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Assessment of Asbestos Removal Carried Out Using EPA Purple Book Guidance

PEI Associates, Inc., Cincinnati, OH

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16. ABSTRACT

This represents a statistical evaluation of airborne asbestos data collected before, during, and after removal of spray-applied asbestos-containing fireproofing at three university buildings. Each abatement project was conducted in accordance with the work practices and procedures recommended by the U.S. Environmental Protection Agency in "Guidance for Controlling Asbestos-Containing Materials in Buildings," (the Purple Book). (560/5-85/024)

Containment barriers should be designed to effectively prevent a significant increase in airborne concentrations outside the work area during and after abatement. An increase in asbestos concentration outside the work area could allow an abatement site to be cleared when the level inside the containment is similarly elevated. This holds true whether PCM or TEM is used for the clearance. This weakness in the guidance for location of sampling outside of the containment barrier is one of the major findings of this study. A requirement to monitor the concentration of asbestos outside the work area before and after abatement is recommended to be added to the clearance procedure.

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by

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and

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This research study provides information on the nature and controllability of releases of toxic substances to air from product uses, specifically asbestos-containing materials used as fireproofing in building construction. It also provides an evaluation of data collected on airborne asbestos concentrations at three asbestos abatement sites, before, during, and after removal of asbestos-containing material (ACM). These historical data are evaluated by standard statistical methods to determine if the areas abated by prescribed EPA guidance meet the clearance criteria of this guidance and the Asbestos Hazard Emergency Response Act (AHERA).

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

This report presents a statistical evaluation of airborne asbestos data collected before, during, and after removal of spray-applied asbestos-containing fireproofing at three university buildings. Each abatement project was conducted in accordance with the work practices and procedures recommended by the U.S. Environmental Protection Agency in "Guidance for Controlling Asbestos-Containing Materials in Buildings," (the Purple Book).

Containment barriers should be designed to effectively prevent a significant increase in airborne concentrations outside the work area during and after abatement. An increase in asbestos concentration outside the work area could allow an abatement site to be cleared when the level inside the containment is similarly elevated. This holds true whether PCM or TEM is used for the clearance. This weakness in the guidance for location of sampling outside of the containment barrier is one of the major findings of this study. A requirement to monitor the concentration of asbestos outside the work area before and after abatement is recommended to be added to the clearance procedure.

CONTENTS

	Page
Foreword	ii
Disclaimer	iii
Abstract	iv
Figures	vi
Tables	viii
Acknowledgments	ix
1. Introduction	1
Background	1
Objectives	2
2. Conclusions and Recommendations	4
3. Study Design and Experimental Methods	6
Site descriptions	6
Sampling strategy	7
Sampling methods	9
Analytical methods	10
Quality assurance	11
Statistical analysis methods	14
4. Results and Discussion	18
References	48
Appendices	
A. Airborne Asbestos Concentrations Before, During, and After Abatement for Samples Analyzed by Transmission Electron Microscopy	50
B. Airborne Total Fiber Concentrations Before, During, and After Abatement for Samples Analyzed by Phase Contrast Microscopy	62
C. Paired Samples Collected on 0.4 µm Pore-Size Polycarbonate and 0.8 µm Pore-Size Mixed Cellulose Ester Membrane Filters	73

FIGURES

Number		Page
1	Mean Airborne Asbestos Concentrations Before, During, and After Abatement for Samples Analyzed by TEM at Sites 1, 2, and 3	22
2	Mean Airborne Asbestos Concentrations Before, During, and After Abatement for Samples Analyzed by TEM at Site 1	23
3	Mean Airborne Fiber Concentrations Before, During, and After Abatement for Samples Analyzed by PCM at Site 1	24
4	Plot of Structure Length and Diameter for Preabatement Air Samples Collected Outside the Work (Perimeter) Area at Site 1	25
5	Plot of Structure Length and Diameter for Air Samples Collected Outside the Work Area (Perimeter) During the Abatement at Site 1	26
6	Plot of Structure Length and Diameter for Postabatement Air Samples Collected Outside the Work Area (Perimeter) at Site 1	27
7	Plot of Structure Length and Diameter For Postabatement Air Samples Collected Inside the Work Area at Site 1	29
8	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Outside the Work Area (Perimeter) at Site 1	30
9	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Inside the Work Area at Site 1	31
10	Mean Airborne Asbestos Concentrations Before, During, and After Abatement for Samples Analyzed by TEM at Site 2	33

(continued)

FIGURES (continued)

Number		Page
11	Mean Airborne Fiber Concentrations Before, During, and After Abatement for Samples Analyzed by PCM at Site 2	34
12	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Inside the Work Area at Site 2	35
13	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Outside the Work Area (Perimeter) at Site 2	36
14	Mean Airborne Asbestos Concentrations Before, During, and After Abatement for Samples Analyzed by TEM at Site 3.	39
15	Mean Airborne Fiber Concentrations Before, During and After Abatement for Samples Analyzed by PCM at Site 3	40
16	Plot of Structure Length and Diameter for Postabatement Air Samples Collected Inside the Work Area at Site 3	42
17	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Outside the Work Area (Perimeter) at Site 3.	44
18	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Inside the Work Area at Site 3	45
19	Relationship Between Airborne Asbestos Concentrations Measured on 0.8 µm Pore-Size Mixed Cellulose Ester and 0.4 µm Pore-Size Polycarbonate Membrane Filters	46
20	Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length for Samples Collected Inside the Exhaust Duct From a Negative Air Filtration System at Site 3	47

TABLES

Number		Page
1	Air Sampling Matrix	8
2	Sampling Scheme for Sampling Outside Work Area Under Static Sampling Conditions	9
3	Results of Analyses of Polycarbonate Filter Field Blanks	13
4	Results of Analyses of Mixed Cellulose Ester Filter Field Blanks	13
5	Comparison of Airborne Asbestos Concentrations on Original and Replicate TEM Analysis	15
6	Summary Statistics of TEM and PCM Analyses for Site 1	19
7	Summary Statistics of TEM and PCM Analyses for Site 2	20
8	Summary Statistics of TEM and PCM Analyses for Site 3	21

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SECTION 1

INTRODUCTION

BACKGROUND

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 abatement actions for potential asbestos hazards. The EPA has published three guidance documents that suggest a structured process for identifying asbestos-containing material (ACM) in buildings, for instituting a special operations and maintenance program, and for developing an asbestos-abatement program.[1,2,3] First published in 1979, these guidance documents were revised in 1983 and again in 1985.

The latest update of the EPA guidance is entitled "Guidance for Controlling Asbestos-Containing Materials in Buildings," EPA 560/5-85-024 (June 1985).[3] This document, known as the "Purple Book," contains the most recent recommendations for work practices and procedures to be used in performing asbestos-abatement projects. The recommendations include 1) constructing airtight plastic containment barriers around the work area, 2) using negative-pressure air filtration systems, 3) wetting all asbestos-containing material (ACM) prior to its removal, 4) containerizing of ACM and asbestos-contaminated debris while it is wet, 5) conducting rigorous post-abatement cleanup with wet cleaning and high-efficiency particulate air (HEPA) filtered vacuuming techniques, and 6) performing visual inspections and air monitoring to determine asbestos-abatement completion and work area decontamination.

The EPA guidance document recommends that air monitoring for postabatement clearance be conducted after the work area has passed a thorough visual inspection. According to the EPA "Purple Book" guidance, two methods for measuring airborne asbestos can be used: transmission electron microscopy (TEM) and phase contrast microscopy (PCM). If TEM is used, at least five samples from inside and five samples from outside each homogeneous work area should be collected. The average of the work-area concentrations should be statistically (t-test) no larger than the average of measured concentrations outside the work area. If PCM is used, at least five samples from inside each homogeneous work area should be collected, and none of the concentrations should be higher than the reliable limit of quantitation (approximately 0.01 f/cm^3). Although the Purple Book recommends TEM as the method of choice based on its sensitivity to smaller fibers and specificity

for asbestos, the decision to select an air sampling protocol for determining successful abatement completion is left to the abatement project manager. Thus, the determination of work-area cleanliness depends on which method is chosen for measuring asbestos fibers.

Although the Purple Book reflects current EPA guidance for work practices and procedures to be used in performing asbestos-abatement projects, the book's guidance on clearance testing has been superseded by a procedure set forth in the final rule (52 CFR 41821) promulgated under the Asbestos Hazard Emergency Response Act (AHERA) of 1986. The final rule sets forth TEM as the analytical method to be used for analysis of samples taken for clearance air monitoring on projects involving removal of greater than 150 square feet or 260 linear feet of asbestos. The final rule also specifies a procedure for determining when an asbestos site is sufficiently clean for the critical containment barriers to be removed. The procedure involves collecting five samples from inside and five samples from outside the abatement work area but not necessarily outside of the building. The average of the work area concentrations must be statistically (Z-test) no larger than the average of measured concentrations outside the work area.

This report presents a statistical evaluation of airborne asbestos data collected before, during, and after removal of ACM at three abatement projects that were conducted in accordance with the procedures recommended in the Purple Book. This study assesses the effectiveness of EPA-recommended work practices and procedures for controlling asbestos fiber concentrations outside the work area during abatement. It also examines whether an abated site meets both the TEM and PCM release criteria. For one abatement project, the report also presents 1) a comparison of TEM analysis on 0.4-µm pore polycarbonate and 0.8-µm pore mixed cellulose ester membrane filters, and 2) asbestos fiber concentrations in discharge air from a HEPA-filtered negative air pressure filtration system.

OBJECTIVES

The following were the primary objectives of the study:

- Determine the effectiveness of containment barriers in preventing the release of asbestos fibers outside of the work area.
- Determine the effectiveness of final cleanup procedures.
- To evaluate the TEM clearance criteria for both the t-test and to the extent that the data allow, the Z-test.
- Determine if an abated site meets both TEM and PCM clearance criteria and evaluate whether PCM provides false positives for clearance decisions.

Determine if 0.8-µm pore size mixed cellulose ester and 0.4-µm pore size polycarbonate membrane filters produce equivalent estimates of airborne asbestos concentrations.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The principal conclusions reached during this study are presented below:

1. Asbestos concentrations measured outside the work area before, during, and after abatement at Sites 1 and 3 did not vary significantly. This indicates that the containment barriers at these two sites were effective in preventing the release of asbestos fibers outside the work area. At Site 2, however, the asbestos concentrations measured after abatement were significantly higher than those measured before and during abatement. The mean asbestos concentrations after abatement was approximately 80 times higher than the mean concentration before abatement. These elevated asbestos concentrations suggest that 1) the containment barrier was not effective at this site, 2) work practices recommended in the Purple Book[3] were not followed, or 3) asbestos-containing material outside the abatement containment was disturbed resulting in elevated asbestos concentrations in that area.

2. At Site 1, asbestos concentrations did not increase significantly after abatement and were not significantly higher than the ambient concentrations. At Sites 2 and 3, however, asbestos concentrations did increase significantly after abatement and were also significantly higher than ambient concentrations. The higher postabatement concentrations may be attributable to improper or inadequate implementation of final cleanup procedures, or they may be due to sampling conditions (i.e., static conditions in the preabatement phase versus aggressive conditions in the postabatement phase), or both.

3. Sites 1, 2, and 3 passed the TEM clearance criteria for both the t-test recommended in the Purple Book and Z-test specified in the final rule under AHERA. At Site 2, the increase in the postabatement asbestos concentration outside the work area, as noted in the preceding discussion, enabled the site to pass both clearance tests. Conversely, a comparison of the postabatement concentrations inside the work area with ambient concentrations resulted in the site failing both clearance tests. This single incident identifies a serious limitation in the comparison of postabatement asbestos concentrations inside the work area with those outside the work area.

4. Sites 1, 2, and 3 passed the TEM clearance criteria based on both the t-test (Purple Book) and the Z-test (AHERA final rule). Sites 1 and 2 also passed the PCM clearance criterion (0.01 f/cm^3); however, Site 3 failed. Thus, this study identified a false positive PCM clearance situation where a site failed PCM and passed TEM.

   The differences in conclusions reached by the two protocols are probably due to the limited ability of PCM to distinguish asbestos from nonasbestos materials. Airborne fiber concentrations estimated by PCM reflect total fiber concentrations, not just asbestos fiber concentrations; therefore, they may lead to erroneous conclusions regarding abatement clearance.

5. The TEM analysis of 69 paired 0.8 µm pore size mixed cellulose ester and 0.4 µm pore size polycarbonate membrane filters revealed a statistically significant difference in asbestos concentrations on the two filter types. (The Purple Book recommends that 0.4 µm pore size polycarbonate filters or 0.8 µm pore size mixed cellulose ester filters be used to collect airborne asbestos fibers, whereas, AHERA specifies the same filter types but a different pore size (0.45 µm) for the mixed cellulose ester filters.) Asbestos concentrations on 0.4 µm pore size polycarbonate filters were significantly higher than those on 0.8 µm pore size mixed cellulose ester filters. The two types of filters do not produce equivalent estimates of airborne asbestos concentrations. The difference in asbestos concentrations may be due to the differences in the pore sizes or chemical composition of the two types of filters.

RECOMMENDATIONS

Because the elevated levels outside the containment area at Site 2 would have allowed a contaminated site to pass under the AHERA sampling strategy, monitoring of contamination level outside the work area during abatement or after abatement should be strongly considered as a prerequisite to using this area as a clearance reference point. If additional monitoring is not considered reasonable, the guidance should be revised to emphasize the importance of the location of the "outside" samples.

SECTION 3

STUDY DESIGN AND EXPERIMENTAL METHODS

SITE DESCRIPTIONS

The objectives of this study, which are formally presented in Section 1, stipulate that air monitoring will be conducted before, during, and after removal of ACM at three asbestos-abatement sites. The three sites selected, which are all school buildings, met the following criteria:

1. No significant abatement of ACM had occurred inside the building site within the last 12 months.

2. Each abatement site was in a different geographical location or building.

3. The abatement project involved the removal of spray-applied asbestos-containing fireproofing from structural members and decking.

4. The abatement project was governed by written specifications that comply with the minimum requirements in the latest EPA guidance document (the Purple Book[3]).

5. The building owner and abatement contractor agreed to cooperate with the EPA and to provide access to selected areas of the building.

During the site selection process, representative bulk samples of the ACM to be removed at each candidate site were collected in accordance with the EPA-recommended sampling scheme for friable surfacing materials and analyzed by polarized light microscopy.[4,5] The type and percentage (by weight) of asbestos in the spray-applied fireproofing removed at the three sites were as follows: 5 to 10 percent chrysotile at Site 1, 20 to 25 percent chrysotile at Site 2, and 20 to 60 percent chrysotile at Site 3. The abatement efforts at Sites 1, 2, and 3 involved the removal of approximately 10,000, 17,000, and 5,000 square feet, respectively, of surface area treated with the spray-applied material.

The abatement contractors prepared the work areas, removed the asbestos-containing fireproofing, and conducted decontamination activities in accordance with the latest EPA guidance (the Purple Book). The abatement activities were performed in three distinct stages: preparation, removal, and decontamination. Work areas were prepared by removing all movable objects; 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 HEPA-filtered, negative-pressure air filtration systems; and constructing two entrance and egress contamination-control facilities--one with showers and change rooms for personnel and the other for waste-material handling. Suspended ceilings and carpeting were either removed and disposed of as contaminated waste or cleaned and disposed of by conventional means.

Workers wearing full protective clothing and approved respiratory protection removed the fireproofing by first wetting the material with an amended water solution and then scraping it off. The asbestos-containing debris was placed in double 6-mil polyethylene bags and disposed of at an approved sanitary landfill. All substrate surfaces from which asbestos was removed were wire-brushed and wet-wiped repeatedly to remove as much of the fireproofing material as possible. All stripped or potentially contaminated surfaces were sprayed with an asbestos sealant to bond any residual fibers to the substrate. During decontamination of the work area, all loose debris was removed, as was the plastic sheeting from the walls and floors. Decontamination also involved two complete final cleanups entailing wet-wiping or mopping of the walls and floors. At Site 1, an 8-hour period elapsed between the final cleanings; at Site 2, a 24-hour period elapsed between cleanings. The work areas were then visually inspected to assure the absence of debris and visible dust on surfaces. When the work area passed a thorough visual inspection and air monitoring showed that the total fiber concentrations were less than 0.01 f/cm^3 (by phase contrast microscopy), all remaining critical containment barriers (on windows, doors, and vents) were removed, and the area was considered acceptable for reoccupancy.

SAMPLING STRATEGY

At each of the three abatement sites, area air samples were collected before, during, and after removal of the spray-applied asbestos-containing fireproofing. Samples were collected inside the work area (i.e., the abatement area); outside the work area (i.e., the perimeter area outside the abatement area); and ambient air (i.e., outside of the building). Side-by-side samples were collected at each location for separate PCM and TEM analysis. The sampling matrix is presented in Table 1.

The preabatement air samples were collected inside and outside the work area before the containment barriers were constructed. The sampling was conducted under static conditions (i.e., activity in the area was minimal and the heating, ventilation, and air-conditioning system was not in operation).

During the removal phase of the abatement, air samples were collected at scheduled intervals outside the work area under static sampling conditions. Table 2 shows the sampling scheme that was followed.

TABLE 1. AIR SAMPLING MATRIX

		Location and number of samples							
		Inside work area		Outside work area		Outdoors		Field blanks	
Site	Abatement phase	PCM	TEM	PCM	TEM	PCM	TEM	PCM	TEM
1	Before	10	10	12	12	3	3	3	3
	During	0	0	31	31	4	4	4	5
	After	5	5	5	5	5	4	1	1
	Total	15	15	48	48	12	11	8	9
2	Before	5	5	5	5	5	5	1	1
	During	0	0	31	31	5	5	3	3
	After	5	5	7	7	0	0	1	1
	Total	10	10	43	43	10	10	5	5
3	Before	8	8	3	3	3	3	2	2
	During	0	0	61	49	0	0	11	10
	After	7	7	5	2	3	3	1	1
	Total	15	15	69	54	6	6	14	13
Total Samples		40	40	160	145	28	27	27	27

TABLE 2. SAMPLING SCHEME FOR SAMPLING OUTSIDE WORK AREA UNDER STATIC SAMPLING CONDITIONS

	Removal Phase	Sampling Phase
Site 1	November 13-24, 1987	November 13, 18, 19, 20, 21, 24
Site 2	April 6-8, 1987	April 6, 7, 8
Site 3	August 20 - September 12	August 20, 31 - September 1, 2, 3, 4, 8, 9, 10, 11, 12

The postabatement air samples outside the work area also were collected under static sampling conditions. The postabatement air samples inside the work area were collected under aggressive sampling conditions. The aggressive sampling conditions were created in the work area by an initial "blowdown" of all horizontal and vertical surfaces with a hand-held electric-powered leaf blower, followed by the use of floor fans to generate continuous air turbulence throughout the duration of the sampling period.

At Site 3, additional limited sampling was conducted during the removal phase to determine the asbestos fiber concentrations in the discharge air of the operating HEPA-filtered negative-air filtration systems.

SAMPLING METHODS

Area Air Samples

Two side-by-side area air samples were collected at each sampling location inside and outside the work area and outdoors. Each pair of samples consisted of a 25-mm, 0.4-µm pore size, Nuclepore polycarbonate filter and a 25-mm, 0.8-µm pore size, Millipore mixed cellulose ester filter. Each 25-mm filter was mounted on a 5-µm pore size, mixed cellulose ester, backup diffusing filter and cellulose support pad and was contained in a three-piece cassette with a 50-mm conductive cowl and face cap. The base and cowl sections of the cassettes were sealed with vinyl adhesive tape to prevent air filtration through the seams of the cassettes during sampling. The filter cassettes were positioned 4 to 5 feet above the floor and were arranged in a horizontal line by clipping them to a sturdy stand. The filter cassettes were placed approximately 5 cm apart and were oriented in the same direction with the filter face angled slightly downward. During sampling, the face cap was removed to expose the full face of the filter to the air stream.

The filter assembly was attached to an electric-powered vacuum pump. An inline calibrated precision rotameter was used to regulate the air-flow rate through the filter assembly at 8 to 12 liters per minute (l/min).

The air samples were generally collected for a period of approximately 6 to 9 hours to achieve a minimum air volume of 3000 liters for each sample; however, a limited number of samples were collected for periods extending up to 17 hours, which yielded air volumes of approximately 11,000 liters. At the end of the sampling period, filters were turned upright before being disconnected from the vacuum pump and were stored in this position.

Isokinetic Air Samples--Negative Air Filtration Unit

An isokinetic sampling train was designed to determine asbestos concentrations in the exhaust duct discharge air from a negative-air filtration unit. Isokinetic sampling is a method of sampling in which the velocity of air entering the sample nozzle (V_n) is the same as the velocity of the air stream (V_s). That is, the sample nozzle tip opening area (A_n, ft^2) and sample volume flow rate (V_m, ft^3) must be adjusted to obtain a velocity ($V_n = V_{m/n}$) equal to the air stream velocity (V_s) at the sampling point. The sampling constraint $V_n = V_s$ is called isokinetic or equal velocity sampling.

The isokinetic sampling train consisted of a nozzle (approximately 10 cm in length); a three-piece filter cassette containing a 25 mm diameter membrane filter; a precision flow control device; and an electric powered vacuum pump. The nozzle was mounted directly to the filter cassette to minimize sample loss, and the assembly was positioned in the duct with the nozzle at the centerline of the duct. Two side-by-side air samples were collected during each test. Each pair of samples consisted of a 25-mm, 0.4-µm pore size Nuclepore polycarbonate filter and a 25-mm, 0.8-pore size Millipore mixed cellulose ester filter. Each 25-mm filter was mounted on a 5-µm pore size, mixed cellulose ester, backup diffusing filter and cellulose support pad.

The sampling flow rate was based on duct velocity measurements made before each test. The centerline air velocity was monitored throughout each test by a calibrated velometer, and the flow rate through the system was adjusted to accommodate the isokinetic sampling procedure. An in-line precision calibrated rotameter was used to regulate the air-flow rate through the filter assembly at 7.5 to 8.3 liters/min (mean 7.7 ± 0.33 liters/min). The sampling period range from 5.1 to 18.6 hours (mean 9.8 ± 6.6 hours) to achieve an air volume of 2.33 to 9.03 cubic meters (mean 4.58 ± 3.20 m^3).

ANALYTICAL METHODS

The mixed cellulose ester membrane filters were analyzed by phase contrast microscopy (PCM), and the polycarbonate membrane filters were analyzed by transmission electron microscopy (TEM). The PCM and TEM analytical protocols are presented in the Quality Assurance Project Plan prepared for this research study.[6]

The mixed cellulose ester filters were prepared and analyzed for total fibers by PCM in accordance with NIOSH Method 7400.[7] All fibers or fiberlike particles measuring at least 5 µm in length and having a 3:1 length-to-width aspect ratio were

counted in accordance with the 7400-A counting rules. Because NIOSH Method 7400 is nonspecific for asbestos, all the fibers counted cannot be assumed to be asbestos, as every fiber or fiberlike particle meeting the NIOSH dimension criteria was counted. Analyses were performed by PEI Associates, Inc., in Cincinnati, Ohio.

The polycarbonate filters were prepared and analyzed for asbestos fibers by TEM in accordance with the Yamate Method.[8] The Yamate methodology[8] describes three levels of TEM analysis. Two of these levels are briefly summarized here. Level I TEM analysis involves examination of the particulates deposited on the sample filter by a 100-kV transmission electron microscope. 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 observance of the selected area electron diffraction (SAED) patterns. The width-to-length ratio of each counted particle is calculated and 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 polycarbonate filter samples collected in this study were analyzed by Level II TEM.

Three laboratories performed the TEM analysis on the field samples under separate contract with EPA's Water Engineering Research Laboratory (WERL) in Cincinnati. The complete set of samples from each abatement site was assigned to a different analytical laboratory designated by the EPA Technical Project Monitor: Site 1 samples to Chatfield Technical Consulting Limited in Mississauga, Ontario, Canada; Site 2 samples to R. J. Lee Group, Inc. (formerly Energy Technology Consultants) in Monroeville, Pennsylvania; and Site 3 samples to Battelle Laboratories, Columbus, Ohio.

Battelle Laboratories also performed TEM Level II analysis on the mixed cellulose ester filter samples collected at abatement Site 3. For consistency across all sites, statistical comparisons were made with polycarbonate filter samples.

QUALITY ASSURANCE

The Quality Assurance Project Plan (QAPP) contains the complete details of the quality assurance procedures followed during this research project.[6] These procedures are summarized in the following subsections.

Sample Chain-of-Custody

Sample chain-of-custody procedures were an integral part of both sampling and analytical activities during this study. They were implemented for all air and bulk samples collected. The applied field custody procedures documented the existence of a sample from its time of collection until its receipt by the analytical laboratory.

Internal laboratory records then documented the custody of the sample through its final disposition.

Standard sample custody (traceability) procedures were used during this project. Each sample was labeled with a unique project identification number, which was recorded in the field log book along with other information specified by the QAPP.

Quality Assurance Sample Analyses

Specific quality assurance procedures used to ensure the accuracy and precision of the TEM and PCM analyses of air samples included the use of laboratory and field blanks and replicate analyses. Laboratory blanks are filters chosen before the start of field work. These blanks are analyzed by the analytical laboratory to check for filter contamination. Field blanks are filters taken into the field and handled in the same manner as exposed air sample filters to check for contamination that might not be a result of air sampling. Replicate analysis refers to analysis of the same sample twice by the analytical laboratory. The degree of agreement between the two analyses indicates the level of precision in the laboratory analysis procedures.

Laboratory blanks--

Two laboratories (McCrone Environmental Services, Inc., Norcross, Georgia, and R. J. Lee Group, Inc., in Monroeville, Pennsylvania) analyzed 5 percent of the total number of polycarbonate filters and 5 percent of the total number of mixed cellulose ester filters used in the 1987 field studies by TEM Level II in accordance with the Yamate procedure.[8] The polycarbonate filters were all from the same lot. The filters were considered "acceptable" for use if the average asbestos structure count per 10 grid openings was less than 3. If the average asbestos structure count for the group exceeded 3 asbestos structures per 10 grid openings, the entire lot of filters was considered contaminated. The TEM analysis of the polycarbonate filter laboratory blanks showed background filter contamination of 1.8 asbestos structures per 10 grid openings (or 180 asbestos structures in 1000 grid squares examined). The TEM analysis of the mixed cellulose ester filter laboratory blanks showed background filter contamination of 0.12 asbestos structure per 10 grid squares (or 12 asbestos structures in 1000 grid openings examined). Therefore, the analysis of the laboratory blanks showed that the background asbestos filter contamination was within specified limits.

The mixed cellulose ester filters were pretested by PCM analysis before their use in the field in the same manner as that described for the polycarbonate filters. The filters were from the same lot. PEI Associates, Inc., Cincinnati performed the prescreening analyses. The analysis of the laboratory blanks indicated that background filter contamination was not a problem.

Field blanks--

During setup of the air sampling pump, preloaded filter cassettes were selected as field blanks. These filters were labeled and handled in a similar manner as the sample filters were, but they were not attached to the sampling pump. Field blanks for both polycarbonate and mixed cellulose ester filters were collected at each of the three abatement sites. A total of 27 polycarbonate filter field blanks were collected at Sites 1, 2, and 3 and analyzed by TEM Level II. Table 3 presents the results of these analyses.

TABLE 3. RESULTS OF ANALYSES OF POLYCARBONATE FILTER FIELD BLANKS

		Asbestos structures		
Site	Number of field blanks	Total number	Average number per 10 grid openings	Range per 10 grid openings
1	9	21	2.3	0 - 6
2	5	0	0	0
3	13	9	0.69	0 - 5
Blank Guideline			3.0	

Therefore, the analysis of the field blanks showed that asbestos filter contamination was within the guideline of 3 asbestos structures average per 10 grid openings.

A total of 10 mixed cellulose ester filter field blanks were collected and analyzed by TEM Level II. All of the mixed cellulose ester filters were collected at Site 3. No asbestos fibers were detected on any of the filters.

A total of 27 mixed cellulose ester filter field blanks were collected and analyzed by PCM (NIOSH Method 7400). Table 4 presents the results of these analyses.

TABLE 4. RESULTS OF ANALYSES OF MIXED CELLULOSE ESTER FILTER FIELD BLANKS

		Total fibers		
Site	Number of field blanks	Total number	Average number per 100 grid openings	Range per 100 grid openings
1	8	5.5	0.69	0 - 1.5
2	5	0	0	0
3	14	17.5	1.3	0 - 4.5

All sample concentrations determined by PCM were blank-corrected by the laboratory; i.e., the fiber contamination level (fibers per 100 fields) was subtracted from the field samples before the sample concentration (f/cm^3) was calculated.

Replicate analysis--

Eleven air samples were selected at random to investigate within-laboratory TEM analysis performance. The samples were reanalyzed by the original laboratory (replicate analysis). Table 5 presents the results of the original and replicate analyses. There was no evidence of inconsistency among the two sets of analyses. A Wilcoxon signed rank test[10] did not detect any significant tendency for any one analysis (original or replicate) to give higher or lower fiber counts ($p = 0.820$).

STATISTICAL ANALYSIS METHODS

The data were grouped for each site by abatement phase (before, during, and after); location of sample (inside the work area, outside the work area, and ambient); and analytical protocol (TEM and PCM). The data were then tested for normality by using the Shapiro-Wilk statistic to determine an appropriate statistical analytic approach for the comparisons.[9] Although most of the TEM data suggested reasonable normality, most of the PCM data were non-normal.

Because the test for normality was on five or fewer samples (which decreases the power of the test to detect aberrations from normality) and to be consistent for all three abatement sites and analytical procedures with respect to analytical approach, nonparametric procedures were chosen to make all comparisons of interest. Nonparametric procedures analyze the relative ranks of the data rather than actual data values and do not require the normality assumption of the parametric procedures.

The only exception to the use of nonparametric procedures was the TEM clearance comparison of postabatement samples inside the work area with those outside the work area. The Purple Book recommends that this comparison be conducted with a Student's t-test; the final rule for AHERA requires that this comparison be conducted with a Z-test. Because all three sites used negative-pressure air filtration systems during abatement and the makeup or "background" air came from other parts of the building rather than directly from outdoors, the postabatement samples inside the work area were compared with the postabatement samples outside the work area but within the building.[3]

Samples with a fiber (PCM) or structure (TEM) count of zero were assigned an estimated airborne concentration of 0 structures per cubic centimeter (s/cm^3). A concentration of 0 s/cm^3 was used in all summary statistic calculations and statistical analyses except the t-test and Z-test used for TEM clearance. The t-test and Z-test are standard comparisons of means for data that are normally distributed. Because these tests are based on a log transformation of the data, the Purple Book and

TABLE 5. COMPARISON OF AIRBORNE ASBESTOS CONCENTRATIONS ON ORIGINAL AND REPLICATE TEM ANALYSES

Original		Replicate	
No. of fibers	f/cm^3	No. of fibers	f/cm^3
8	0.00990	1	0.00124
10	0.01509	13	0.01962
6	0.01013	9	0.01519
8	0.00956	7	0.00837
15	0.01965	4	0.00524
0	0	0	0
5	0.00827	13	0.02150
13	0.02115	11	0.01790
9	0.02943	14	0.04578
2	0.00254	2	0.00254
5	0.00683	3	0.00410

AHERA suggests that 0 concentrations be replaced by the analytical sensitivity for the sample before the t-statistic and Z-statistic are calculated. (The analytical sensitivity for TEM, also referred to as the detection limit, is the estimated airborne structure concentration calculated when a single structure is counted in a sample.)

When more than one analysis was completed on a single filter, the average of these results was used in the statistical analysis.

Summary statistics (arithmetic mean and standard deviation) were calculated for each site by abatement phase (before, during, and after), location of sample (inside the work area, outside the work area, and ambient), and microscopic technique (TEM and PCM).

Statistical analyses were designed to address each of the following objectives for samples analyzed by PCM and TEM:

Comparison of Fiber Concentrations Outside the Work Area Before, During, and After Abatement

The Kruskall-Wallis one-way analysis of variance test was used to examine the differences between airborne fiber concentrations outside the work area before, during, and after the abatement activity.[10] When overall differences were detected, Dunn's multiple comparison procedure, which is based on the Kruskall-Wallis rank sums, was used to identify where the differences occurred.[10]

Comparison of Fiber Concentrations Inside the Work Area Before and After Abatement

The Wilcoxon rank sum test was used to examine the differences between airborne fiber concentrations inside the work area before and after the abatement activity.[10] It is important to note that static sampling techniques were used for preabatement sampling, whereas aggressive sampling techniques were used for postabatement sampling inside the work area. For this reason, this is not strictly a comparison of preabatement and postabatement concentrations inside the work area, but rather a comparison of prestatic and postaggressive sampling concentrations.

TEM Clearance Comparison

All three sites in this study used negative-pressure air filtration systems during the abatement activity. Thus, for clearance comparison purposes it is appropriate to compare postabatement concentrations inside the work area with postabatement concentrations outside the work area (but inside the building). The averages of inside and outside log concentrations are compared by using the Student's t-test, as described in the Purple Book. As noted earlier, the samples with an asbestos count of 0 structures were assigned a concentration equal to the analytical sensitivity for that sample (defined as the concentration that would be present if a single fiber were detected). If the mean asbestos concentration inside the work area is not statistically

greater than the mean asbestos concentration outside the work area (but inside the building), the abatement site passes the clearance test.

Although the monitoring data (Table 4) are not totally consistent with the requirements in the final rule (October 30, 1987; 52 FR 41826) under AHERA, the postabatement concentrations inside the work area and those concentrations outside the work area (but inside the building) are also compared using the Z-test to determine if abated work areas meet the AHERA TEM clearance criteria. The Z-test is a standard comparison of means for data that are normally distributed with a known variance. Because it is based on a log transformation of the data, the particular form of the Z-test required under the AHERA final rule (October 1987; 52 FR 41286) specifies that 0 concentrations are to be replaced by the analytical sensitivity before the Z statistic is calculated. The abatement work area passes the test if the asbestos concentrations inside the work area are not statistically higher than the asbestos concentrations outside the work area. The clearance test is based on a minimum of five samples inside the abatement work area and five samples outside the abatement work area to control the false negative error rate. "Outside" means outside the abatement work area, but not necessarily outside the building.

PCM Clearance Comparison

The release criterion the Purple Book recommends for use with PCM involves comparing postabatement fiber concentrations inside the work area with the PCM limit of reliable quantitation (approximately 0.01 f/cm^3 for 3000 liters of air sampled). Abatement activity for which PCM protocols are used is considered complete if the airborne asbestos concentration for each sample concentration is no higher than 0.01 f/cm^3.

Comparison of Concentrations Inside the Work Area With Ambient Air Concentrations After Abatement

The Wilcoxon rank sum test was used to determine whether asbestos concentrations inside the work area after abatement were statistically greater than postabatement ambient air concentrations.

Comparison of TEM Analysis on 0.4-µm Pore-Size Polycarbonate and 0.8-µm Pore-Size Mixed Cellulose Ester Filters

The Wilcoxon signed rank test for paired samples was used to determine if a statistically significant difference in airborne asbestos fiber concentration existed between the filter types.

The Purple Book recommends that 0.4-µm pore size polycarbonate filters (preferred) or 0.8-µm pore size mixed cellulose ester filters be used to collect airborne asbestos fibers for TEM analysis. The final rule under AHERA specifies the same sample filter types, but a different pore size (0.45-µm) for the mixed cellulose ester filter.

SECTION 4

RESULTS AND DISCUSSION

Summary statistics (arithmetic mean and standard deviation) for Sites 1, 2, and 3 are presented in Tables 6, 7, and 8, respectively. The results are presented for Sites 1, 2, and 3 by abatement phase (before, during, and after) and location of sample (inside the work area, outside the work area, and ambient). The mean asbestos concentrations are graphically presented for Sites 1, 2, and 3 according to abatement phase and location of sample in Figure 1. The individual air sampling results by TEM analysis are listed in Appendix A and those by PCM analysis are listed in Appendix B. The statistical evaluation of the data for each site is presented according to the objectives stated in Section 3.

SITE 1

Comparison of Fiber Concentrations Outside the Work Area Before, During, and After Abatement

The Kruskall-Wallis test revealed no statistically significant differences in the airborne asbestos concentrations outside the work area between the three abatement phases (Figure 2) for those samples analyzed by TEM ($p = 0.773$). The test, however, did reveal a statistically significant difference in fiber concentrations between the three phases (Figure 3) for those samples analyzed by PCM ($p = 0.0002$). The fiber concentrations outside the work area both during abatement and after abatement were significantly greater than the fiber concentrations before abatement (Table 6).

The apparent differences in the conclusions reached by the two analytical protocols confirm the two serious limitations in the use of PCM for measuring airborne asbestos. First, PCM cannot distinguish asbestos from nonasbestos fibers; all particles of the required length and aspect ratio are counted. Second, only particles >0.25 µm in diameter are detected and only particles ≥5 µm in length are counted. These limitations in PCM analysis are illustrated in Figures 4, 5, and 6, which show the structural characteristics (length and diameter) of particles in samples collected outside the work area and analyzed by TEM. The asbestos concentrations are based primarily on particles outside the PCM window (i.e., particles <0.25 µm in diameter and <5 µm in length), which PCM resolution and counting protocols will not detect. Hence, differences in mean PCM fiber concentrations among the three abatement phases at Site 1 are probably due to nonasbestos particles.

TABLE 6. SUMMARY STATISTICS OF TEM AND PCM ANALYSES FOR SITE 1

	Airborne concentration, f/cm^3					
	TEM			PCM		
Location	Sample size	Mean	Standard deviation	Sample size	Mean	Standard deviation
			Preabatement Phase			
Ambient	3	0.0041	0.0009	3	0.0007	0.0006
Perimeter	12	0.0052	0.0035	12	0.0003	0.0006
Work area	10	0.0091	0.0053	10	0.0000	0.0000
			During Abatement Phase			
Ambient	4	0.0034	0.0040	4	0.0008	0.0010
Perimeter	31	0.0089	0.0098	31	0.0023	0.0019
Work area	0*	-	-	0*	-	-
			Postabatement Phase			
Ambient	4	0.0067	0.0045	5	0.0002	0.0004
Perimeter	5	0.0057	0.0046	5	0.0022	0.0011
Work area	5	0.0056	0.0039	5	0.0015	0.0010

* No samples were collected.

TABLE 7. SUMMARY STATISTICS OF TEM AND PCM ANALYSES FOR SITE 2

	Airborne concentration, f/cm^3					
	TEM			PCM		
Location	Sample size	Mean	Standard deviation	Sample size	Mean	Standard deviation
			Preabatement Phase			
Ambient	5	0.0011	0.0016	5	0.0012	0.0004
Perimeter	5	0.0030	0.0030	5	0.0014	0.0005
Work area	5	0.0367	0.0739	5	0.0012	0.0004
			During Abatement Phase			
Ambient	5	0.0005	0.0006	5	0.0010	0.0000
Perimeter	31	0.0304	0.0459	31	0.0015	0.0014
Work area	0*	-	-	0*	-	-
			Postabatement Phase			
Ambient	0*	-	-	0*	-	-
Perimeter	7	0.2410	0.1495	7	0.0027	0.0025
Work area	5	0.3082	0.1767	5	0.0024	0.0011

* No samples were collected.

TABLE 8. SUMMARY STATISTICS OF TEM AND PCM ANALYSES FOR SITE 3

	Airborne concentration, f/cm^3					
	TEM			PCM		
Location	Sample size	Mean	Standard deviation	Sample size	Mean	Standard deviation
			Preabatement Phase			
Ambient	3	0.0000	0.0000	3	0.0020	0.0017
Perimeter	3	0.0008	0.0014	3	0.0040	0.0010
Work area	8	0.0001	0.0004	8	0.0020	0.0011
			During Abatement Phase			
Ambient	0*	-	-	0*	-	-
Perimeter	49	0.0129	0.0270	61	0.0106	0.0133
Work area	0*	-	-	0*	-	-
			Postabatement Phase			
Ambient	3	0.0000	0.0000	3	0.0107	0.0015
Perimeter	2	0.0028	0.0039	5	0.0074	0.0068
Work area	7	0.0023	0.0019	7	0.0080	0.0031

* No samples were collected.

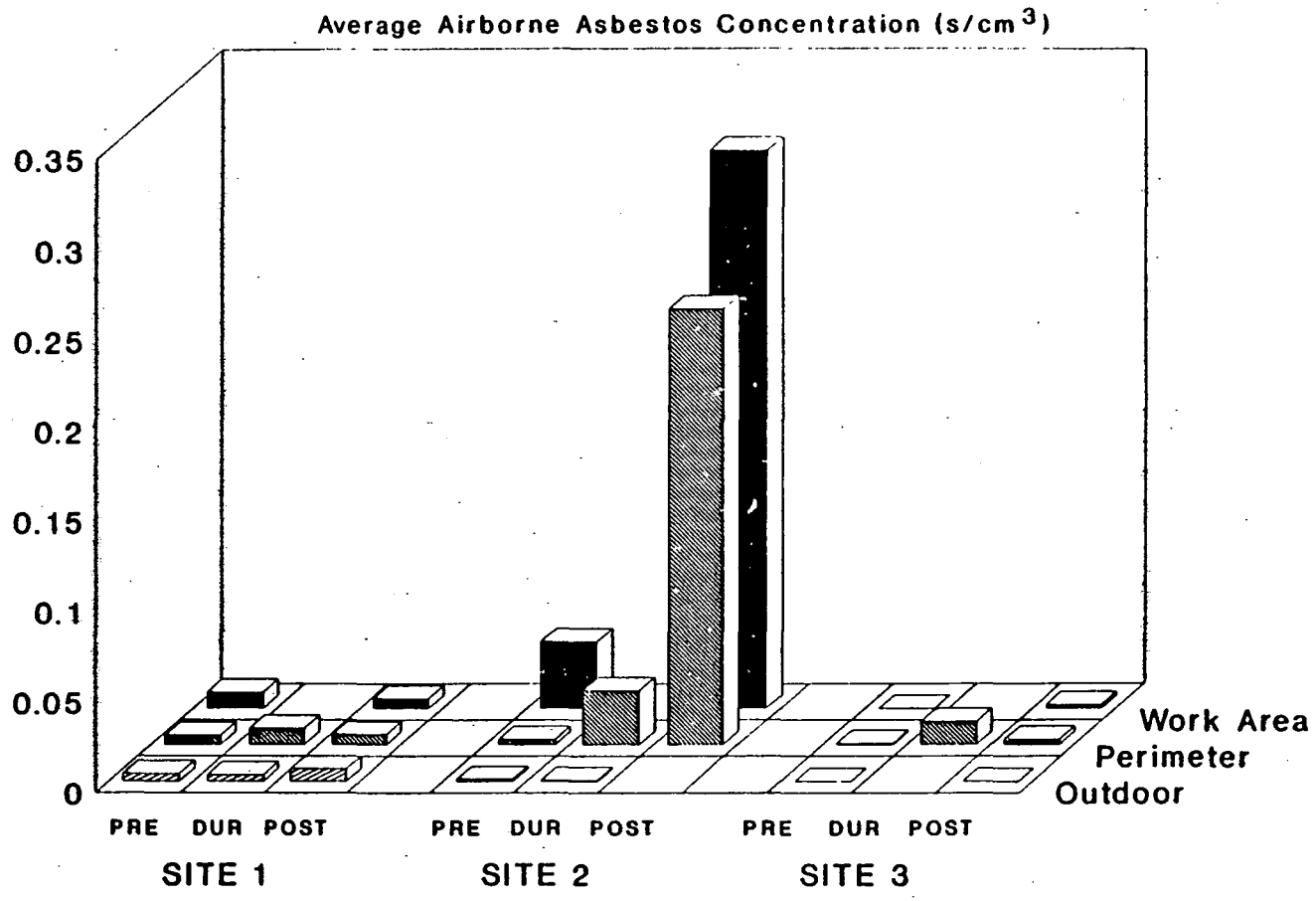


Figure 1. Mean airborne asbestos concentrations before, during, and after abatement for samples analyzed by TEM at sites 1, 2, and 3.

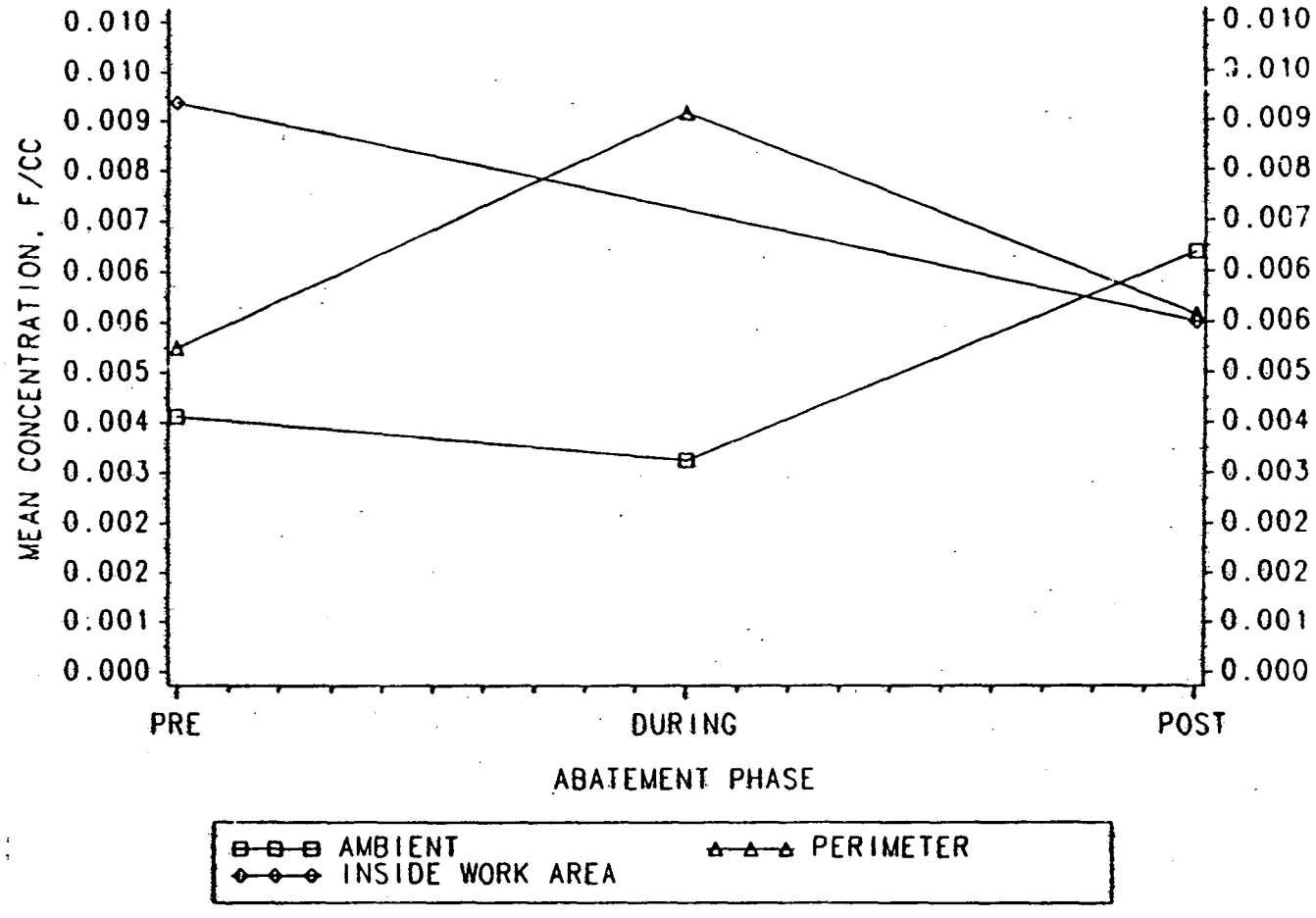


Figure 2. Mean airborne asbestos concentrations before, during, and after abatement for samples analyzed by TEM at site 1.

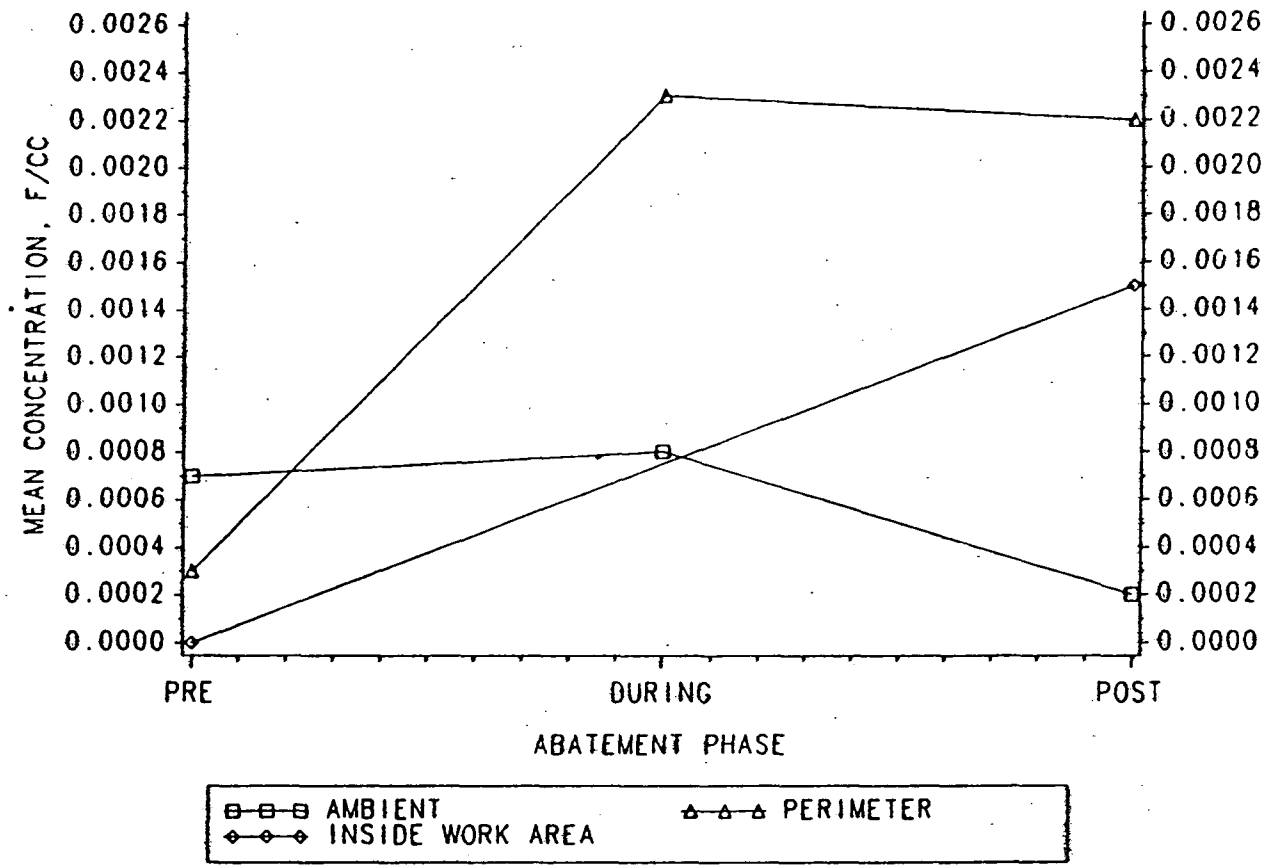
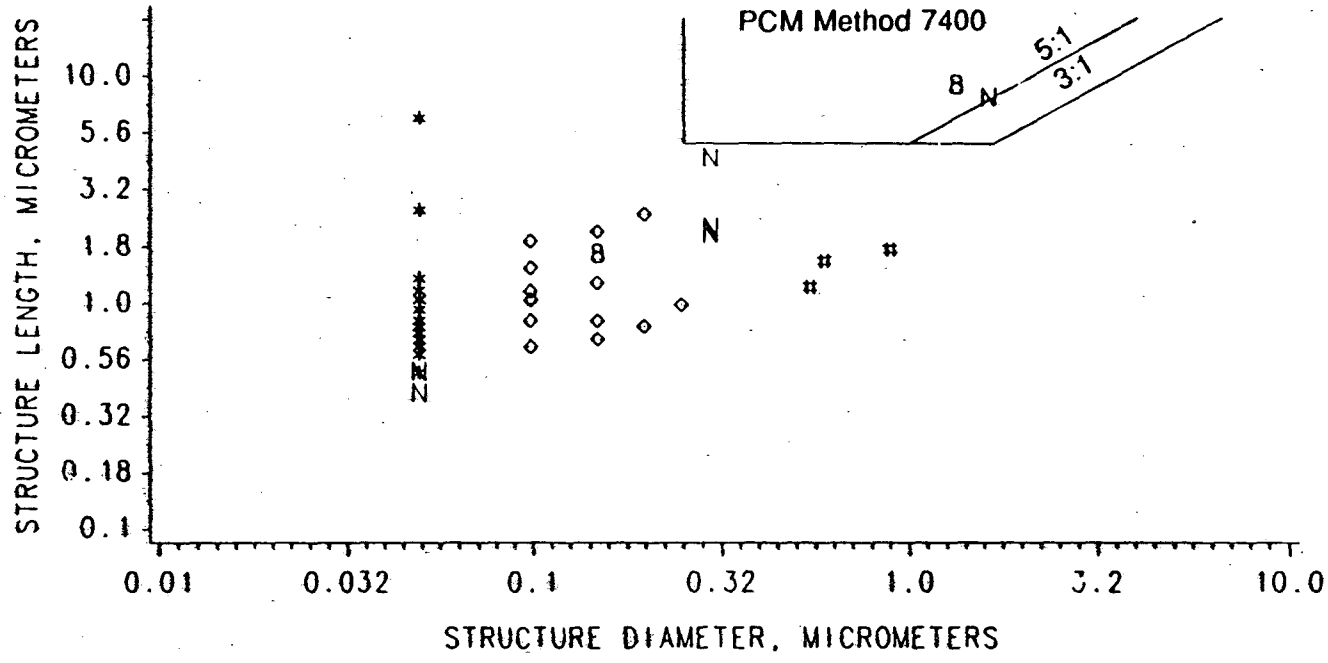
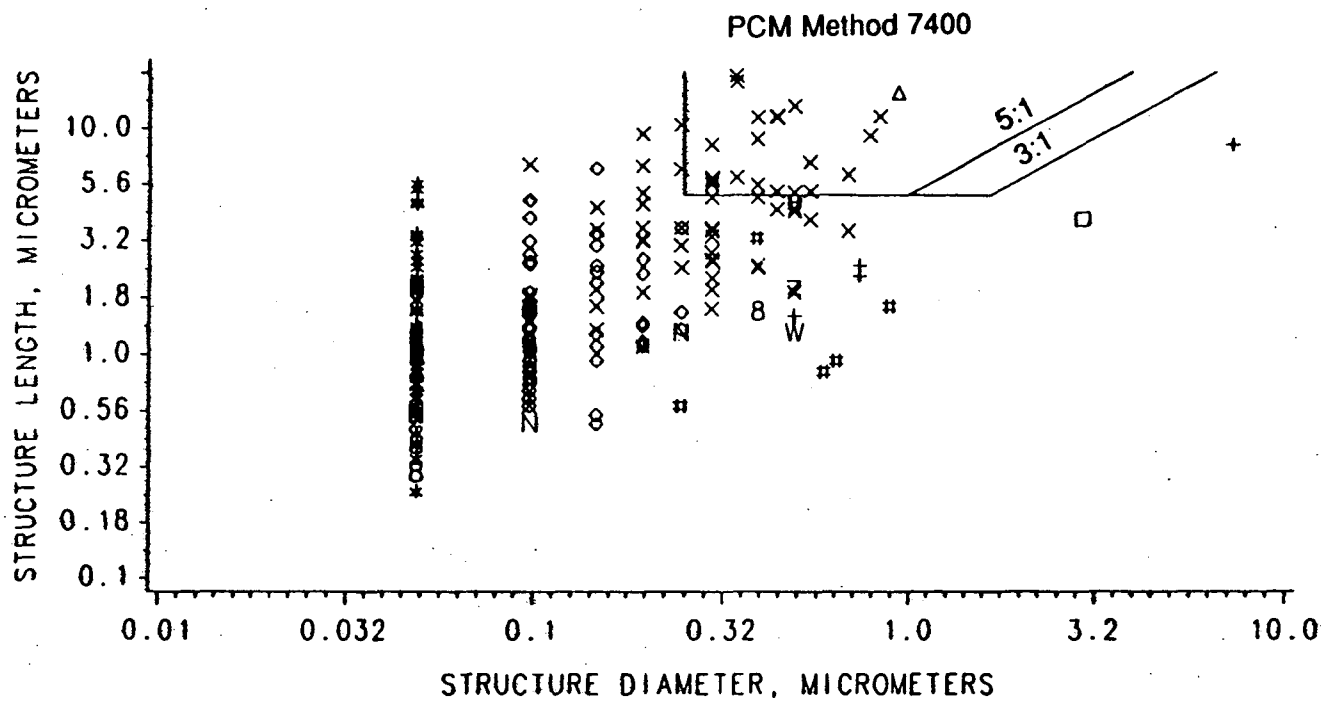


Figure 3. Mean airborne fiber concentrations before, during, and after abatement for samples analyzed by PCM at site 1.



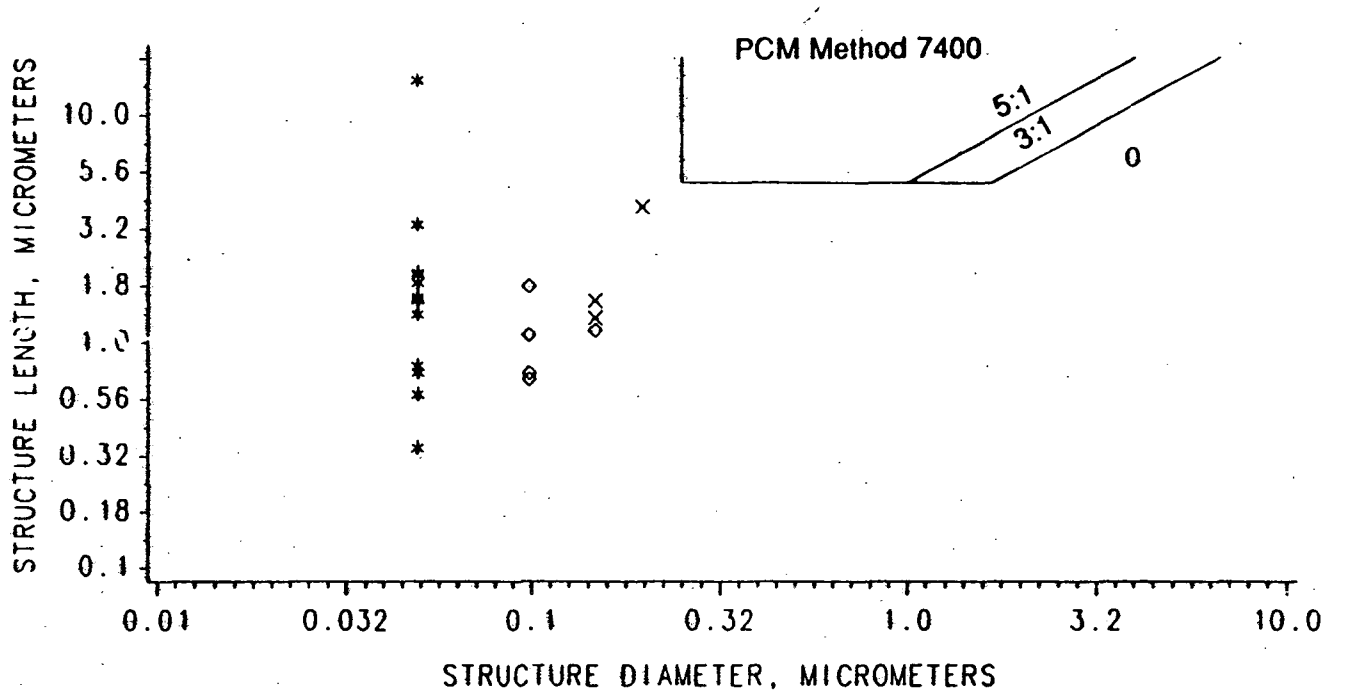
—— PCM METHOD 7400	* * * 1 CHRYSOTILE F	◇ ◇ ◇ 1 CHRYSOTILE B
+ + 1 CHRYSOTILE M	# # # 1 CHRYSOTILE C	× × × 1 AMPHIBOLE F
△ △ 1 AMPHIBOLE B	O O O 1 AMPHIBOLE M	□ □ □ 1 AMPHIBOLE C
8 8 1 AMBIGUOUS F	⊙ ⊙ ⊙ 1 AMBIGUOUS B	Z Z Z 1 AMBIGUOUS M
C C 1 AMBIGUOUS C	N N N 1 NON ASBESTOS F	V V V 1 NON ASBESTOS B
W W 1 NON ASBESTOS M	Y Y Y 1 NON ASBESTOS C	

Figure 4. Plot of structure length and diameter for preabatement air samples collected outside the work area (perimeter) for site 1.



—— PCM METHOD 7400	* * * 1 CHRYSOTILE F	◇ ◇ ◇ 1 CHRYSOTILE B
+ + 1 CHRYSOTILE M	# # # 1 CHRYSOTILE C	× × × 1 AMPHIBOLE F
△ △ 1 AMPHIBOLE B	O O O 1 AMPHIBOLE M	□ □ □ 1 AMPHIBOLE C
8 8 1 AMBIGUOUS F	⊙ ⊙ ⊙ 1 AMBIGUOUS B	Z Z Z 1 AMBIGUOUS M
C C 1 AMBIGUOUS C	N N N 1 NON ASBESTOS F	V V V 1 NON ASBESTOS B
W W 1 NON ASBESTOS M	Y Y Y 1 NON ASBESTOS C	

Figure 5. Plot of structure length and diameter for air samples collected outside the work area (perimeter) during the abatement at site 1



—— PCM METHOD 7400	* * * 1 CHRYSOTILE F	◇ ◇ ◇ 1 CHRYSOTILE B
+ + 1 CHRYSOTILE M	# # # 1 CHRYSOTILE C	× × × 1 AMPHIBOLE F
△ △ 1 AMPHIBOLE B	O O O 1 AMPHIBOLE M	□ □ □ 1 AMPHIBOLE C
B B 1 AMBIGUOUS F	⊙ ⊙ ⊙ 1 AMBIGUOUS B	Z Z Z 1 AMBIGUOUS M
C C 1 AMBIGUOUS C	N N N 1 NON ASBESTOS F	V V V 1 NON ASBESTOS B
W W 1 NON ASBESTOS M	Y Y Y 1 NON ASBESTOS C	

Figure 6. Plot of structure length and diameter for postabatement air samples collected outside the work area (perimeter) at site 1.

Comparison of Fiber Concentrations Inside the Work Area Before and After Abatement

The Wilcoxon rank sum test revealed no statistically significant difference in mean airborne asbestos concentration inside the work area before and after abatement (Figure 2) for TEM-analyzed samples ($p = 0.254$). The test, however, did reveal a significant difference in concentrations for the PCM-analyzed samples ($p = 0.012$). The mean fiber concentration increased approximately 1.5 times after abatement activity (Figure 3).

As in the case of samples taken outside the work area, the difference found in the PCM-analyzed samples is probably due to nonasbestos particles (Figure 7). The TEM-determined asbestos concentrations for the postabatement samples inside the work area are based on particles outside the PCM resolution window (i.e., particles that are too small for PCM detection).

Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length

Figures 8 and 9 graphically present the mean asbestos fiber concentrations of the samples analyzed by TEM based on minimum fiber length for samples outside the work area and samples inside the work area, respectively. Because PCM analysis counts only particles ≥5 µm in length, these plots show the portion of the total asbestos fiber concentrations consisting of those particles <5 µm in length.

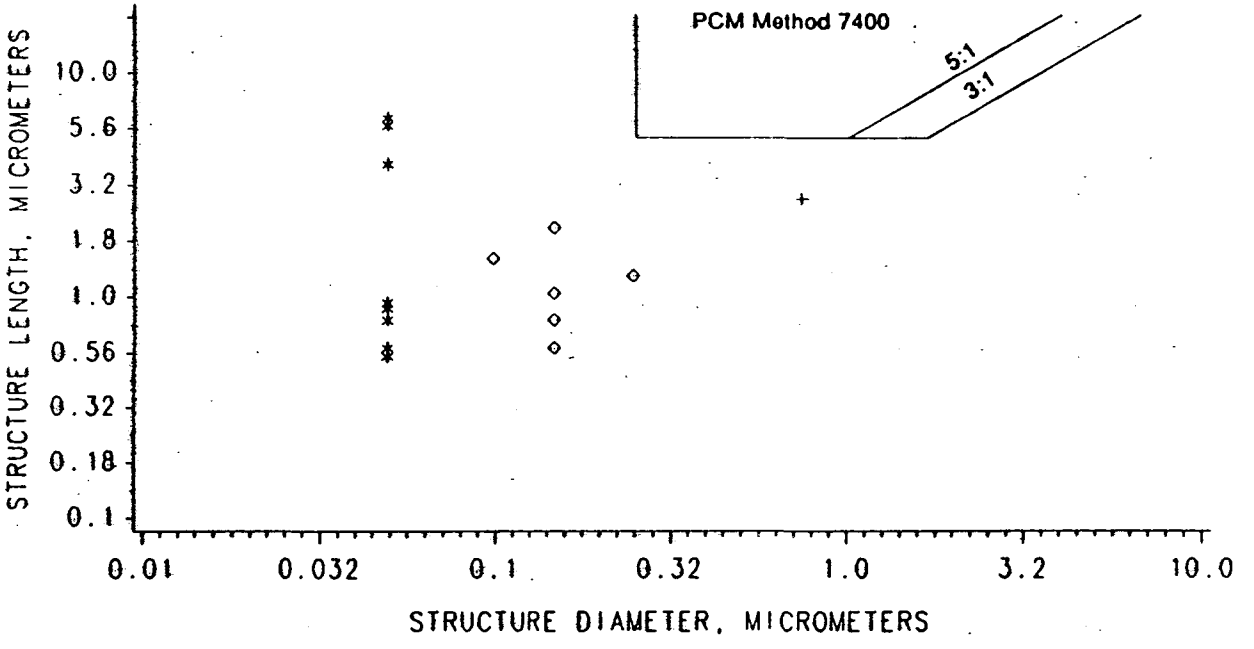
TEM Clearance Comparison

The clearance comparison made with the Student's t-test indicated that the mean asbestos concentration (0.0056 f/cm^3) inside the work area after the abatement was not statistically greater than the mean asbestos concentration (0.0057 f/cm^3) outside the work area after abatement ($t = 0.14$, $p = 0.447$). The comparison made with the Z-test also showed that the concentrations inside the work area were not significantly greater than the concentrations outside the work area ($Z = 0.14$, $p = 0.444$). Therefore, Site 1 passed both the Purple Book and AHERA TEM clearance criteria.

Comparison of the postabatement asbestos concentrations inside the work area with those outside the building also show no statistically significant differences with either the t-test ($t = 0.45$, $p = 0.666$) or the Z-test ($Z = 0.45$, $p = 0.674$). Thus, this comparison would also result in Site 1 passing both Purple Book and AHERA clearance criteria.

PCM Clearance Comparison

Each postabatement sample collected inside the work area showed a fiber concentration of <0.01 f/cm^3. Therefore, Site 1 also passed the PCM clearance criteria.



—— PCM METHOD 7400	* * * 1 CHRYSOTILE F	◇ ◇ ◇ 1 CHRYSOTILE B
+ + 1 CHRYSOTILE M	# # # 1 CHRYSOTILE C	× × × 1 AMPHIBOLE F
△ △ 1 AMPHIBOLE B	O O O 1 AMPHIBOLE M	□ □ □ 1 AMPHIBOLE C
B B 1 AMBIGUOUS F	⊙ ⊙ ⊙ 1 AMBIGUOUS B	Z Z Z 1 AMBIGUOUS M
C C 1 AMBIGUOUS C	N N N 1 NON ASBESTOS F	V V V 1 NON ASBESTOS B
W W 1 NON ASBESTOS M	Y Y Y 1 NON ASBESTOS C	

Figure 7. Plot of structure length and diameter for postabatement air samples collected inside the work area for site 1.

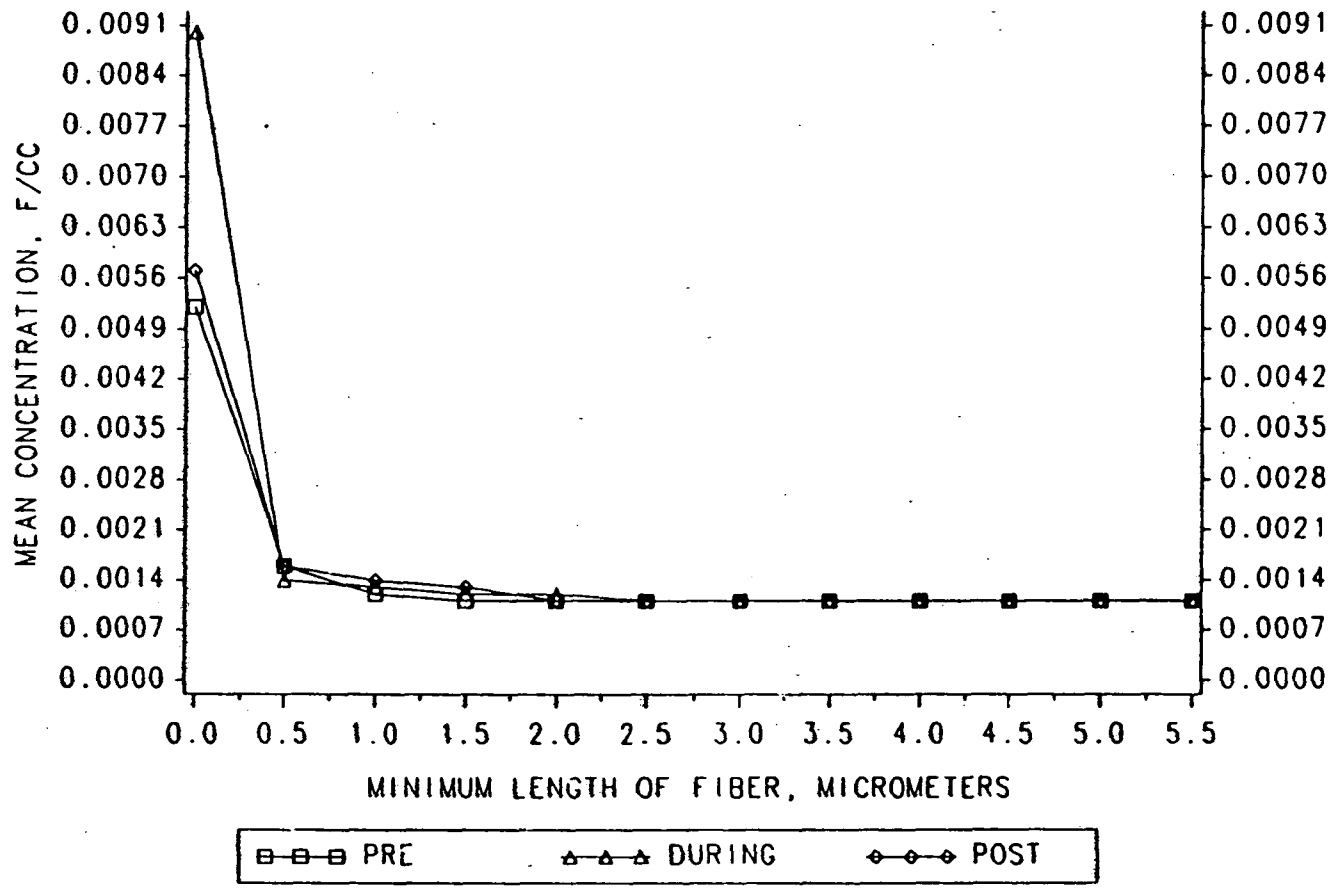


Figure 8. Plot of mean asbestos concentrations based on minimum fiber length for samples collected outside the work area (perimeter) for site 1.

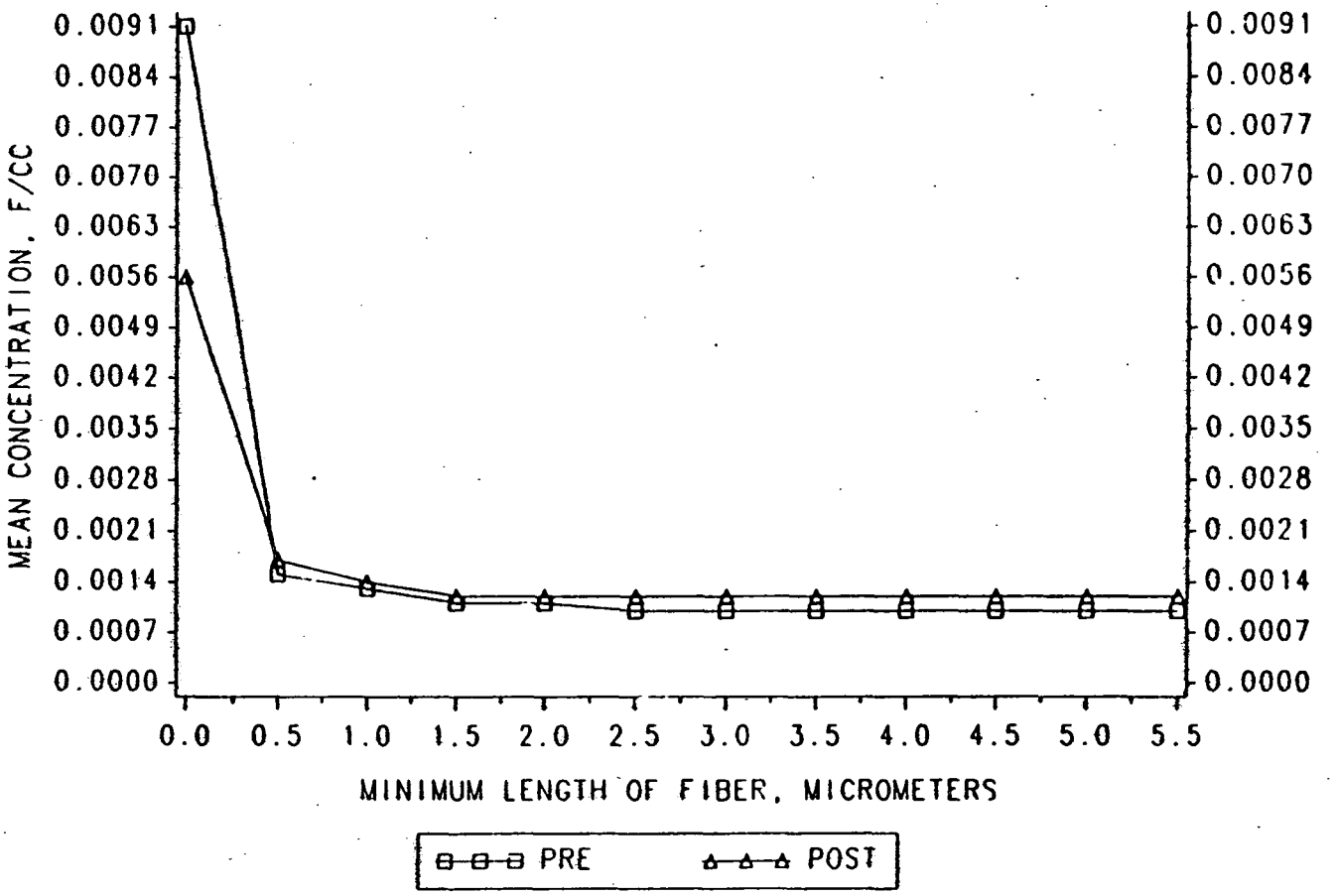


Figure 9. Plot of mean asbestos concentrations based on minimum fiber length for samples collected inside the work area for site 1.

Comparison of Concentrations Inside the Work Area With Ambient Air Concentrations After Abatement

The Wilcoxon rank sum test indicated that the mean airborne asbestos concentration for TEM-analyzed samples inside the work area after abatement was not statistically greater than the mean ambient concentration after abatement ($p = 0.635$). For PCM-analyzed samples, however, analysis indicated that the mean fiber concentration inside the work area after abatement was significantly greater than the mean ambient concentration after abatement ($p = 0.038$). The mean fiber concentration inside the work area after abatement was approximately twice as high as the mean fiber concentration in the ambient air after abatement (Table 6). This difference found in the PCM-analyzed samples is probably due to the presence of nonasbestos form particles. As shown in Figure 7, the asbestos fiber concentration determined by TEM for the postabatement samples inside the work area is based on particles outside the resolution window of PCM.

SITE 2

Comparison of Fiber Concentrations Outside the Work Area Before, During, and After Abatement

The Kruskall-Wallis test revealed statistically significant differences in airborne asbestos concentrations outside the work area between the three abatement phases (Figure 10) for TEM-analyzed samples ($p = 0.0002$). The mean asbestos concentration after abatement was approximately 8 times greater than the mean concentration during abatement and approximately 80 times greater than the mean concentration before abatement (Table 7). The asbestos concentrations outside the work area before abatement were not significantly different from the concentrations during abatement.

The Kruskall-Wallis test revealed no statistically significant difference in the mean fiber concentrations between the three abatement phases (Figure 11) for those samples analyzed by PCM ($p = 0.229$). The PCM mean fiber concentrations are considerably lower than the corresponding TEM mean asbestos concentrations (Table 7) even though PCM counts all fiber types and TEM counts only asbestos fibers. This suggests that most of the fibers counted by TEM are too small to be detected by PCM. This corroborates previous findings that PCM estimates of airborne fiber concentrations do not accurately reflect estimates of asbetos concentrations based on TEM.[3,12]

Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length

Figures 12 and 13 graphically present mean asbestos fiber concentrations of the samples analyzed by TEM based on minimum fiber length for inside-work-area samples and outside work area samples, respectively. Because PCM analysis counts only particles >5 µm in length, these plots show the portion of the total asbestos fiber concentration consisting of those particles <5 µm in length.

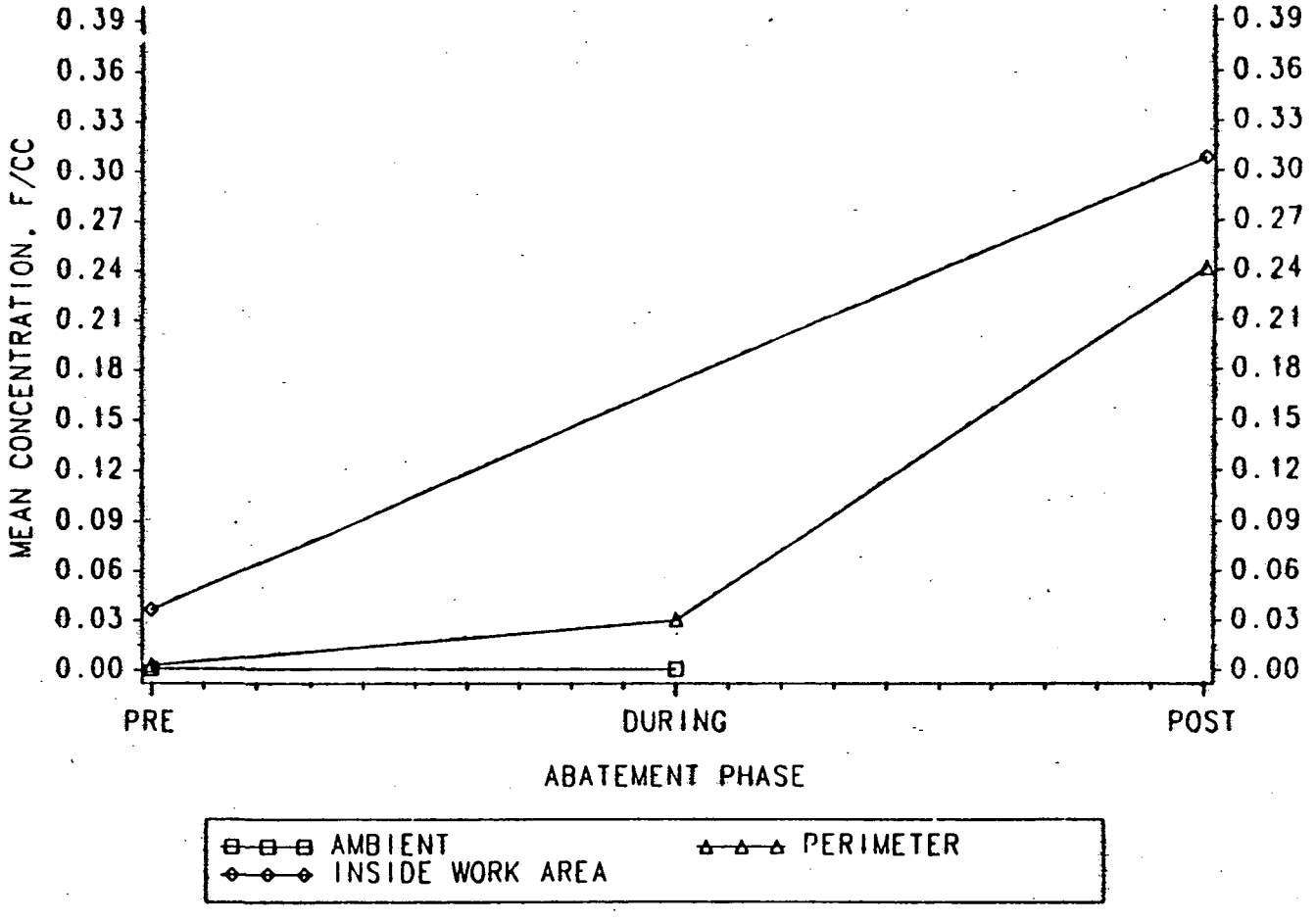


Figure 10. Mean airborne asbestos concentrations before, during, and after abatement for samples analyzed by TEM at site 2.

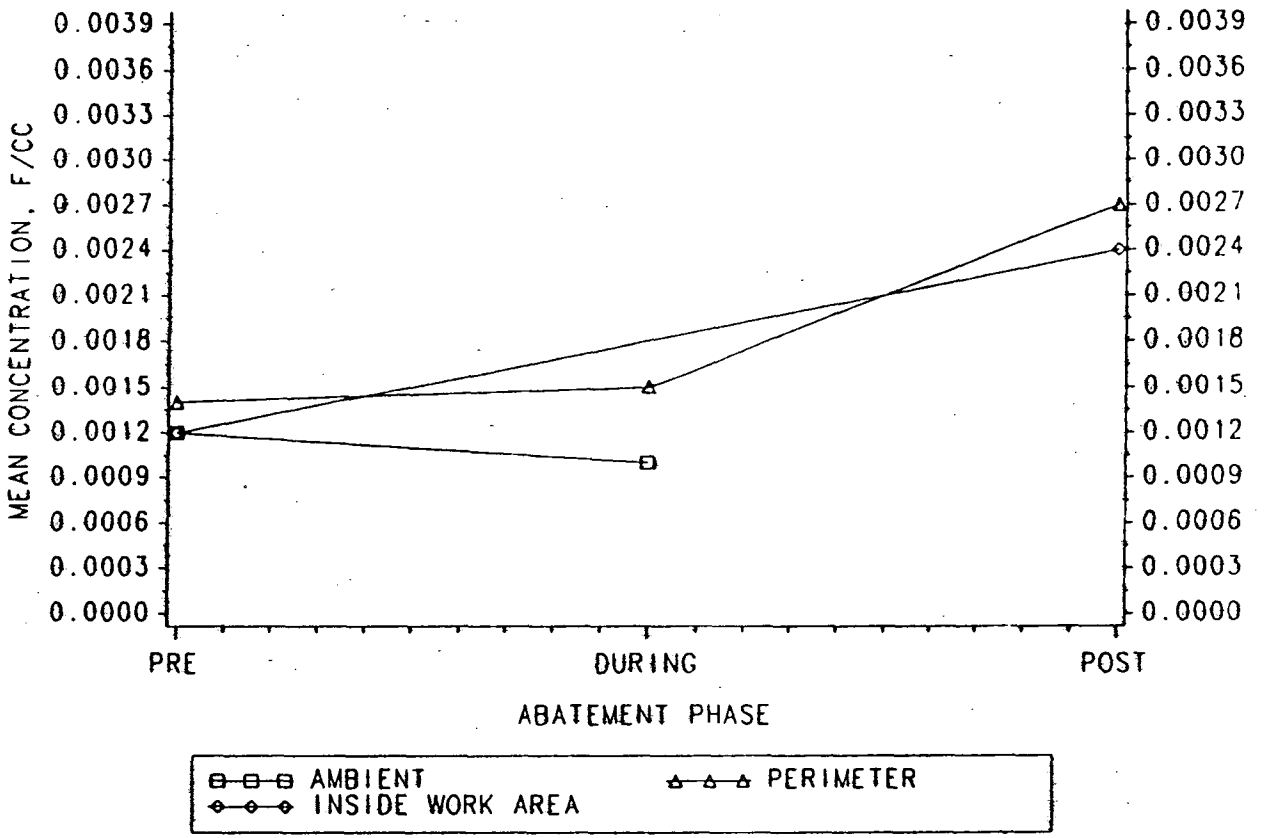


Figure 11. Mean airborne fiber concentrations before, during, and after abatement for samples analyzed by PCM at site 2.

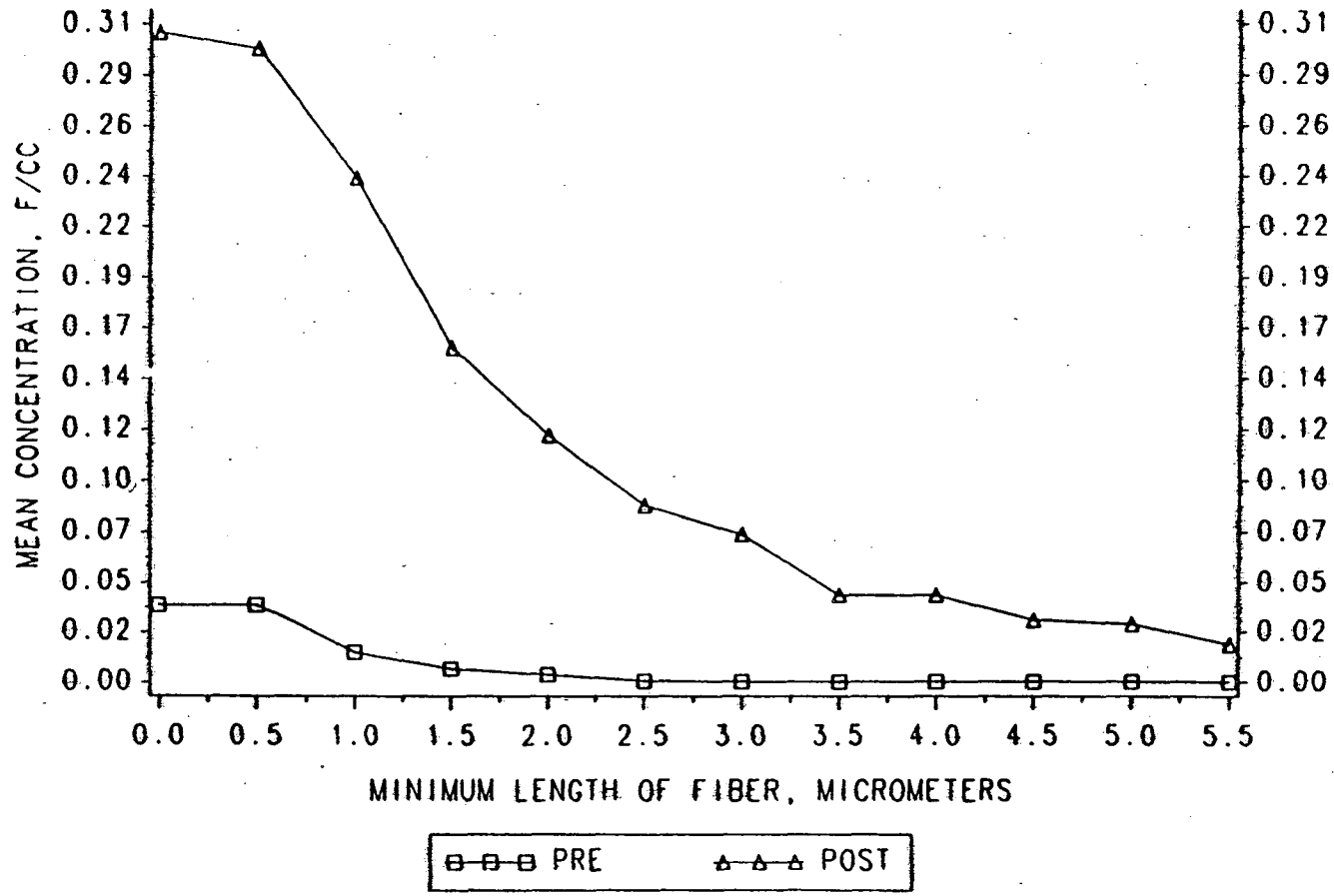


Figure 12. Plot of mean asbestos concentrations based on minimum fiber length for samples collected inside the work area for site 2.

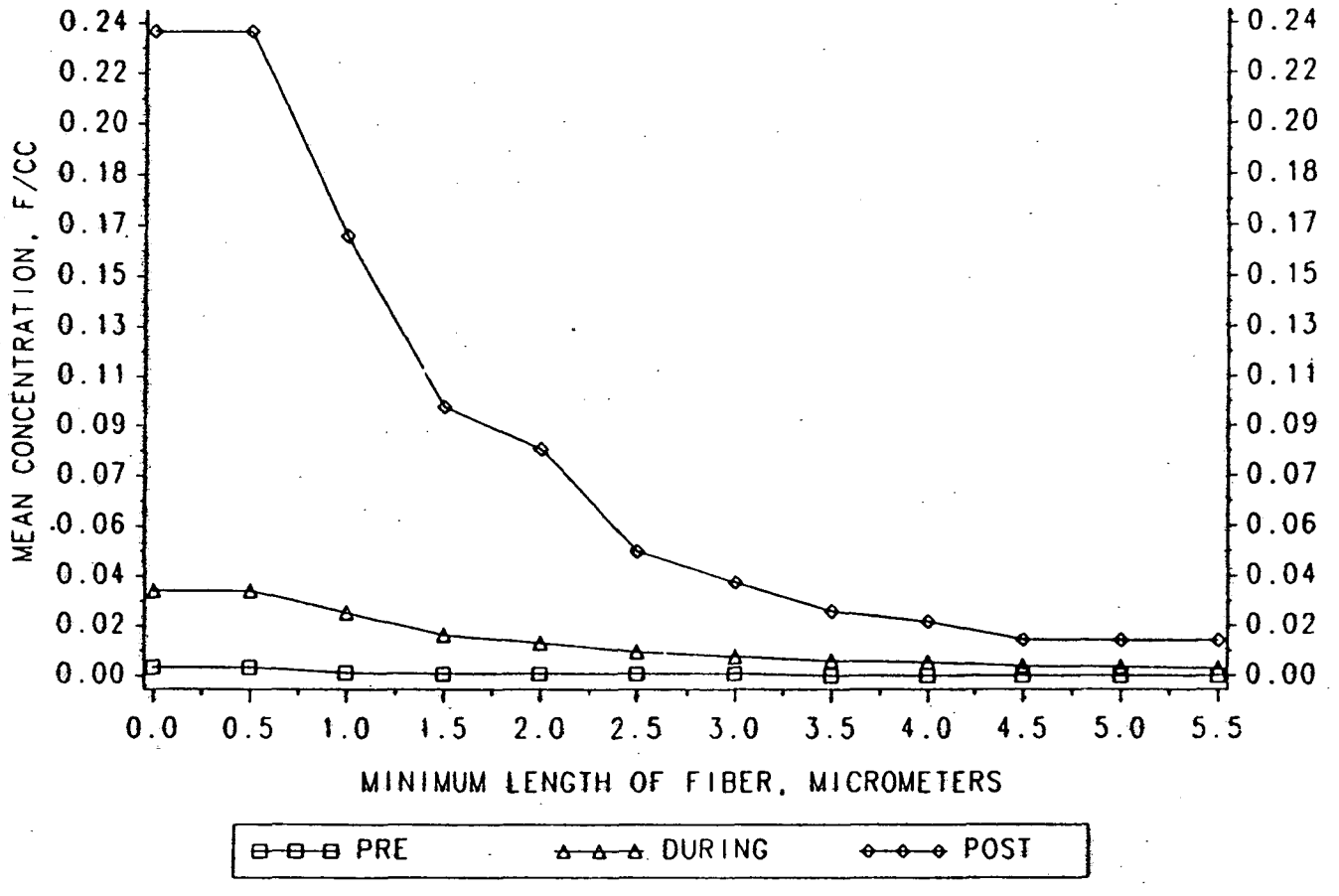


Figure 13. Plot of mean asbestos concentrations based on minimum fiber length for samples collected outside the work area (perimeter) for site 2.

Comparison of Fiber Concentrations Inside the Work Area Before and After Abatement

The Wilcoxon rank sum test revealed a statistically significant difference in the mean airborne asbestos concentration of TEM-analyzed samples inside the work area after abatement ($p = 0.008$). The mean asbestos concentration increased significantly after abatement (Figure 10). This increase may be attributable to the difference in sampling conditions (i.e., static sampling conditions in the preabatement phase versus aggressive sampling conditions in the postabatement phase).[11]

The test revealed no statistically significant difference in the mean fiber concentration of PCM-analyzed samples after abatement ($p = 0.096$) (Figure 11).

TEM Clearance Comparison

The clearance comparison made with the Student's t-test indicated that the mean asbestos concentration inside the work area after abatement (0.308 f/cm^3) was not statistically greater than the mean asbestos concentration outside the work area after abatement (0.241 f/cm^3) ($t = 0.97$, $p = 0.179$). This same comparison made using the Z-test also showed that the concentrations inside the work area were not significantly higher than the concentrations outside the work area ($Z = 1.26$, $p = 0.104$). Therefore, Site 2 passed both the Purple Book and AHERA TEM clearance criteria.

Although the site passed both statistical clearance tests, there was a statistically significant increase in the concentration of airborne asbestos fibers between the preabatement and postabatement periods. As shown earlier, there was a significant increase inside the abatement work area ($p = 0.008$), as well as outside the abatement area ($p = 0.0002$). This increase in asbestos concentration outside of the abatement area enabled the site to pass both the Purple Book and AHERA clearance criteria. However, comparison of the postabatement inside work area concentrations with outside building concentrations show statistically significant differences using both the t-test ($t = 17.3$, $p = 0.0001$) and Z-test ($Z = 12.4$, $p = 0.0001$). Thus, comparison of the inside work area concentrations with outside building concentrations causes the site to fail both Purple Book and AHERA release criteria. (Because no postabatement ambient air samples were taken outside the building, it is assumed that postabatement ambient air concentrations are consistent with preabatement and during-abatement ambient concentrations.)

A single incident such as this is not sufficient basis for proposing a change in the clearance criteria; however, it does identify a serious limitation of comparing postabatement asbestos concentrations inside the work area to those outside the work area, but inside the building. In essence, it demonstrates that a significant increase in asbestos concentration outside the abatement work area could facilitate passing of the clearance test. As preabatement samples for TEM analysis typically are not collected inside or outside of the abatement work area, the increase in concentration would not be detected. Thus, an asbestos abatement project could result in an overall increase in the asbestos contamination level in a building.

PCM Clearance Comparison

Each postabatement sample collected inside the work area showed a fiber concentration of <0.01 f/cm^3. Therefore, Site 2 also passed the PCM clearance criteria.

Comparison of Concentrations Inside the Work Area With Ambient Air Concentrations After Abatement

No postabatement ambient air samples were collected at this site; however, ambient air samples were collected both before and during abatement. The Wilcoxon rank sum test indicated no statistically significant difference between the mean asbestos concentrations of the preabatement ambient samples and the ambient samples taken during abatement as determined by TEM analysis ($p = 0.766$) or PCM analysis ($p = 0.690$). Therefore, the ambient air results were pooled for comparison with the postabatement asbestos concentration inside the work area.

Analysis revealed that the mean asbestos concentration inside the work area after abatement was significantly greater than the overall mean ambient asbestos concentration for samples analyzed by both TEM ($p = 0.0001$) and PCM ($p = 0.012$). The mean asbestos concentration after abatement as determined by TEM was approximately 385 times greater than the overall mean ambient concentrations, whereas the mean fiber concentration determined by PCM analysis inside the work area after abatement was about twice as high as the overall mean ambient concentrations (Table 7).

SITE 3

Comparison of Fiber Concentrations Outside the Work Area Before, During, and After Abatement

The Kruskall-Wallis test revealed no statistically significant differences in asbestos concentrations outside the work area between the three abatement phases for samples analyzed by either TEM ($p = 0.276$) or PCM ($p = 0.762$) (Figures 14 and 15, respectively).

Although the mean TEM-determined asbestos concentration outside the work area during the abatement (0.0129 f/cm^3) is larger than both preabatement (0.0008 f/cm^3) and postabatement (0.0028 f/cm^3) mean concentrations, no statistically significant differences exist in asbestos concentrations among the three abatement phases (Table 8). The mean asbestos concentration outside the work area during the abatement is heavily weighted by samples taken on September 11, 1987, which suggests a breach in the containment barrier. The omission of these samples would decrease the mean concentration to 0.0064 f/cm^3.

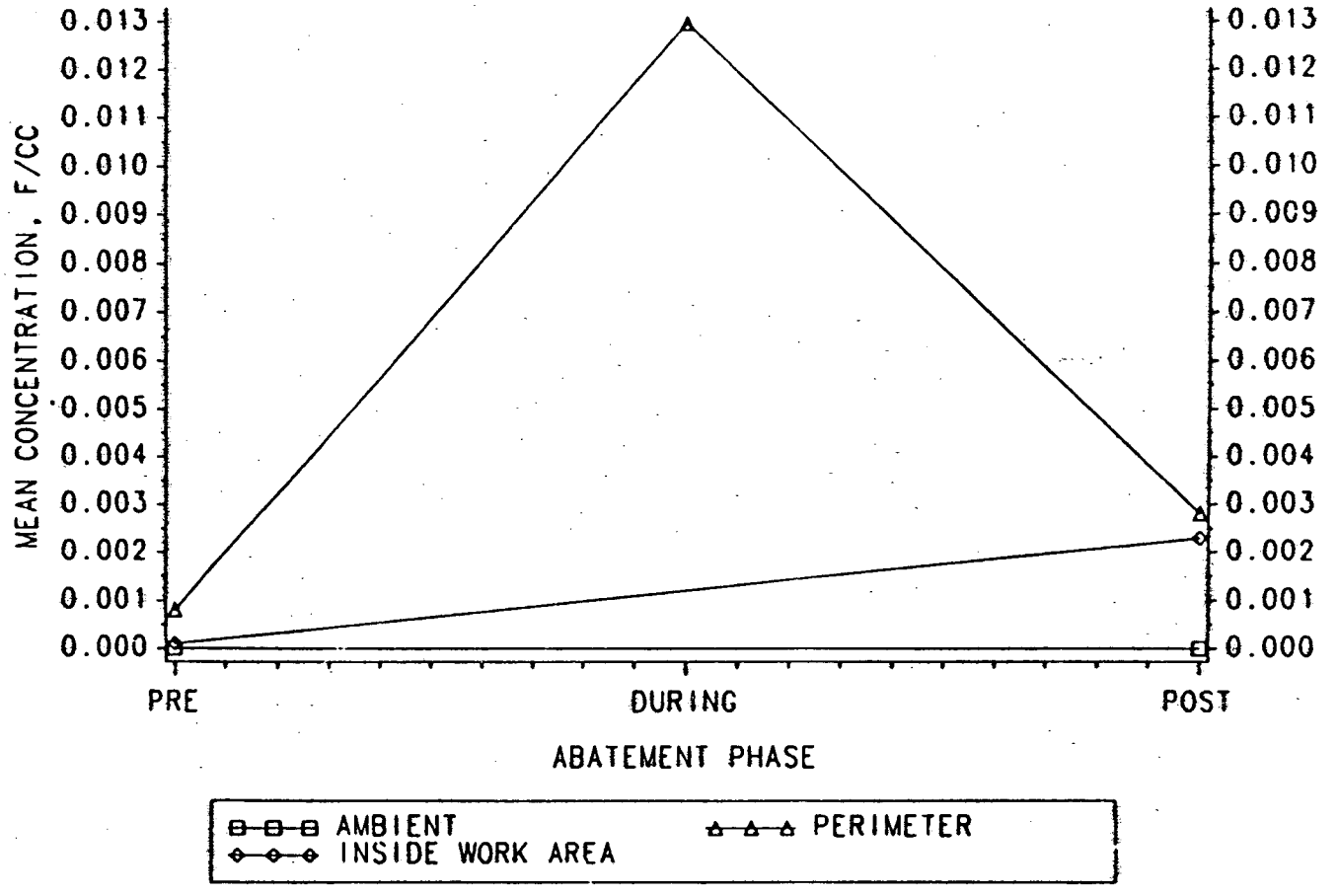


Figure 14. Mean airborne asbestos concentrations before, during, and after abatement for samples analyzed by TEM at site 3.

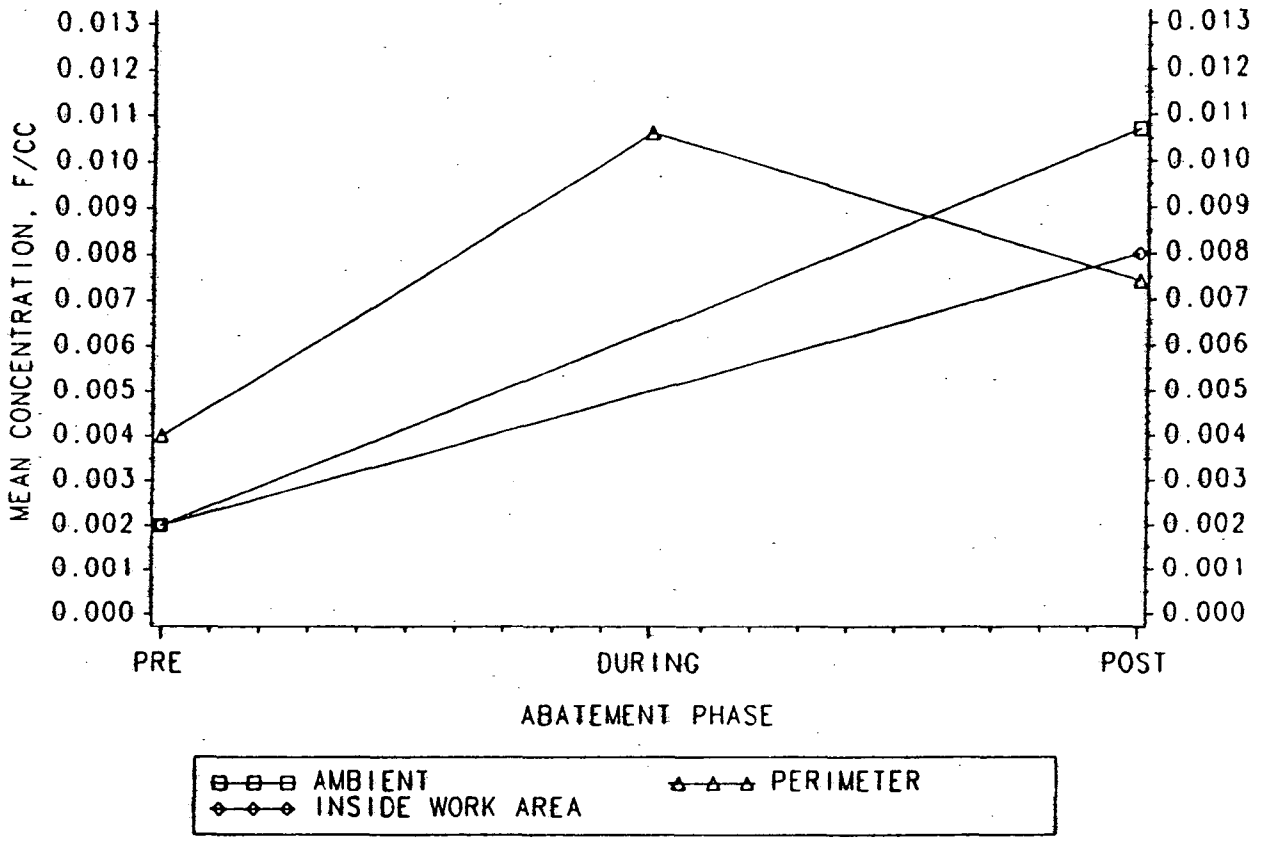


Figure 15. Mean airborne fiber concentrations before, during, and after abatement for samples analyzed by PCM at site 3.

A comparison of median asbestos concentrations between the three abatement phases actually illustrates the comparability of these concentrations better than an examination of the mean concentrations. The median concentrations before, during, and after abatement were 0.0000, 0.0032, and 0.0028 f/cm^3, respectively.

Comparison of Fiber Concentrations Inside the Work Area Before and After Abatement

The Wilcoxon rank sum test revealed a statistically significant difference in the mean airborne asbestos concentration inside the work area before and after abatement for samples analyzed by both TEM ($p = 0.012$) and PCM ($p = <0.001$). Mean asbestos concentrations increased significantly after abatement for samples analyzed by both techniques (Table 8). The increase may be attributable to the difference in sampling conditions (i.e., static conditions in the preabatement phase versus aggressive conditions in the postabatement phase.

TEM Clearance Comparison

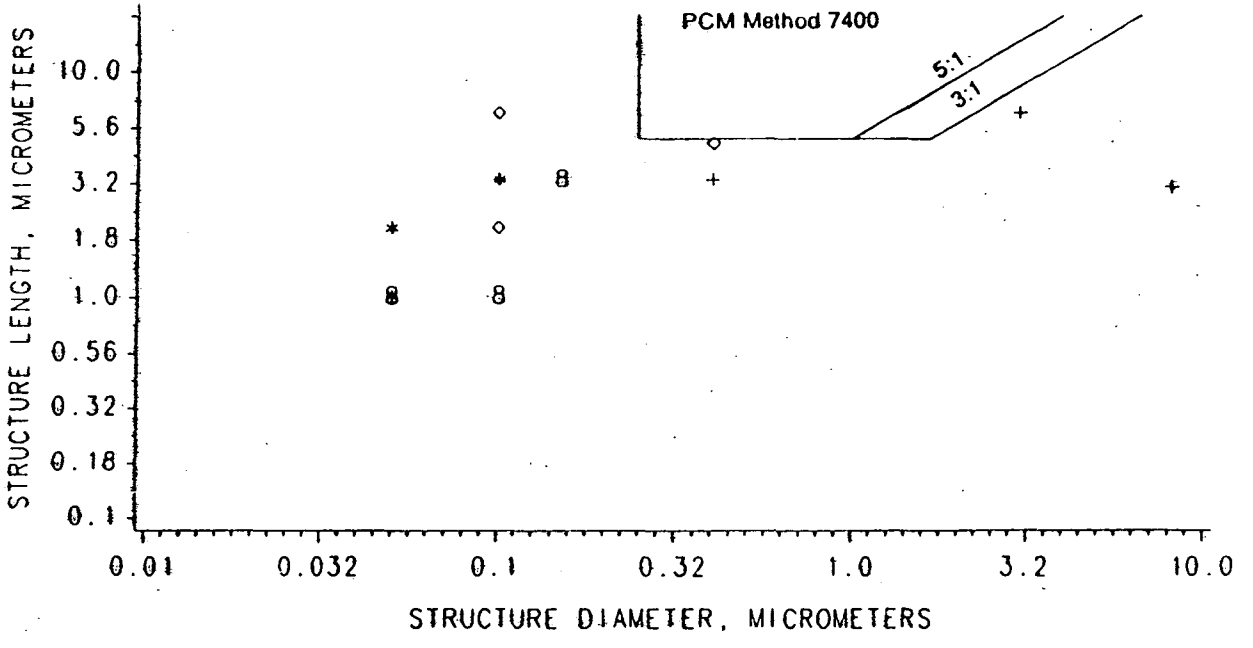
The clearance comparison made with the Student's t-test indicated that the mean asbestos concentration inside the work area after the abatement (0.0023 f/cm^3) was not statistically greater than the mean asbestos concentration outside the work area after abatement (0.0028 f/cm^3) ($t = -0.43$, $p = 0.659$). This same comparison made using the Z-test also showed that the concentrations inside the work area were not significantly greater than the concentrations outside the work area ($Z = -0.41$, $p = 0.659$). Therefore Site 3 passed both the Purple Book and AHERA TEM clearance test.

Comparison of the postabatement asbestos concentrations inside the work area with those outside the building also show no statistically significant differences with either the t-test ($t = 1.58$, $p = 0.077$) or the Z-test ($Z = 1.22$, $p = 0.111$). Thus, comparison of postabatement concentrations inside the work area with those outside the building also result in Site 3 passing both Purple Book and AHERA clearance criteria.

PCM Clearance Comparison

One of the postabatement samples collected inside the work area showed fiber concentrations of 0.014 f/cm^3 versus the clearance criterion of 0.01 f/cm^3 (Table 8). Therefore, Site 3 failed the PCM clearance criteria.

As discussed under Site 1, the difference in the conclusion reached by the two analytical protocols confirms a serious limitation of PCM analysis (i.e., PCM cannot distinguish asbestos from nonasbestos fibers). Figure 16 suggests that the fibers counted by PCM were nonasbestos forms. Therefore, this site's failure to pass the abatement clearance criteria, in terms of the presence of airborne asbestos, is believed to be erroneous.



—— PCM METHOD 7400	* * * 1 CHRYSOTILE F	◇ ◇ ◇ 1 CHRYSOTILE B
+ + 1 CHRYSOTILE M	# # # 1 CHRYSOTILE C	× × × 1 AMPHIBOLE F
△ △ 1 AMPHIBOLE B	O O O 1 AMPHIBOLE M	□ □ □ 1 AMPHIBOLE C
8 8 1 AMBIGUOUS F	⊙ ⊙ ⊙ 1 AMBIGUOUS B	Z Z Z 1 AMBIGUOUS M
C C 1 AMBIGUOUS C	N N N 1 NON ASBESTOS F	V V V 1 NON ASBESTOS B
W W 1 NON ASBESTOS M	Y Y Y 1 NON ASBESTOS C	

Figure 16. Plot of structure length and diameter for postabatement air samples collected inside the work area for site 3.

Plot of Mean Asbestos Concentrations Based on Minimum Fiber Length

Figures 17 and 18 graphically present mean asbestos fiber concentrations of the samples analyzed by TEM based on minimum fiber length for samples outside the work area and samples inside the work area, respectively. Because PCM analysis counts only particles ≥5 µm in length, these plots show that portion of the total asbestos fiber concentration consisting of particles <5 µm in length.

Comparison of Concentrations Inside the Work Area With Ambient Air Concentrations After Abatement

The Wilcoxon rank sum test revealed that the mean asbestos concentration inside the work area after abatement was significantly greater than the mean ambient air asbestos concentration for TEM-analyzed samples ($p = 0.025$), but not for PCM-analyzed samples ($p = 0.918$). The mean asbestos concentration for TEM analyzed samples inside the work area after abatement was approximately twice as large as the mean ambient air concentration in TEM-analyzed samples after abatement (Table 8).

Comparison of Concentrations in Samples Collected on 0.4 µm Pore Size Polycarbonate and 0.8 µm Pore Size Mixed Cellulose Ester Membrane Filters

The asbestos concentrations measured on 0.8 µm pore size mixed cellulose ester filters are plotted against the corresponding measurements made on 0.4 µm pore size polycarbonate filters (Figure 19). The asbestos concentrations are higher on 0.4 µm pore size polycarbonate filters than on the 0.8 µm pore size mixed cellulose ester filters.

The Wilcoxon signed rank test revealed a significant difference in mean asbestos concentrations between the two filter types ($p = 0.0001$). The mean asbestos concentration of samples collected on 0.4 µm pore size polycarbonate filters was 0.0058 f/cm^3 greater than the mean asbestos concentration of samples collected on 0.8 µm pore size mixed cellulose ester filters.

Asbestos Concentrations in Exhaust Duct Discharge Air From a Negative Air Filtration Unit

Figure 20 graphically presents the mean asbestos concentrations of the sample analyzed by TEM based on cumulative fiber length for five mixed cellulose ester and six polycarbonate filter samples obtained in the exhaust duct from a negative air filtration unit at Site 3. Overall, the mean asbestos concentrations were 0.0010 f/cm^3 on mixed cellulose ester filters and 0.0029 f/cm^3 on polycarbonate filters. A higher mean concentration on the polycarbonate filters is consistent with the concentration comparison presented above for these two filter types.

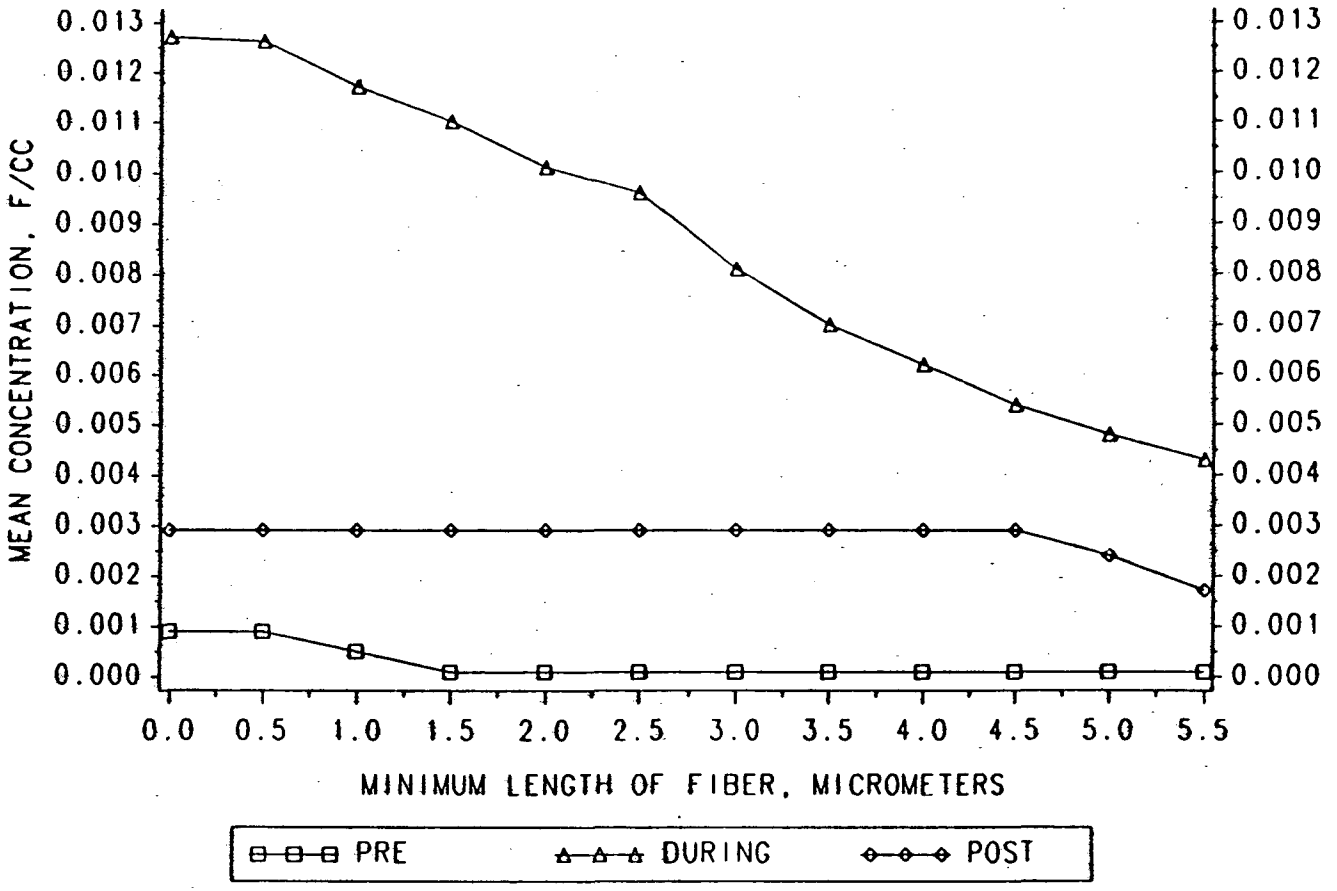


Figure 17. Plot of mean asbestos concentrations based on minimum fiber length for samples collected outside the work area (perimeter) for site 3.

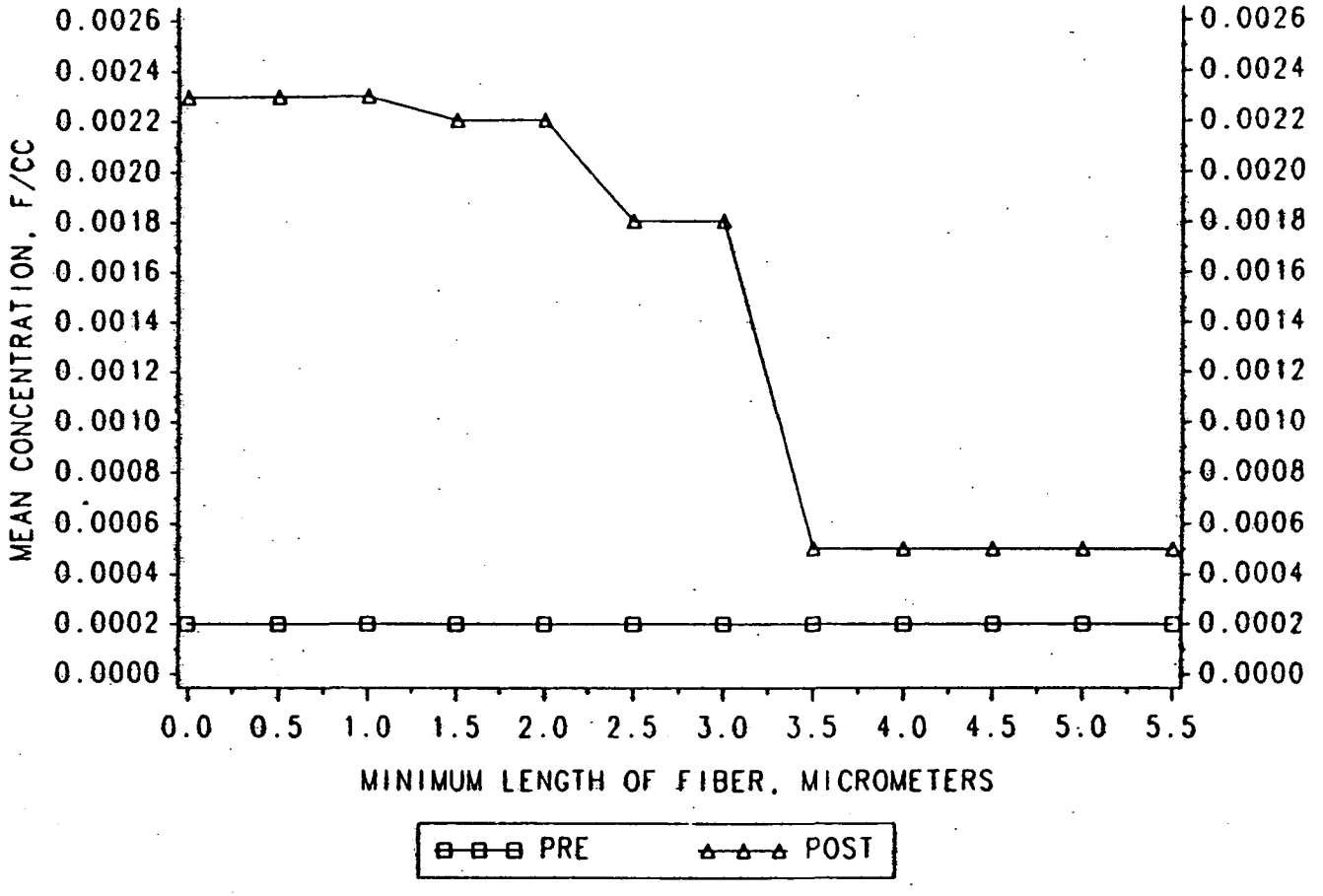


Figure 18. Plot of mean asbestos concentrations based on minimum fiber length for samples collected inside the work area for site 3.

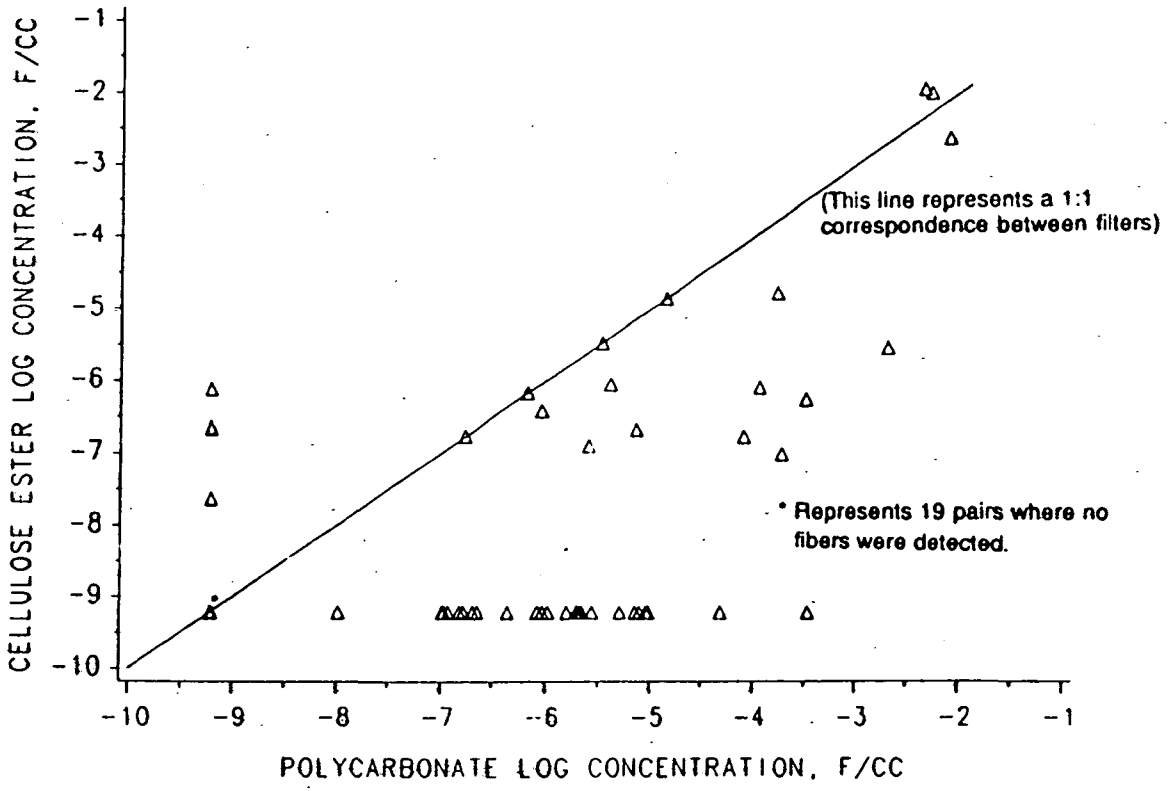


Figure 19. Relationship between average airborne asbestos concentrations measured on 0.8 pore-size mixed cellulose ester and 0.4 pore-size polycarbonate membrane filters.

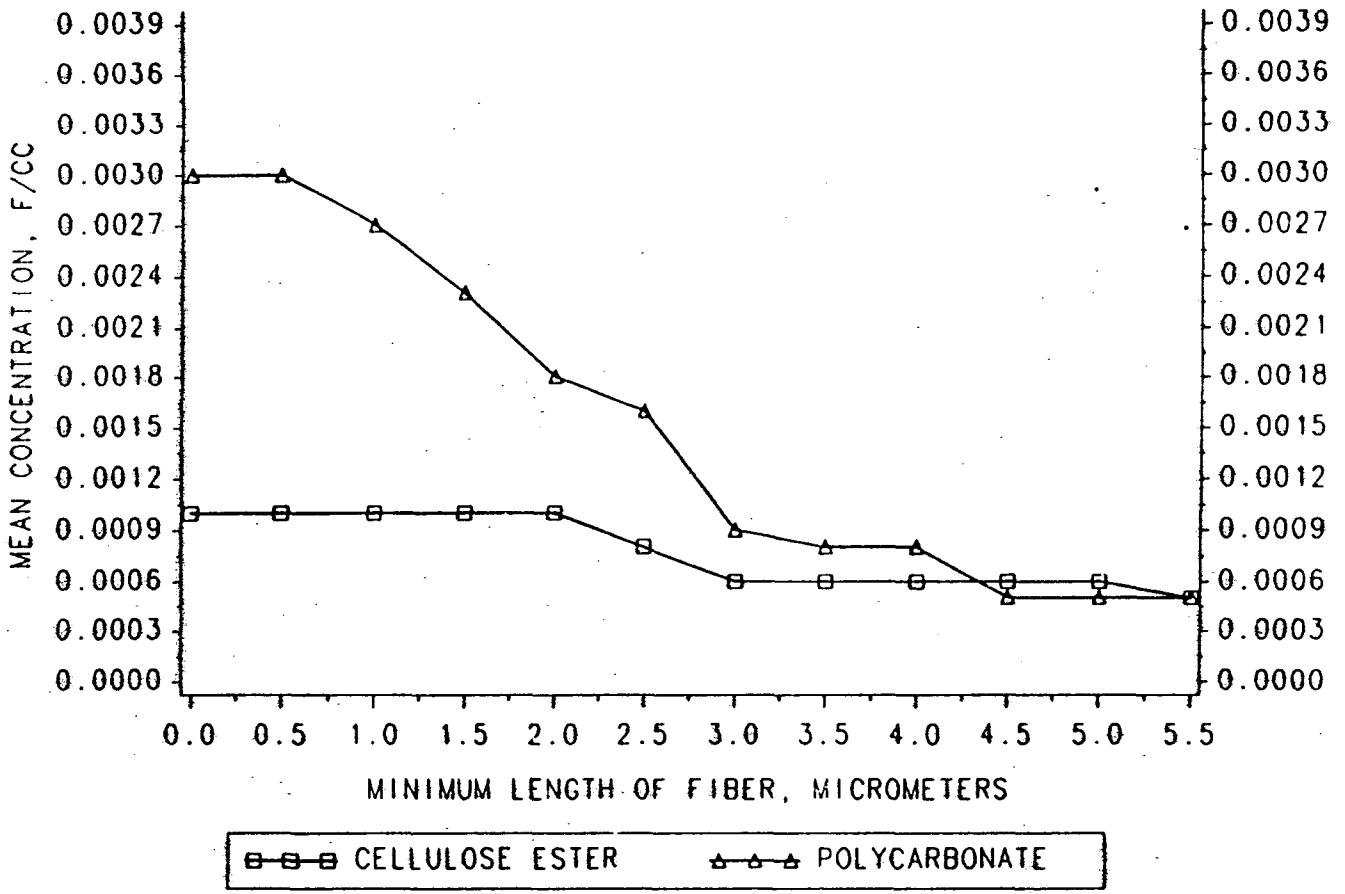


Figure 20. Plot of mean asbestos concentrations based on minimum fiber length for samples collected inside the exhaust duct from a negative air filtration system at site 3.

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APPENDIX A

AIRBORNE TOTAL FIBER CONCENTRATIONS BEFORE, DURING, AND AFTER ABATEMENT FOR SAMPLES ANALYZED BY TRANSMISSION ELECTRON MICROSCOPY

The column headings for Appendix A are defined below:

DATE_SAM	=	Date sampled
SAMP	=	Sample number
CONC	=	Asbestos concentration in structures per cubic centimeter of air sampled
N	=	Total number of asbestos particles
SENSTVTY	=	Analytical sensitivity
STRMM2	=	Asbestos structures per square millimeter

TABLE A-1. SITE 1 PREABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
10/31/86	2013	0.005080	3	0.002	42.1
11/01/86	2019	0.003182	2	0.002	28.0
11/01/86	2025	0.004150	3	0.001	42.1

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
10/31/86	2004	0.003383	2	0.002	28.0
10/31/86	2005	0.006954	4	0.002	56.1
10/31/86	2006	0.003510	2	0.002	28.0
10/31/86	2010	0.009762	6	0.002	84.2
10/31/86	2011	0.008101	5	0.002	70.1
10/31/86	2012	0.001573	1	0.002	14.0
11/01/86	2016	0.003244	2	0.002	28.0
11/01/86	2017	0.011476	7	0.002	98.2
11/01/86	2018	0.001732	1	0.002	14.0
11/01/86	2022	0.008445	6	0.001	84.2
11/01/86	2023	0.001433	1	0.001	14.0
11/01/86	2024	0.002836	2	0.001	28.0

ABATEMENT AREA

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
10/31/86	2001	0.011728	7	0.002	98.2
10/31/86	2002	0.008620	5	0.002	70.1
10/31/86	2003	0.008459	5	0.002	70.1
10/31/86	2007	0.008160	5	0.002	70.1
10/31/86	2008	0.014886	9	0.002	126.3
10/31/86	2009	0.003225	2	0.002	28.0
11/01/86	2014	0.006540	4	0.002	56.1
11/01/86	2015	0.019525	12	0.002	168.4
11/01/86	2020	0.001396	1	0.001	14.0
11/01/86	2021	0.008730	6	0.001	84.2

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DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
10/31/86	2026	.	2	.	28.0
11/01/86	2027	.	.	.	<14.0
11/01/86	2028	.	4	.	56.1

TABLE A-2. SITE 1 DURING ABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
11/18/86	2039	0.007999	4.0	0.002	56.1
11/19/86	2044	0.005568	4.5	0.001	63.1
11/21/86	2079	<0.001188	.	0.001	<14.0
11/20/86	2086	<0.001298	.	0.001	<14.0

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
11/13/86	2029	0.037603	11.5	0.003	161.4
11/13/86	2030	0.002541	2.0	0.001	28.0
11/13/86	2031	0.001215	1.0	0.001	14.0
11/13/86	2032	0.007486	6.0	0.001	84.2
11/13/86	2033	0.038808	29.0	0.001	407.1
11/13/86	2034	0.001935	1.0	0.002	14.0
11/18/86	2035	0.005460	4.0	0.001	112.3
11/18/86	2036	0.002781	2.0	0.001	28.0
11/18/86	2037	0.005441	3.0	0.002	42.1
11/18/86	2038	0.001442	1.0	0.001	14.0
11/19/86	2040	0.003547	3.0	0.001	42.1
11/19/86	2041	0.025067	16.0	0.002	224.6
11/18/86	2042	0.001487	1.0	0.001	14.0
11/19/86	2043	0.007245	6.0	0.001	84.2
11/19/86	2045	0.004897	4.0	0.001	56.1
11/19/C6	2046	<0.001238	.	0.001	<14.0
11/24/86	2052	0.012936	11.0	0.001	154.4
11/21/86	2055	0.009483	8.0	0.001	112.3
11/24/86	2056	<0.001183	.	0.001	<14.0
11/24/86	2057	0.018719	16.0	0.001	224.6
11/21/86	2064	0.017358	11.5	0.002	161.4
11/24/86	2074	0.001192	1.0	0.001	14.0
11/21/86	2078	0.007131	6.0	0.001	84.2
11/21/86	2080	0.008965	7.5	0.001	105.2
11/21/86	2083	0.003568	3.0	0.001	42.1
11/20/86	2086	0.009163	7.0	0.001	98.2
11/20/87	2090	0.001540	1.0	0.002	14.0
11/20/86	2091	0.013056	10.0	0.001	140.3
11/20/86	2092	0.012445	9.5	0.001	133.3
11/20/86	2093	0.005192	4.0	0.001	56.1
11/24/86	2095	0.007468	5.0	0.001	70.1

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DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
11/18/86	2047	.	1	.	14.0
11/20/86	2062	.	.	.	<14.0
11/24/86	2065	.	2	.	28.0
11/19/86	2072	.	2	.	28.0
11/21/86	2075	.	4	.	56.1

TABLE A-3. SITE 1 POSTABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
12/03/86	2050	0.009836	6	0.002	84.2
12/03/86	2054	<0.001525	.	0.002	<14.0
12/03/86	2089	0.008017	5	0.002	70.1
12/03/86	2094	0.008978	5	0.002	70.1

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
12/03/86	2049	0.001574	1.0	0.002	14.0
12/03/86	2066	0.012656	7.5	0.002	105.2
12/03/86	2076	0.004950	3.0	0.002	42.1
12/03/86	2077	0.007574	5.0	0.002	70.1
12/03/86	2085	0.001709	1.0	0.002	14.0

ABATEMENT AREA

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
12/03/86	2068	0.008260	5	0.002	70.1
12/03/86	2069	0.011040	7	0.002	98.2
12/03/86	2070	0.003517	2	0.002	28.0
12/03/86	2071	0.001783	1	0.002	14.0
12/03/86	2073	0.003213	2	0.002	28.0

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DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
12/03/86	2058	.	6	.	84.2

TABLE A-4. SITE 2 PREABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/03/87	2151	<0.001659	.	0.002	<16.0
04/03/87	2154	<0.001632	.	0.002	<16.0
04/03/87	2157	<0.001702	.	0.002	<16.0
04/03/87	2163	0.001837	1	0.002	16.0
04/03/87	2167	0.003612	2	0.002	32.0

PERIMETER

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/03/87	2149	0.004910	3	0.002	48.0
04/03/87	2156	<0.002059	.	0.002	<16.0
04/03/87	2159	0.003323	2	0.002	32.0
04/03/87	2162	<0.001717	.	0.002	<16.0
04/03/87	2165	0.006827	4	0.002	64.1

ABATEMENT AREA

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/03/87	2152	<0.001609	.	0.002	<16.0
04/03/87	2160	0.168596	45	0.004	802.8
04/03/87	2161	<0.001671	.	0.002	<16.0
04/03/87	2163A	0.013446	8	0.002	128.2
04/03/87	2168	0.001679	1	0.002	16.0

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DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/03/87	2166	.	.	.	<16.0

TABLE A-5. SITE 2 DURING ABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/06/87	2298A	0.001034	2	0.001	32.0
04/06/87	2307	<0.000551	.	0.001	<16.0
04/06/87	2333	<0.000572	.	0.001	<16.0
04/06/87	2334	<0.000613	.	0.001	<16.0
04/06/87	2336	0.001226	2	0.001	32.0

PERIMETER

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/03/87	2270	0.015672	29	0.001	464.7
04/07/87	2297	0.006121	1	0.006	80.1
04/06/87	2298B	0.058950	22	0.003	762.8
04/06/87	2299	0.004759	8	0.001	128.2
04/07/87	2300	0.099514	39	0.003	250.0
04/06/87	2306	<0.000558	.	0.001	<16.0
04/06/87	2308	0.011790	22	0.001	352.5
04/07/87	2309	0.012350	1	0.012	160.2
04/07/87	2310	0.014012	12	0.001	192.3
04/06/87	2329	0.000538	1	0.001	16.0
04/06/87	2331	0.000623	1	0.001	16.0
04/06/87	2332	0.019655	31	0.001	620.9
04/07/87	2338	0.017689	15	0.001	240.3
04/09/87	2374	0.021215	34	0.001	544.8
04/08/87	2375	0.016553	23	0.001	460.7
04/08/87	2376	0.003270	5	0.001	80.1
04/08/87	2377	0.027337	23	0.001	368.5
04/08/87	2378	0.003453	3	0.001	48.0
04/08/87	2379	0.095269	40	0.002	282.0
04/09/87	2380	0.016122	26	0.001	416.6
04/08/87	2381	0.033610	28	0.001	448.7
04/08/87	2382	0.038957	37	0.001	592.9
04/09/87	2383	0.015430	27	0.001	432.6
04/07/87	2384	0.013108	6	0.002	160.2
04/08/87	2385	0.017865	17	0.001	454.0
04/08/87	2386	0.091711	40	0.002	282.0
04/07/87	2387	0.228608	18	0.013	884.6
04/09/87	2388	0.001169	1	0.001	16.0
04/09/87	2389	0.001331	2	0.001	32.0
04/08/87	2390	0.045762	28	0.002	641.0
04/08/87	2393	0.011464	10	0.001	160.2

FIELD BLANK

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/07/87	2267	.	.	.	<16.0
04/06/87	2274	.	.	.	<16.0
04/08/87	2392	.	.	.	<16.0

TABLE A-6. SITE 2 POSTABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

PERIMETER

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/09/87	2344	0.298708	29	0.010	323.7
04/09/87	2345	0.341401	18	0.019	884.6
04/09/87	2346	0.328553	57	0.006	44.8
04/09/87	2355	0.027676	14	0.002	224.3
04/09/87	2356	0.354704	18	0.020	884.6
04/09/87	2364	0.019832	10	0.002	160.2
04/09/87	2365	0.316302	48	0.007	564.1

ABATEMENT AREA

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/09/87	2347	0.173197	17	0.010	362.1
04/09/87	2357	0.230291	36	0.006	923.0
04/09/87	2358	0.617811	30	0.021	807.6
04/09/87	2366	0.266739	13	0.021	83.3
04/09/87	2367	0.253060	37	0.007	976.4

FIELD BLANK

DATE_SAM	SAMPLE	CONC	N	SENSTVTY	STRMM2
04/09/87	2368	.	.	.	<32.0

TABLE A-7. SITE 3 PREABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMP*	CONC	N	SENSTVTY	STRMM2
08/19/87	P1494	0.001193	1	0.001	8.8
08/19/87	P1504	<0.001205	.	0.001	<8.8
08/19/87	P1505	<0.001197	.	0.001	<8.8
08/19/87	2429	<0.001193	.	0.001	<8.8
08/19/87	2440	<0.001197	.	0.001	<8.8
08/19/87	2465	<0.001205	.	0.001	<8.8

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
08/19/87	P1485	<0.001210	.	0.001	<8.8
08/19/87	P1490	<0.001205	.	0.001	<8.8
08/19/87	P1495	<0.001205	.	0.001	<8.8
08/19/87	2441	<0.001205	.	0.001	<8.8
08/19/87	2442	0.002419	2	0.001	17.6
08/19/87	2452	<0.001205	.	0.001	<8.8

ABATEMENT AREA

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
08/19/87	P1478	<0.001161	.	0.001	<8.8
08/19/87	P1479	<0.001122	.	0.001	<8.8
08/19/87	P1480	<0.001141	.	0.001	<8.8
08/19/87	P1481	<0.001144	.	0.001	<8.8
08/19/87	P1486	<0.001144	.	0.001	<8.8
08/19/87	P1488	<0.001133	.	0.001	<8.8
08/19/87	P1489	<0.001176	.	0.001	<8.8
08/19/87	P1491	<0.001122	.	0.001	<8.8
08/19/87	2425	<0.001141	.	0.001	<8.8
08/19/87	2428	0.001144	1	0.001	8.8
08/19/87	2443	<0.001122	.	0.001	<8.8
08/19/87	2444	<0.001161	.	0.001	<8.8
08/19/87	2451	<0.001133	.	0.001	<8.8
08/19/87	2456	<0.001122	.	0.001	<8.8
08/19/87	2460	<0.001176	.	0.001	<8.8
08/19/87	2501	<0.001144	.	0.001	<8.8

FIELD BLANK

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
08/19/87	P1500	.	.	.	<8.8
08/19/87	P1506	.	.	.	<8.8
08/19/87	2266	.	.	.	<8.8
08/19/87	2450	.	.	.	<8.8

*1000 series are mixed cellulose ester filters; 2000 series are polycarbonate filters.

TABLE A-8. SITE 3 DURING ABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

NEGATIVE AIR EXHAUST

DATE_SAM	SAMP*	CONC	N	SENSTVTY	STRMM2
09/01/87	P1555	0.000376	1	0.000	8.8
09/02/87	P1571	<0.001249	.	0.001	<8.8
09/04/87	P1653	0.004061	10	0.000	88.2
09/04/87	P1660	<0.001337	.	0.001	<8.8
09/08/87	P1669	<0.001462	.	0.001	<8.8
09/08/87	2405	0.002924	2	0.001	17.6
09/04/87	2521	<0.001341	.	0.001	<8.8
09/03/87	2531	0.006867	5	0.001	44.1
09/04/87	2532	0.004061	10	0.000	88.2
09/01/87	2548	<0.000376	.	0.000	<8.8
09/02/87	2553	0.003746	3	0.001	26.4

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
09/01/87	P1487	<0.000826	.	0.001	<8.8
09/01/87	P1497	<0.000822	.	0.001	<8.8
09/01/87	P1498	<0.000857	.	0.001	<8.8
09/01/87	P1501	<0.000912	.	0.001	<8.8
08/31/87	P1508	<0.000835	.	0.001	<8.8
09/01/87	P1512	0.000794	1	0.001	8.8
08/31/87	P1524	0.001512	2	0.001	17.6
08/31/87	P1549	<0.000743	.	0.001	<8.8
08/20/87	P1550	<0.001416	.	0.001	<8.8
08/20/87	P1551	<0.001416	.	0.001	<8.8
08/20/87	P1552	<0.000236	.	0.000	<8.8
08/31/87	P1554	0.000897	1	0.001	8.8
08/31/87	P1558	<0.000994	.	0.001	<8.8
09/01/87	P1569	0.001157	1	0.001	8.8
09/04/87	P1570	<0.000876	.	0.001	<8.8
08/20/87	P1573	<0.001662	.	0.002	<8.8
09/01/87	P1574	<0.001034	.	0.001	<8.8
08/20/87	P1577	<0.001416	.	0.001	<8.8
09/01/87	P1579	<0.001100	.	0.001	<8.8
08/20/87	P1580	<0.001416	.	0.001	<8.8
08/20/87	P1581	<0.001416	.	0.001	<8.8
08/20/87	P1586	<0.000236	.	0.000	<8.8
09/01/87	P1590	<0.001149	.	0.001	<8.8
09/01/87	P1592	<0.001233	.	0.001	<8.8
08/20/87	P1595	<0.000276	.	0.000	<8.8
09/03/87	P1652	<0.001185	.	0.001	<8.8
09/03/87	P1655	0.002215	2	0.001	17.6
09/04/87	P1656	<0.000823	.	0.001	<8.8
09/03/87	P1658	0.001028	1	0.001	8.8
09/04/87	P1661	<0.001068	.	0.001	<8.8
09/04/87	P1662	<0.001196	.	0.001	<8.8
09/08/87	P1670	<0.001130	.	0.001	<8.8
09/08/87	P1671	<0.001040	.	0.001	<8.8
09/08/87	P1672	.	2	.	17.6
09/08/87	P1674	<0.001028	.	0.001	<8.8

(continued)

TABLE A-8 (continued)

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRAN2
09/09/87	P1675	<0.001079	.	0.001	<8.8
09/09/87	P1676	0.007641	7	0.001	61.7
09/09/87	P1677	0.002130	2	0.001	17.6
09/09/87	P1678	<0.001098	.	0.001	<8.8
09/10/87	P1681	0.002081	2	0.001	17.6
09/10/87	P1682	0.001864	2	0.001	17.6
09/09/87	P1686	<0.002249	.	0.002	<8.8
09/10/87	P1687	0.000951	1	0.001	8.8
09/09/87	P1689	<0.003582	.	0.004	<8.8
09/09/87	P1690	<0.002179	.	0.002	<8.8
09/10/87	P1693	0.003791	4	0.001	35.3
09/10/87	P1694	<0.000977	.	0.001	<8.8
09/11/87	P1696	0.008300	8	0.001	70.6
09/09/87	P1697	0.019609	9	0.002	79.4
09/10/87	P1698	<0.002179	.	0.002	<8.8
09/11/87	P1699	0.133702	128	0.001	130.0
09/10/87	P1704	0.004358	2	0.002	17.6
09/11/87	P1706	0.001787	2	0.001	17.6
09/10/87	P1707	<0.002179	.	0.002	<8.8
09/11/87	P1709	0.071121	67	0.001	591.5
09/11/87	P1715	0.141181	133	0.001	174.1
09/04/87	2424	<0.000842	.	0.001	<8.8
09/10/87	2434	0.031264	32	0.001	282.5
09/13/87	2438	0.000803	1	0.001	8.8
09/10/87	2445	0.013311	14	0.001	123.5
08/20/87	2447	0.000236	1	0.000	8.8
09/10/87	2463	0.067297	71	0.001	626.8
08/20/87	2467	<0.000274	.	0.000	<8.8
09/09/87	2469	0.019167	18	0.001	158.9
09/11/87	2476	0.022826	22	0.001	194.2
08/20/87	2477	<0.000276	.	0.000	<8.8
09/11/87	2480	0.095536	90	0.001	794.5
09/11/87	2482	0.030372	34	0.001	300.1
09/11/87	2483	0.102366	98	0.001	865.1
09/11/87	2490	0.122074	115	0.001	15.2
09/09/87	2493	0.006585	6	0.001	52.9
09/09/87	2495	<0.000981	.	0.001	<8.8
09/10/87	2497	<0.001040	.	0.001	<8.8
09/13/87	2498	<0.000808	.	0.001	<8.8
09/09/87	2503	0.007641	7	0.001	61.7
09/09/87	2505	0.003236	3	0.001	26.4
09/08/87	2510	0.003390	3	0.001	26.4
09/03/87	2511	<0.001185	.	0.001	<8.8
09/03/87	2512	0.004430	4	0.001	35.3
09/08/87	2520	<0.001040	.	0.001	<8.8
09/03/87	2522	0.004353	4	0.001	35.3
09/02/87	2523	0.001034	1	0.001	8.8
09/04/87	2524	0.001199	1	0.001	8.8
09/01/87	2525	0.001652	2	0.001	17.6
09/01/87	2526	0.023813	30	0.001	264.8
09/01/87	2527	0.006386	7	0.001	61.7
09/01/87	2528	0.005753	7	0.001	61.7

(continued)

TABLE A-8 (continued)

PERIMETER

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
08/31/87	2529	0.003587	4	0.001	35.3
09/08/87	2530	0.004536	4	0.001	35.3
09/02/87	2533	<0.001157	.	0.001	<8.8
09/02/87	2534	0.002297	2	0.001	17.6
09/04/87	2536	0.003205	3	0.001	26.4
09/04/87	2537	0.000876	1	0.001	8.8
09/01/87	2538	0.006001	7	0.001	61.7
09/08/87	2540	0.001028	1	0.001	8.8
09/03/87	2542	0.016455	16	0.001	141.2
09/02/87	2544	0.004933	4	0.001	35.3
09/04/87	2545	0.000823	1	0.001	8.8
09/03/87	2546	0.006509	6	0.001	52.9
09/02/87	2547	0.002199	2	0.001	17.6
09/08/87	2550	0.001170	1	0.001	8.8
08/31/87	2554	0.000835	1	0.001	8.8
08/31/87	2555	0.002268	3	0.001	26.4
08/31/87	2556	<0.000994	.	0.001	<8.8
08/31/87	2557	<0.000743	.	0.001	<8.8

FIELD BLANK

DATE_SAM	SAMP	CONC	N	SENSTVTY	STRMM2
08/31/87	P1566	.	.	.	<8.8
09/02/87	P1588	.	.	.	<8.8
09/01/87	P1589	.	.	.	<8.8
08/20/87	P1596	.	.	.	<8.8
08/20/87	P1597	.	.	.	<8.8
09/04/87	P1663	.	.	.	<8.8
09/10/87	P1685	.	.	.	<8.8
09/11/87	P1717	.	.	.	<8.8
09/13/87	2455	.	.	.	<8.8
08/20/87	2459	.	.	.	<8.8
08/20/87	2473	.	.	.	<8.8
09/11/87	2488	.	.	.	<8.8
09/10/87	2496	.	2	.	17.6
09/02/87	2535	.	.	.	<8.8
09/01/87	2539	.	.	.	<8.8
09/04/87	2541	.	.	.	<8.8
08/31/87	2549	.	.	.	<8.8
09/03/87	2552	.	2	.	17.6

P1000 series are mixed cellulose ester filters; 2000 series are polycarbonate filters.

TABLE A-9. SITE 3 POSTABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY TEM

AMBIENT

DATE_SAM	SAMP*	CONC	#	SENSTVTY	STRMM2
09/14/87	P1713	<0.001019	-	0.001	<8.8
09/14/87	P1718	<0.001082	-	0.001	<8.8
09/14/87	P1722	<0.000957	-	0.001	<8.8
09/14/87	2613	<0.001019	-	0.001	<8.8
09/14/87	2636	<0.000957	-	0.001	<8.8
09/14/87	2637	<0.001082	-	0.001	<8.8

PERIMETER

DATE_SAM	SAMP	CONC	#	SENSTVTY	STRMM2
09/14/87	P1692	0.026889	22	0.001	194.2
09/14/87	2628	0.005567	5	0.001	44.1
09/14/87	2635	<0.001215	-	0.001	<8.8

ABATEMENT AREA

DATE_SAM	SAMP	CONC	#	SENSTVTY	STRMM2
09/14/87	P1701	<0.000982	-	0.001	<8.8
09/14/87	P1702	<0.001111	-	0.001	<8.8
09/14/87	P1708	0.001038	1	0.001	8.8
09/14/87	P1711	<0.000992	-	0.001	<8.8
09/14/87	P1719	0.001149	1	0.001	8.8
09/14/87	P1721	<0.001089	-	0.001	<8.8
09/14/87	P1724	0.001984	2	0.001	17.6
09/14/87	2602	<0.000982	-	0.001	<8.8
09/14/87	2603	0.001038	1	0.001	8.8
09/14/87	2611	0.000992	1	0.001	8.8
09/14/87	2612	0.003332	3	0.001	26.4
09/14/87	2619	0.001984	2	0.001	17.6
09/14/87	2621	0.003267	3	0.001	26.4
09/14/87	2627	0.005783	5	0.001	44.1

FIELD BLANK

DATE_SAM	SAMP	CONC	#	SENSTVTY	STRMM2
09/14/87	2604	-	5	-	44.1

* P1000 series are mixed cellulose ester filters; 2000 series are polycarbonate filters.

APPENDIX B

AIRBORNE ASBESTOS CONCENTRATIONS BEFORE, DURING, AND AFTER ABATEMENT FOR SAMPLES ANALYZED BY PHASE CONTRAST MICROSCOPY

TABLE B-1. SITE 1 PREABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
10/31/86	1013	0.001
11/01/86	1019	0.001
11/01/86	1025	<0.001
	PERIMETER	
10/31/86	1004	0.001
10/31/86	1005	0.002
10/31/86	1006	0.001
10/31/86	1010	<0.001
10/31/86	1011	<0.001
10/31/86	1012	<0.001
11/01/86	1016	<0.001
11/01/86	1017	<0.001
11/01/86	1018	<0.001
11/01/86	1023	<0.001
11/01/86	1022	<0.001
11/01/86	1024	<0.001
	ABATEMENT AREA	
10/31/86	1001	<0.001
10/31/86	1002	<0.001
10/31/86	1003	<0.001
10/31/86	1007	<0.001
10/31/86	1008	<0.001
10/31/86	1009	<0.001
11/01/86	1014	<0.001
11/01/86	1015	<0.001
11/01/86	1021	<0.001
11/01/86	1020	<0.001
	FIELD BLANK	
10/31/86	1026	1.5 f/100 fields
11/01/86	1027	0 f/100 fields
11/01/86	1028	1.0 f/100 fields

TABLE B-2. SITE 1 DURING ABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
11/18/86	1039	0.002
11/19/86	1041	0.001
18/20/86	1072	<0.001
11/21/86	1058	<0.001
	PERIMETER	
11/13/86	1029	0.003
11/13/86	1030	0.006
11/13/86	1031	0.002
11/13/86	1032	0.009
11/13/86	1033	0.002
11/13/86	1034	0.006
11/18/86	1035	0.003
11/18/86	1036	0.002
11/18/86	1037	0.001
11/18/86	1038	0.001
11/18/86	1042	0.002
11/19/86	1049	<0.001
11/19/86	1040	<0.001
11/19/86	1050	0.001
11/19/86	1051	0.002
11/19/86	1052	0.001
11/20/86	1066	0.003
11/20/86	1068	0.001
11/20/86	1070	0.002
11/20/86	1074	0.002
11/20/86	1076	<0.001
11/21/86	1056	0.003
11/21/86	1057	0.001
11/21/86	1055	0.002
11/21/86	1059	0.002
11/21/86	1060	0.003
11/24/86	1079	0.002
11/24/86	1062	0.001
11/24/86	1086	0.001
11/24/86	1054	0.004
11/24/86	1064	0.003
	FIELD BLANK	
11/19/86	1063	0 f/100 fields
11/20/86	1078	0 f/100 fields
11/21/86	1061	1.0 f/100 fields
11/24/86	1065	0.5 f/100 fields

TABLE B-3. SITE 1 POSTABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
12/03/86	1093	<0.001
12/03/86	1092	<0.001
12/03/86	1105	0.001
12/03/86	1238	<0.001
12/03/86	1244	<0.001
	PERIMETER	
12/03/86	1237	0.002
12/03/86	1241	0.002
12/03/86	1239	0.004
12/03/86	1243	0.002
12/03/86	1232	0.001
	ABATEMENT AREA	
12/03/86	1100	0.002
12/03/86	1240	0.002
12/03/86	1234	0.002
12/03/86	1094	0.001
12/03/86	1242	<0.001
	FIELD BLANK	
12/03/87	1084	1.5 f/100 fields

TABLE B-4. SITE 2 PREABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
1/21/87	1276	0.001
1/21/87	1290	0.001
1/21/87	1270	0.001
1/21/87	1291	0.002
1/21/87	1269	0.001
	PERIMETER	
1/21/87	1281	0.001
1/21/87	1274	0.002
1/21/87	1288	0.001
1/21/87	1287	0.001
1/21/87	1273	0.002
	ABATEMENT AREA	
1/21/87	1282	0.001
1/21/87	1272	0.001
1/21/87	1289	0.001
1/21/87	1259	0.002
1/21/87	1257	0.001
	FIELD BLANK	
1/21/87	1266	0 f/100 fields

TABLE B-5. SITE 2 DURING ABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
4/6/87	1435	0.001
4/6/87	1437	0.001
4/6/87	1430	0.001
4/6/87	1432	0.001
4/6/87	1431	0.001
	PERIMETER	
4/6/87	1443	0.001
4/6/87	1444	0.001
4/6/87	1445	0.001
4/6/87	1434	0.001
4/6/87	1453	0.001
4/6/87	1436	0.001
4/6/87	1433	0.001
4/6/87	1391	0.001
4/7/87	1442	0.001
4/7/87	1439	0.001
4/7/87	1448	0.001
4/7/87	1429	0.005
4/7/87	1440	0.004
4/7/87	1454	0.007
4/7/87	1451	0.001
4/7/87	1399	0.001
4/7/87	1471	0.001
4/7/87	1458	0.001
4/7/87	1464	0.001
4/8/87	1476	0.002
4/8/87	1474	0.003
4/8/87	1461	0.001
4/8/87	1438	0.001
4/8/87	1473	0.001
4/8/87	1452	0.001
4/8/87	1441	0.001
4/8/87	1450	0.001
4/9/87	1470	0.001
4/9/87	1477	0.001
4/9/87	1469	0.001
4/9/87	1475	0.001
		FIELD BLANKS
4/6/87	1447	0 f/100 fields
4/7/87	1463	0 f/100 fields
4/8/87	1446	0 f/100 fields

TABLE B-6. SITE 2 POSTABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	PERIMETER	
4/9/87	1462	0.002
4/9/87	1468	0.001
4/9/87	1466	0.003
4/9/87	1449	0.003
4/9/87	1455	0.008
4/9/87	1457	0.001
4/9/87	1390	0.001
	ABATEMENT AREA	
4/9/87	1501	0.002
4/9/87	1502	0.002
4/9/87	1504	0.001
4/9/87	1503	0.003
4/9/87	1459	0.004
	FIELD BLANK	
4/9/87	1456	0 f/100 fields

TABLE B-7. SITE 3 PREABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
7/14/87	P1504	0.001
7/14/87	P1505	0.004
7/14/87	P1494	0.001
	PERIMETER	
7/14/87	P1490	0.003
7/14/87	P1495	0.004
7/14/87	P1485	0.005
8	ABATEMENT AREA	
7/14/87	P1478	0.001
7/14/87	P1489	0.002
7/14/87	P1488	0.001
7/14/87	P1486	0.003
7/14/87	P1480	0.002
7/14/87	P1481	0.004
7/14/87	P1479	0.001
7/14/87	P1491	0.002
	FIELD BLANK	
7/14/87	P1500	1 f/100 fields
7/14/87	P1506	0 f/100 fields

TABLE B-8. SITE 3 DURING ABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	PERIMETER	
8/20/87	P1595	0.008
8/20/87	P1572	0.003
8/20/87	P1586	0.009
8/20/87	P1577	0.006
8/20/87	P1551	0.004
8/20/87	P1581	0.007
8/20/87	P1573	0.006
8/20/87	P1550	0.010
8/20/87	P1580	0.009
8/31/87	P1549	0.006
8/31/87	P1558	0.013
8/31/87	P1524	0.047
8/31/87	P1554	0.027
8/31/87	P1508	0.012
9/01/87	P1512	0.028
9/01/87	P1497	0.001
9/01/87	P1487	0.001
9/01/87	P1498	0.004
9/01/87	P1501	0.004
9/02/87	P1574	0.005
9/02/87	P1592	0.003
9/02/87	P1579	0.013
9/02/87	P1590	0.014
9/02/87	P1569	0.004
9/03/87	P2655	0.011
9/03/87	P1652	0.006
9/03/87	P1658	0.028
9/03/87	P1654	0.007
9/03/87	P1656	0.002
9/04/87	P1667	0.001
9/04/87	P1661	0.005
9/04/87	P1662	0.007
9/09/87	P1677	0.024
9/09/87	P1678	0.008
9/09/87	P1675	0.004
9/09/87	P1680	0.001
9/09/87	P1676	0.002
9/08/87	P1671	0.006
9/08/87	P1668	0.002
9/08/87	P1674	0.003
9/08/87	P1670	0.003
9/08/87	P1683	0.017
9/09/87	P1686	0.009
9/09/87	P1689	0.010
9/09/87	P1688	0.003
9/09/87	P1690	0.001
9/09/87	P1697	0.046

TABLE B-8 (continued)

DATE	SAMPLE NUMBER	CONCENTRATION
	PERIMETER	
9/10/87	P1693	0.052
9/10/87	P1694	0.015
9/10/87	P1687	0.003
9/10/87	P1682	0.001
9/10/87	P1681	0.001
9/10/87	P1707	0.001
9/10/87	P1704	0.006
9/10/87	P1698	0.001
9/11/87	P1715	0.061
9/11/87	P1709	0.026
9/11/87	P1699	0.026
9/11/87	P1706	0.002
9/11/87	P1696	0.001
9/13/87	P1679	0.002
	FIELD BLANK	
8/20/87	P1597	1.0 f/100 fields
8/20/87	P1596	0 f/100 fields
8/31/87	P1566	0.5 f/100 fields
9/01/87	P1589	1.5 f/100 fields
9/02/87	P1588	0.5 f/100 fields
9/03/87	P1560	1.5 f/100 fields
9/03/87	P1663	0.5 f/100 fields
9/09/87	P1672	2.5 f/100 fields
9/10/87	P1685	3.0 f/100 fields
9/11/87	P1717	1.0 f/100 fields
9/13/87	P1570	4.5 f/100 fields

TABLE B-9. SITE 3 POSTABATEMENT AIRBORNE ASBESTOS CONCENTRATIONS (f/cm^3) BY PCM

DATE	SAMPLE NUMBER	CONCENTRATION
	AMBIENT	
9/14/87	P1718	0.012
9/14/87	P1722	0.011
9/14/87	P1713	0.009
	PERIMETER	
9/14/87	P1723	0.006
9/14/87	P1692	0.015
9/14/87	P1714	0.014
9/14/87	P1695	0.001
9/14/87	P1720	0.001
	ABATEMENT AREA	
9/14/87	P1721	0.008
9/14/87	P1702	0.006
9/14/87	P1724	0.006
9/14/87	P1710	0.005
9/14/87	P1708	0.010
9/14/87	P1719	0.007
9/14/87	P1711	0.014
	FIELD BLANK	
9/14/87	P1705	0 f/100 fields

APPENDIX C

PAIRED SAMPLES COLLECTED ON 0.4 μm PORE SIZE POLYCARBONATE AND 0.8 μm PORE SIZE MIXED CELLULOSE ESTER MEMBRANE FILTERS

TABLE C-1. PAIRED SAMPLES COLLECTED ON 0.4 μm PORE SIZE POLYCARBONATE AND 0.8 μm PORE SIZE MIXED CELLULOSE ESTER MEMBRANE FILTERS

Polycarbonate *	Mixed cellulose ester*
2429	P1494
2465	P1504
2440	P1505
2442	P1485
2452	P1490
2441	P1495
2444	P1478
2443	P1479
2425	P1480
2428	P1481
2501	P1486
2451	P1488
2460	P1489
2456	P1491
2548	P1555
2553	P1571
2532	P1653
2521	P1660
2405	P1669
2613	P1713
2637	P1718
2636	P1722
2602	P1701
2612	P1702
2603	P1708
2611	P1711
2627	P1719
2621	P1721
2619	P1724
2525	P1487
2528	P1497
2538	P1498
2527	P1501
2554	P1508
2526	P1512
2555	P1524
2557	P1549

(continued)

TABLE C-1 (continued)

Polycarbonate *	Mixed cellulose ester*
2529	P1554
2556	P1558
2533	P1569
2537	P1570
2523	P1574
2547	P1579
2447	P1586
2534	P1590
2544	P1592
2477	P1595
2511	P1652
2512	P1655
2545	P1656
2542	P1658
2536	P1661
2524	P1662
2510	P1670
2520	P1671
2540	P1674
2505	P1675
2503	P1676
2469	P1677
2493	P1678
2497	P1681
2445	P1687
2463	P1693
2434	P1694
2476	P1696
2483	P1699
2482	P1706
2490	P1709
2480	P1715

* See Tables A-7, A-8, and A-9 for the corresponding sample concentrations.

END
DATE
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