Under these aggressive sampling conditions, most asbestos fibers susceptible to entrainment will become airborne and remain suspended for the duration of the sampling period, as long as the use of fans or the hourly introduction of air turbulence is continued. Thus an aggressive environment provided the best possible setting for high or "worst-case" airborne asbestos fiber concentrations following abatement. Figure 1 compares airborne fiber concentrations for PCM and TEM under static and aggressive conditions.

The blower used in this study was a 1-hp electric power blower (Figure 2). The airflow rate at the blower outlet is approximately 8.5 m^3/min (300 ft^3/min). The electric blower was equipped with a two-piece plastic tube extension and concentrator nozzle that enabled the operator to direct the airstream at objects and surfaces within the sampling area.

Aggressive sampling conditions were created in each of the work areas sampled by an initial blow-down of all surfaces, followed by hourly agitation with the blower throughout the duration of the sampling period. During aggressive sampling, all containment barriers isolating the work area were intact, and building air-handling systems remained off. In some instances, it was necessary for the contractor to remove the HEPA filtration units for use in another active work area. Figure 3 shows the aggressive sampling procedure in progress. The sequence of operations is summarized below:

1. A technician entered the work area, positioned the sampling equipment, and started the sampling pumps.
2. Using a back-and-forth motion, the technician directed the airstream of the electric blower at all surfaces within the sampling area (walls, floors, ceilings, all structures between walls, ceilings, and floors, and any other exposed surfaces within the enclosed area). The technician then exited from the sampling area.
3. After approximately 1 hr, the technician reentered the work area and repeated the blow-down of all surfaces. This procedure was then repeated hourly for the duration of the sampling period. Unless actively engaged in manipulating the electric blower, the technician did not remain within the enclosure.
4. At the end of the sampling period, samples were collected, sampling pumps were turned off, and the sampling equipment was removed from the area.

The technician used appropriate respiratory protection and decontamination procedures.

Methods of Analysis

Phase-Contrast Microscopy

All PCM samples were analyzed in accordance with NIOSH Method No. P&CAM 239.[9] This optical microscopic technique is the method the OSHA uses to measure

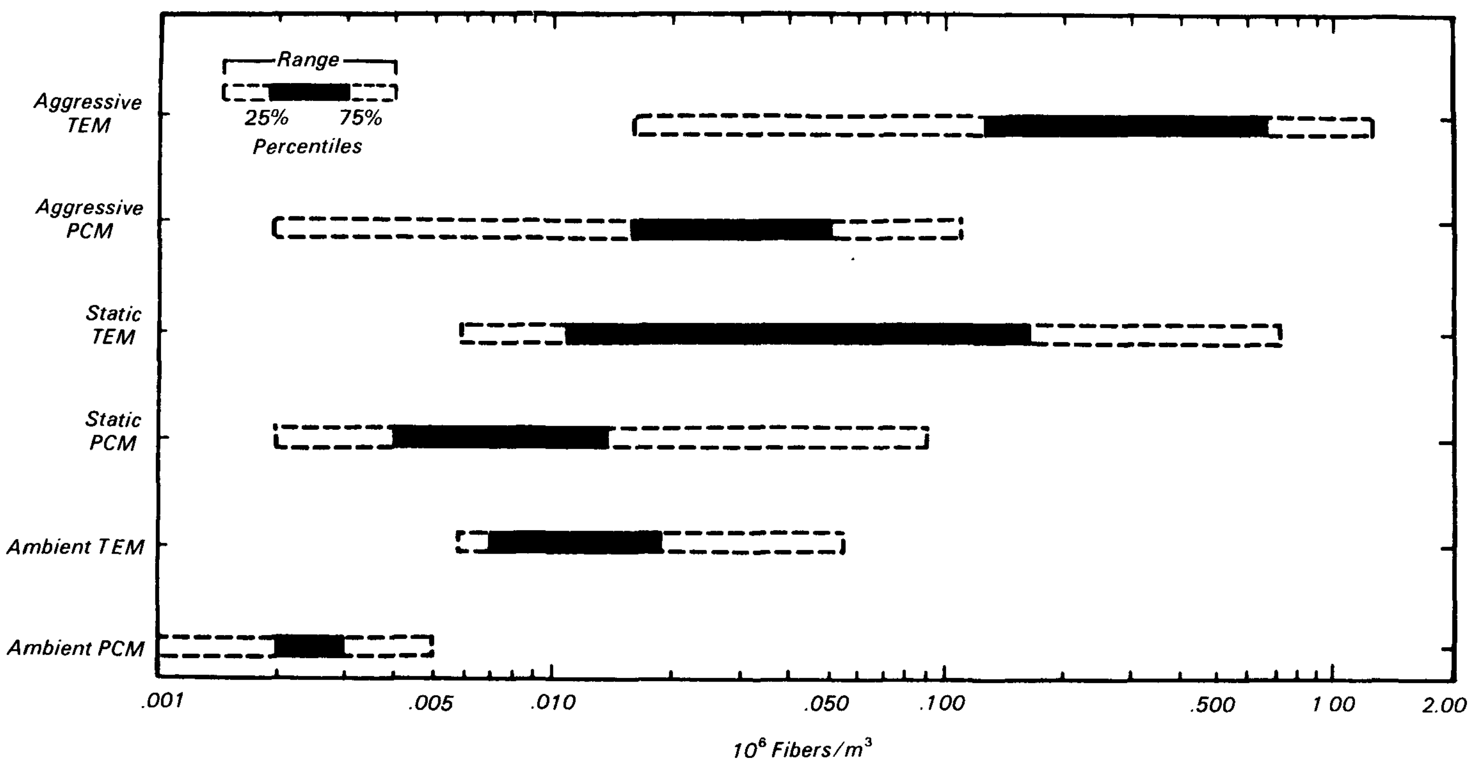

Figure 1. *Comparison of airborne fiber concentrations measured by TEM and PCM under aggressive and static conditions.*

total airborne fibers in occupational environments. The EPA guidance document pertaining to asbestos in buildings recommends a visual inspection followed by air monitoring by the membrane filter collection technique and PCM analysis as one method for evaluating satisfactory completion of asbestos abatement and decontamination of the work site.[3]

Airborne fiber concentrations are determined by NIOSH Method No. P&CAM 239 through microscopic examination of the fibers collected on a mixed-cellulose ester membrane filter. A triangular wedge constituting approximately one-eighth of the entire surface area of the 37-mm-diameter filter is removed from the sample cassette, mounted on a microscope slide, and examined. The filter wedge is rendered into an optically transparent homogeneous gel by the use of a slidemounting solution of 1:1 (by volume) dimethyl phthalate and diethyl oxalate. A microscope equipped with a phase-contrast condenser is used to size and count the fibers at 400 to 450X magnification. Only those fibers longer than 5 μm with a length-to-width ratio of 3 to 1 or greater are counted. Fibers are sized by comparing fiber length with the diameters of the calibrated circles of a Porton reticle. Sample analysis continues until at least 20 fibers or 100 microscopic fields have been counted. Microscopic field areas generally range from 0.003 to 0.006 mm^2.

Transmission Electron Microscopy

Nuclepore filters were prepared and analyzed for asbestos content by TEM in accordance with the *Methodology for the Measurement of Airborne Asbestos by Electron Microscopy.*[10] The current TEM methodology was developed particularly for application to samples collected from a volume of air in which the asbestos concentration is considered a minor component of the total particulate loading. Carbon coating of the samples was performed by the EPA staff. Sample preparation and analyses were completed by the TEM laboratory.

Three levels of TEM analysis are described in the methodology. Briefly summarized, Level I TEM analysis involves examination of the particulates deposited on the sample filter by a 100-kV TEM. Asbestos structures (fibers, bundles, clusters, and matrices) are counted, sized, and identified as to asbestos type (chrysotile, amphibole, ambiguous, or no identity) by morphology and by observing the selected area electron diffraction (SAED) patterns. The width-to-length ratio of each particle that is counted is recorded. Level II TEM analysis consists of a Level I analysis plus chemical elemental identification by energy-dispersive spectrum (EDS) analysis. Energy-dispersive analysis is used to determine the spectrum of the X-rays generated by an asbestos structure. X-ray elemental analysis is used for further categorization of the amphibole fibers, identification of the ambiguous fibers, and confirmation or validation of chrysotile fibers. All Nuclepore samples collected in this study were analyzed by Level II TEM.

Figure 2. Electric blower used for aggressive sampling.

Results

Air Monitoring Results

The results of TEM analyses of samples collected under static and aggressive conditions are compared in Figures 4 and 5. The measured fiber concentrations after abatement varied widely under both static and aggressive sampling conditions, regardless of the analytical method used. For example, fiber concentrations determined by PCM ranged from less than 2,000 to 90,000 fibers/m^3 for static sampling and from 2,000 to 110,000 fibers/m^3 for aggressive sampling. Similarly, concentrations determined by TEM ranged from 6,000 to 583,000 fibers/m^3 for static sampling and from 14,700 to 1.27 million fibers/m^3 for aggressive sampling.

Statistical Comparisons

Statistical Method of Analysis

The Mann-Whitney test was used to determine whether the observed differences in analytical methods and sampling conditions were statistically significant.[11] Use of the Mann-Whitney test required no prior assumption regarding the nature of the underlying probability distribution function of measurements of asbestos fiber concentrations.

Analytical Methods

Table 1 compares the asbestos fiber levels detected by the PCM and TEM methods of analysis under various sampling conditions. PCM and TEM concentrations relate to different fiber populations, as defined by their detection limits and by their standard protocols. Based on the application of the Mann-Whitney test and the assumption that the fiber/volume concentrations are comparable, the difference between PCM and TEM results is statistically significant (i.e., $p < 0.02$) for ambient sampling and for indoor sampling under static and aggressive conditions. The ratios of TEM/PCM concentrations for static sampling were 6.5 for ambient samples and 5.2 for indoor samples. For aggressive sampling, the ratio of TEM/PCM was 9.8.

Sampling Conditions

The difference between the geometric average fiber concentrations under static and aggressive sampling conditions (Table 1) was statistically significant (i.e., p

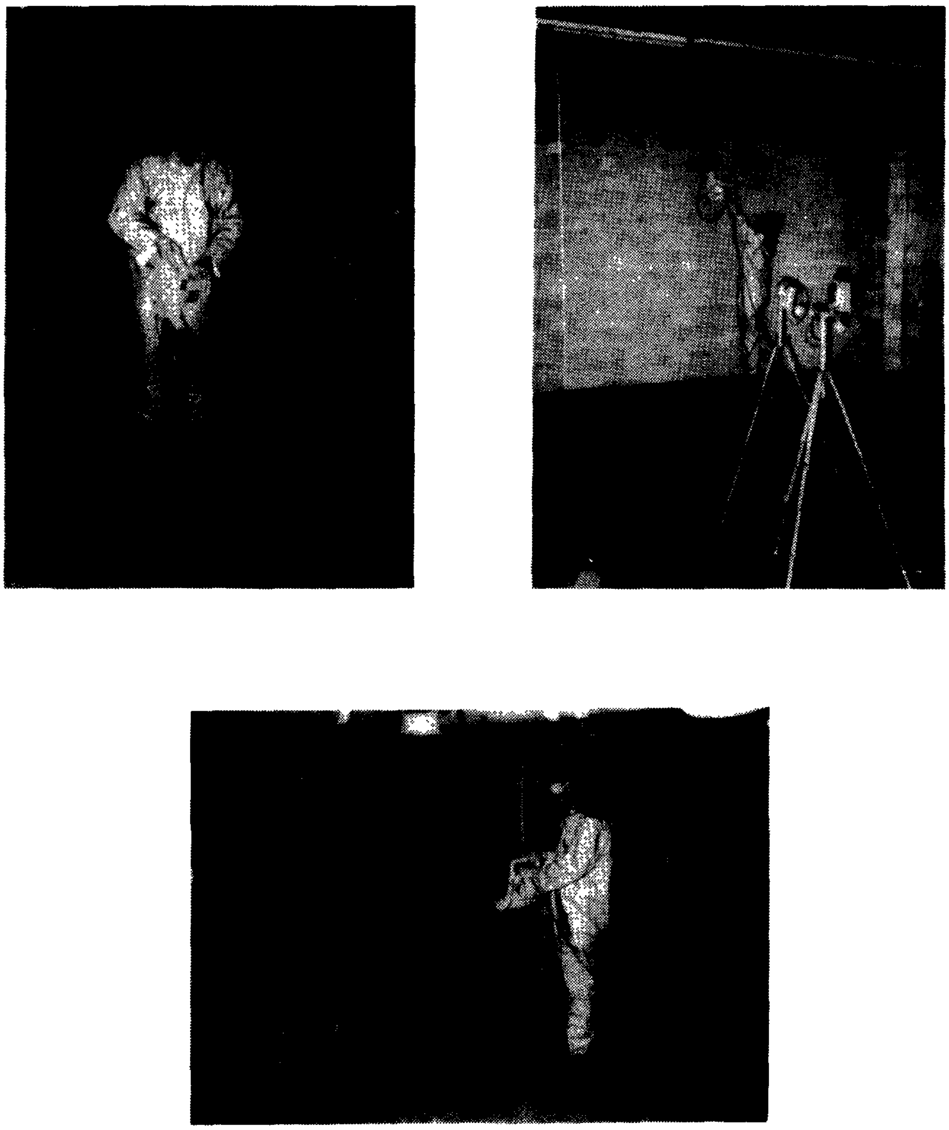

Figure 3. *Aggressive sampling in progress.*

Table 1. *Comparison of Asbestos Fiber Levels* Detected by PCM and TEM Analyses Under Various Sampling Conditions*

	Sampling Conditions		
Analytical Technique	*Outdoor (Ambient)*	*Postabatement Static*	*Postabatement Aggressive*
PCM analysis, fibers/m³	2,000⁺ [10]#	8,000 [20]	27,000 [14]
TEM analysis			
Asbestos fibers/m³	13,000 [10]	42,000 [26]	266,000 [20]
Asbestos structures/m³	15,000	64,000	725,000

**All values are geometric means.*
+Below limit of reliable quantitation (=21,000 fibers/m³). Detection limit = fibers/m³.
#[ ] = number of samples.

<0.001) for PCM and TEM. The ratio of aggressive to static fiber concentrations was 3.4 for PCM analyses and 6.3 for TEM analyses.

Indoor Versus Ambient Samples

Also included in Table 1 are the PCM and TEM analyses for samples collected in the ambient atmosphere. For samples analyzed by PCM, the geometric mean fiber concentration was 8,000 fibers/m³ for indoor samples compared with 2,000 fibers/m³ for ambient samples—a ratio of 4.1. However, the PCM method is not sufficiently sensitive for effective detection of these ambient and indoor (static) concentrations because they are below the lower limit of reliable quantitation by the method. Consequently, the observed differences between the two sample groups are probably not meaningful.

For the TEM samples collected indoors under static conditions, the geometric mean asbestos fiber concentration was 42,000 fibers/m³ compared with 13,000 fibers/m³ for ambient samples—a ratio of 3.2. The observed difference between these indoor, static TEM concentrations and the ambient TEM concentrations was statistically significant ($p = 0.009$). The ratio of indoor asbestos concentrations under aggressive sampling conditions to ambient asbestos concentrations was 20.5.

TEM Data from Static and Aggressive Sampling Conditions

Figures 4 and 5 present data from the TEM asbestos analysis reports. Figure 4 is the static TEM measurement, and Figure 5 is the aggressive TEM analysis. The analysis includes:

- Types of asbestos fibers observed.
- Number of other fibrous structures.
- Numbers of nonfibrous asbestos particles.
- Diameters and lengths of fibers observed by analyst.
- Total asbestos structures per cubic centimeter of air.

The structural analysis data for each TEM sample were entered into EPA's DEC PDP 11/70 computer in Cincinnati and transferred to the IBM 3081 at EPA's National Computer Center in North Carolina. The data were processed by using the statistical analysis system (SAS) and plotted by use of the TELLAGRAF system. Length-to-width plots were made for the fibers.

Conclusions and Recommendations

The following conclusions resulted from this study:

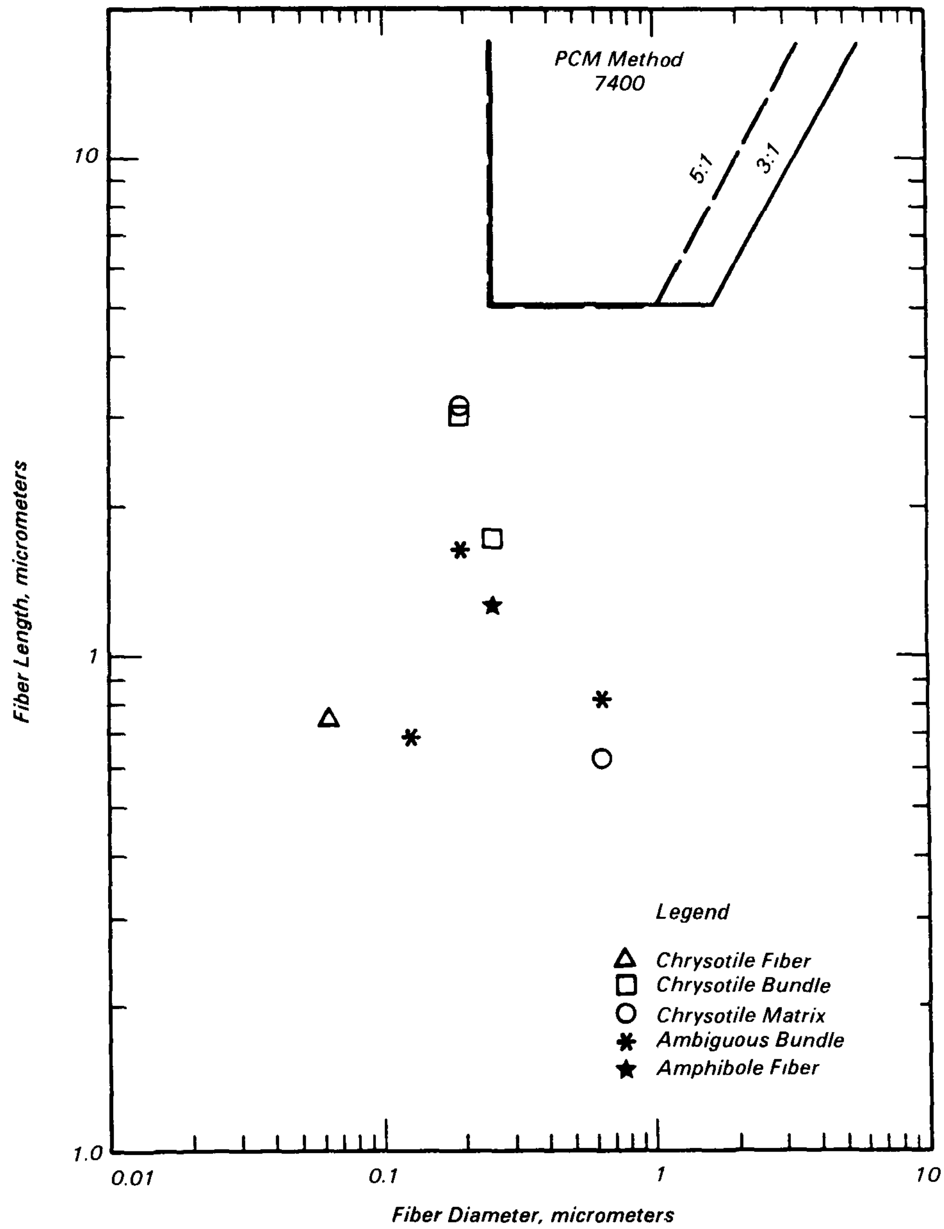

Figure 4. *Results of TEM analysis under static conditions. Plot of fiber length and diameter for a static postabatement air sample in Room M112. Total asbestos structures/cc of air = 0.067.*

1. The aggressive sampling technique used in this problem-definition study revealed that air-entrainable asbestos remained at this site immediately after completion of abatement actions. The mean asbestos fiber concentration during aggressive sampling, as determined by TEM, was about 6 times that of the mean asbestos fiber concentrations during static sampling.
2. The fiber concentrations measured under aggressive sampling conditions were higher than those measured under static conditions regardless of the analytical method used. The ratio of aggressive to static fiber concentrations during PCM analyses was 3.4, whereas this ratio during TEM analyses was 6.3. The average PCM concentration during aggressive sampling conditions was 0.03 fiber/cm^3—less than the NIOSH-recommended occupational limit of 0.1 fiber/cm^3. This 8-hr time-weighted average is frequently cited in abatement contractor specifications as the final postabatement acceptance criterion.
3. The study results clearly demonstrate that under similar sampling conditions, TEM analysis detects more fibers than PCM. The ratio of TEM/PCM concentrations for static sampling was 6.5 for ambient samples and 5.2 for indoor samples; the ratio for aggressive sampling was 9.8.
4. Concentrations of work area asbestos fibers that were determined by TEM and measured by both aggressive and static sampling methods were significantly higher than ambient TEM concentrations. The actual environmental conditions that exist in a building after reoccupancy, reactivation of ventilation systems, and the return to typical usage patterns are somewhere between the static and aggressive sampling conditions.

The following recommendations are based on the study findings:

1. TEM should be recommended as the analytical method of choice for measuring airborne asbestos fiber concentrations for final clearance testing in atmospheres of buildings that have undergone asbestos abatement. However, the current TEM protocols are very time-consuming and expensive for routine use in large surveys.
2. PCM analyses should be conducted as a preliminary check to determine whether additional cleaning is necessary before final clearance testing by TEM. The PCM analyses are relatively inexpensive and can be performed quickly.
3. A criterion should be established to define an acceptable asbestos fiber concentration in building areas after asbestos abatement, but not until a standardized TEM protocol and an aggressive sampling procedure have been developed and validated. Once developed, these methods should be required for all postabatement assessments.
4. Research should continue in the areas of asbestos measurement, sampling, hazard assessment, and abatement control technology so that asbestos hazards in buildings can be effectively reduced. One important research avenue should be the development of quicker, less expensive methods for monitoring the atmosphere in buildings after asbestos abatement.

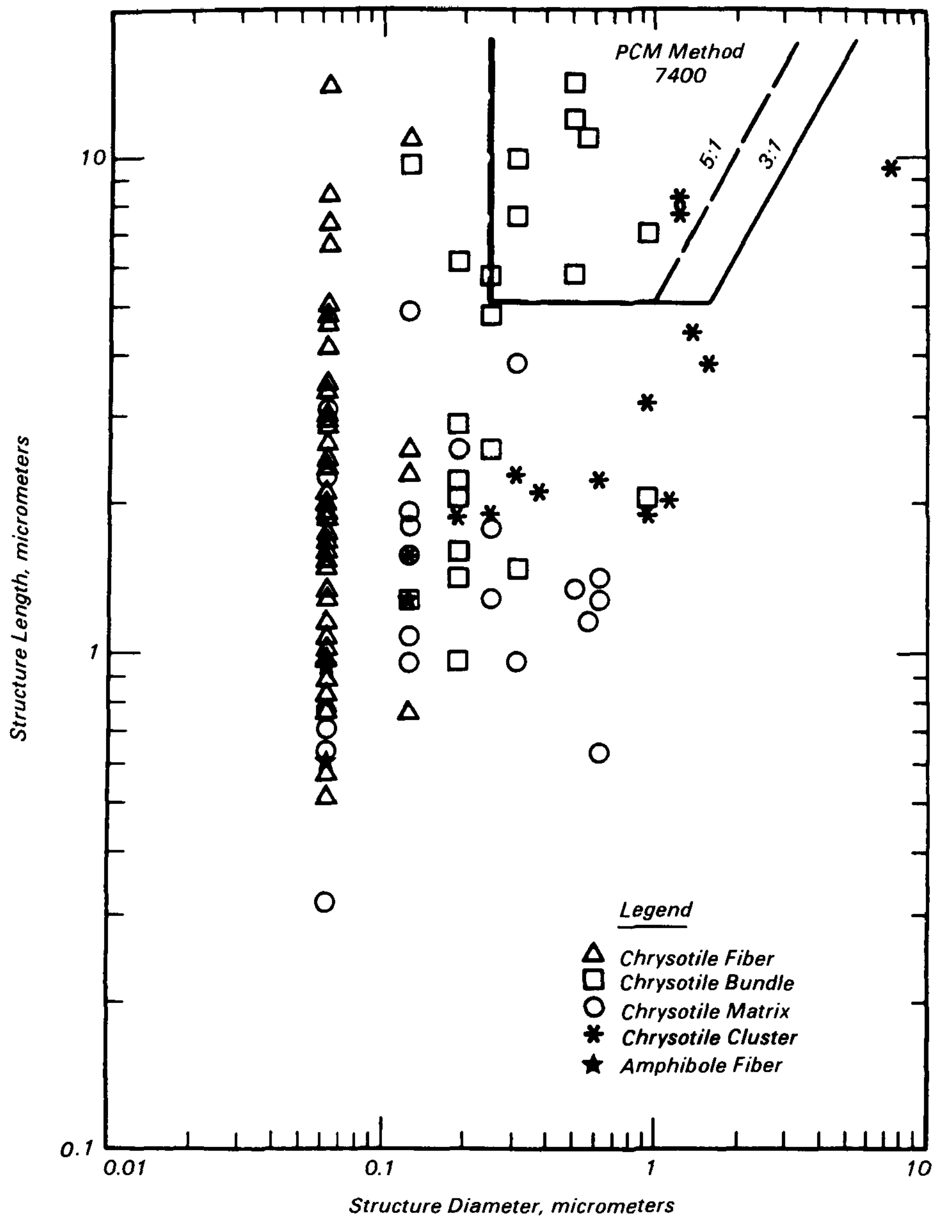

Figure 5. *Results of TEM analysis under aggressive conditions. Plot of fiber length and diameter for an aggressive postabatement air sample in Room M112. Total asbestos structures/cc of air = 1.112.*

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The complete report, entitled "Assessment of Assay Methods for Evaluating Asbestos Abatement Technology," (Order No. PB 86-194 446/AS; Cost: $11.95, subject to change) will be available only from:

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