United States
Environmental Protection
Agency

Risk Reduction Engineering
Laboratory
Cincinnati OH 45268

Research and Development

EPA/600/S2-90/053 Apr. 1991

EPA

Project Summary

Evaluation of Two Cleaning Methods for Removal of Asbestos Fibers from Carpet

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The effectiveness of dry-vacuuming and wet-cleaning for the removal of asbestos fibers from carpet was examined, and the potential for fiber reentrainment during carpet cleaning activities was evaluated. Routine carpet cleaning operations were simulated by using high-efficiency particulate air (HEPA) filtered dry vacuum cleaners and HEPA-filtered hot-water extraction cleaners on carpet artificially contaminated with asbestos fibers. Overall, wet-cleaning with a hot-water extraction cleaner reduced the level of asbestos contamination in the carpet by approximately 70%. There was no significant change in carpet asbestos concentration after dry-vacuuming. The level of asbestos contamination had no significant effect on the difference between the asbestos concentrations before and after cleaning. Airborne asbestos concentrations were two to four times greater during than before the carpet cleaning activities. Neither the level of asbestos contamination in the carpet nor the type of cleaning method used greatly affected the difference between the airborne asbestos concentration before and during cleaning.

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

Introduction

Buildings that contain friable asbestos-containing materials (ACMs) may present uncommon exposure problems for custodial workers. Under certain conditions, asbestos fibers can be released from fireproofing, acoustical plaster, and other surfacing material. The episodic release of asbestos from aging and deteriorating ACM relates to several factors, such as the condition and amount of asbestos present, the accessibility of the material, activity within the area, vibration, temperature, humidity, airflow, use patterns, etc. Of major concern is the extent to which carpet and furnishings may be serving as reservoirs of asbestos fibers and what happens to these fibers during normal custodial cleaning operations.

The Asbestos Hazard Emergency Response Act (AHERA) requires that all carpet in areas of school buildings in which ACMs are present be cleaned with either a HEPA-filtered vacuum cleaner or a hot-water extraction cleaner ("steam-cleaner"). Little quantitative information is available on how well these cleaners remove asbestos fibers from carpet or on the potential for reentrainment of airborne asbestos fibers during these carpet cleaning activities.

The report summarized here evaluates the concentration of asbestos fibers in the carpet before and after cleaning for each of the two cleaning methods and summarizes the air monitoring results obtained during cleaning. A separate EPA report entitled "Asbestos Fiber Reentrainment During Dry

Vacuuming and Wet Cleaning of Asbestos-Contaminated Carpet" contains a complete description of the air monitoring portion of the study.

Study Design

Test Facility

This study was conducted in an unoccupied building at Wright-Patterson Air Force Base in Dayton, Ohio. Two rooms, each containing approximately 500 ft^2 of floor space, were constructed in a large bay of the building.

The rooms were constructed of 2- x 4-in. lumber with studs spaced on 24-in. centers and 3/4-in. plywood floors. The ceiling, floor, and walls were double-covered with 6-mil polyethylene sheeting. (The interior layer of polyethylene sheeting was encapsulated and replaced after each experiment.) Where separate sheets of polyethylene were joined, the sheets were overlapped at least 12 in. and joined with an unbroken line of adhesive to prohibit air movement. Three-inch-wide tape was then used to seal the joint further on both the inside and outside of the plastic sheeting.

Entry from one room to another was through a triple-curtained doorway consisting of two overlapping sheets of 6-mil polyethylene placed over a framed doorway; each sheet was secured along the top of the doorway, and the vertical edge of one sheet was secured along one side of the doorway and the vertical edge of the other sheet, along the opposite side of the doorway.

Room size (approximately 29 x 17 x 7.5 ft) was based on the minimum amount of time required to vacuum or wet-clean the room and to attain an adequate volume of sample air to achieve a specified analytical sensitivity. A 52-in., ceiling-mounted, axial-flow, propeller fan was installed in each room to facilitate air movement and to minimize temperature stratification.

Separate decontamination facilities for workers and waste materials were connected to the experimental areas. The worker decontamination facility consisted of three totally enclosed chambers: an equipment-change room, a shower room, and a clean change room.

Air Filtration

HEPA filtration systems were used to reduce the airborne asbestos concentrations to background levels after each experiment. These units were operated during both preparation and decontamination of the test rooms. The air filtration units did not operate during the carpet cleaning phase of each experiment.

One HEPA filtration system was dedicated to each test room. Each unit provided approximately eight air changes every 15-min period. The negative pressure inside the test rooms ranged from -0.08 to -0.06 in. of water. All exhaust air passed through a HEPA filter and was discharged to the outdoors. All makeup air was obtained from outside the building through a window located on the opposite side of the building from the exhaust for the HEPA filtration systems.

Experimental Design

Experiments 1 Through 16

Two carpet cleaning methods, dry-vacuuming with a HEPA-filtered vacuum and wet-cleaning with a HEPA-filtered hot-water extraction cleaner, were evaluated on carpet artificially contaminated at two different levels—approximately 100 million and 1 billion asbestos structures per square foot (s/ft^2). Each combination of cleaning method and contamination level was replicated four times. Four different (same model) HEPA-filtered vacuums and four different (same model) HEPA-filtered hot-water extraction units were used so the results would not be influenced by the peculiarities of a single unit. Each machine was used only once per combination of cleaning method and contamination level. This experimental design yielded a total of 16 experiments.

Work-area air samples were collected to establish airborne asbestos concentrations before and during cleaning. For each experiment, three air samples were collected before and three during cleaning. In each test room, the air samplers were positioned in a triangular pattern. A total of 96 air samples were collected.

Bulk carpet and microvacuum samples were collected to establish the pre- and post-cleaning carpet contamination levels. During each experiment, six samples were collected before and six after cleaning. A total of 192 bulk carpet samples and 192 microvacuum samples were collected.

Two experiments were conducted each day of the study. Each combination of cleaning method and contamination level was tested twice in each test room. A single experiment consisted of contaminating a new piece of carpet (approximately 500 ft^2) with asbestos fibers, collecting work-area air samples, collecting microvacuum and bulk carpet samples, dry-vacuuming or wet-cleaning the carpet while collecting a second set of work-area air samples, collecting a second set of microvacuum and bulk carpet samples, removing the carpet, and decontaminating the test room. Each test room was decontaminated by encapsulating the carpet and the polyethylene sheeting on the ceiling and walls before their removal. These materials were removed and replaced after each experiment.

Experiments 17 Through 24

To evaluate the differences in the asbestos-retention characteristics of new carpet versus new carpet that has been wet-cleaned, eight additional experiments were conducted. These experiments were designed for comparison with Experiments 1 through 16.

Experimental procedures for this second set of experiments were identical to those in the first 16 except that the carpet was dry-vacuumed, wet-cleaned, and then dry-vacuumed again when dry. The same test area was also used; however, the two 500-ft^2 test rooms were converted to four 160-ft^2 test rooms, each with dimensions of approximately 8 x 20 ft.

Each of the two cleaning methods was tested at two carpet contamination levels (100 million and 1 billion s/ft^2). Each cleaning method was tested twice in two different rooms. The same four HEPA-filtered dry vacuums and hot-water extraction cleaners were used. Each machine was used only once per cleaning method and contamination level combination. This experimental design yielded a total of eight experiments.

Bulk carpet and microvacuum samples were again collected to establish the pre- and post-cleaning carpet contamination levels. During each experiment, four samples were collected before and four after carpet cleaning. During each experiment, a total of 32 bulk samples were collected. No work-area air samples were collected during these eight experiments.

A single experiment consisted of dry-vacuuming, wet-cleaning, and dry-vacuuming again a new piece of carpet in a previously cleaned room; contaminating the carpet with asbestos fibers; collecting microvacuum and bulk carpet samples; dry-vacuuming or wet-cleaning the carpet; collecting a second set of microvacuum and bulk carpet samples; removing the carpet; and decontaminating the test room. Decontamination methods were the same as for Experiments 1 through 16.

Preliminary Sampling and Analytical Performance Study

Preliminary experiments were conducted to document the performance of the microvacuum sampling and sonic extraction techniques for recovering the asbestos from the carpet. The mean asbestos recovery from carpet contaminated with 1 billion s/ft^2 was 23 million s/ft^2 with microvacuuming and 794 million s/ft^2 with sonic extraction. The coefficient of variation (CV) for the microvacuuming techniques was 166%, whereas the CV for the sonic

extraction technique was 43%. Because the sonic extraction method was clearly superior for determining carpet contamination levels, the microvacuum samples were not analyzed.

The preliminary experiments provided information regarding the variability associated with this analytical technique, which was not available when the sampling strategy was being developed. The original sample size calculations for this study assumed a CV of 100% with this method, whereas the calculated CV was 43%. This information permitted the number of samples needed to achieve statistical significance to be modified downward, which greatly reduced analytical costs and analytical turnaround time for this study.

Materials and Methods

A survey of 14 General Service Administration (GSA) field offices in 11 States distributed across the country provided information for the selection of the carpet and cleaning equipment to be used in this study. When the GSA offices lacked the needed information with regard to wet-cleaning equipment, six trade organizations were contacted for recommendations concerning a HEPA-filtered hot-water extraction cleaner.

Selection of Carpet

The carpet of choice was first-grade, 100% nylon, with 0.25-in. cut pile, 28 oz of yarn/ft^2, and dual vinyl backing.

Selection of Carpet Cleaning Equipment

HEPA-Filtered Vacuum

The HEPA-filtered vacuum of choice was a unit with an airflow capacity of 87 ft^3/min, a suction power of 200 watts, and 75 in. static waterlift. This unit was also equipped with a motor-driven carpet nozzle with a rotating brush

HEPA-Filtered Hot-Water Extraction Cleaner

The hot-water extraction unit of choice was equipped with a HEPA-filtered power head with a moisture-proof, continuous-duty, 2-horsepower vacuum motor that developed a 100-in. static waterlift. This unit was also equipped with an extractor tool that uses a motor-driven cylindrical nylon-bristle brush, 4 in. in diameter and 14 in. long, to agitate and scrub the carpet during the extraction process.

Sampling Methodology

Bulk Carpet Samples

A 4-in.^{2} template and a utility razor knife were used to collect carpet samples before and after cleaning. Each carpet sample was cut in half to provide a duplicate sample for archiving. Each piece was placed in a separate, labeled, wide-mouth, polyethylene jar with a polypropylene screw cap. The template and utility razor were thoroughly cleaned before each experiment to avoid cross-sample contamination.

Microvacuum Samples

Microvacuum samples were collected by vacuuming a 100-cm^2 area of carpet with a membrane filter air-sampling cassette and a vacuum pump. The sampling assembly consisted of a 25-mm-diameter, 0.45-µm-pore-size, mixed cellulose ester filter contained in a three-piece cassette connected to a sampling pump with flexible tubing. The pump and cassette assembly was calibrated to 10 L/min. The 100-cm^2 area was vacuumed by dragging the filter cassette across the carpet to agitate the carpet pile. The carpet was vacuumed for 30 sec in one direction and another 30 sec in a direction 90 degrees to the first. After 1 min of vacuuming, the pump was turned off and the filter cassette was labeled and sealed.

Air Samples

Air samples were collected on open-face, 25-mm-diameter, 0.45-µm pore-size, mixed cellulose ester membrane filters with a 5-µm pore size, mixed cellulose ester backup diffusing filter and cellulose ester support pad contained in a three-piece cassette. The filter cassettes were positioned approximately 5 ft above the floor with the filter face at approximately a 45-degree angle toward the floor. The filter assembly was attached to an electric-powered vacuum pump operating at a flow rate of approximately 10 L/min. Air samples were collected for 65 min before and during carpet cleaning to achieve a minimum air volume of approximately 650 L.

Analytical Methodology

Bulk Carpet Samples

A sonication procedure developed by McCrone Environmental Services, Inc., was used to extract asbestos particles from the bulk carpet samples for subsequent analysis by transmission electron microscopy (TEM). Asbestos structures were identified and counted as specified in EPA provisional method, Level II.

Microvacuum Samples

The mixed cellulose ester filters used to collect the microvacuum carpet samples were analyzed by TEM. These samples were prepared according to the analytical laboratory's Standard Operating Procedure for dust sample collection. Asbestos structures were identified and counted as specified in the EPA provisional method, Level II.

Air Samples

The mixed cellulose ester filters were analyzed by TEM. These filters were prepared and analyzed in accordance with the nonmandatory TEM method as described in the Asbestos Hazard Emergency Response Act (AHERA) final rule (52 CFR 41821).

Statistical Analysis

Carpet Samples

For each experiment, a single estimated concentration was obtained before and after cleaning by taking the arithmetic mean of the individual estimates. This gave 24 pairs of concentrations, one for each experiment. The natural logarithm of each of the 48 concentrations was used for subsequent statistical analyses. This is equivalent to assuming that the data follow a lognormal distribution.

The geometric mean and a 95% confidence interval were calculated for each contamination level and cleaning method. A three-way analysis of variance (ANOVA) with contamination level (low, high), cleaning method (wet, dry), and experimental set (1 to 16, 17 to 24) as the three experimental factors was performed on the difference (on the log scale) between the concentration before cleaning and the concentration after cleaning. (The difference on the log scale is equivalent to the ratio on the original scale.) A 95% confidence interval for the difference in concentration before and after cleaning was calculated using the error mean square of the ANOVA. Results were transformed back to the original scale for reporting purposes.

Air Samples

Airborne asbestos concentrations were determined before and during carpet cleaning to study the effect of the cleaning method and contamination loading on fiber reentrainment during carpet cleaning. Three work-area samples were collected before and during carpet cleaning for each experiment. A single estimate of the airborne asbestos concentrations before and during cleaning was then determined by averaging the three respective work-area samples. The natural logarithm of each of the concentrations was used for subsequent statis-

tical analyses. This is equivalent to assuming that the data follow a lognormal distribution. A two-factor ANOVA with cleaning method (wet, dry) and contamination level (low, high) as the experimental factors was performed on the difference (on the log scale) between the concentration before cleaning and the concentration during cleaning.

Carpet Contamination

Selected levels of carpet contamination for this study were based on field data collected from buildings in which ACMs were present. Asbestos concentrations in contaminated carpet ranging from approximately 8,000 s/ft² to 2 billion s/ft² were detected by use of a microvac technique. Bulk sample sonication of the samples revealed levels ranging from 30 million to 4 billion s/ft². Based on these preliminary results, the target experimental asbestos contamination levels of approximately 100 million and 1 billion s/ft² were believed to represent likely carpet contamination in buildings where ACMs are present.

Sealed ampules of fiber dispersions were prepared so that the contents of one ampule dispersed in 6 L of freshly distilled water would provide the concentration of suspension required for artificial contamination of one 500-ft² sample of carpet. Calculations of the amount of chrysotile required were based on the assumption that all of the fibers needed to contaminate one carpet sample could be contained in a volume of 50 mL sealed in one ampule.

Application of Dispersion to Carpet

A meticulously cleaned hand-pumped garden sprayer was used to apply the asbestos dispersion to the carpet. The desired controlled spray was experimentally determined by trial and error before the tests with asbestos began. The pressure was kept within the desired range by adding a fixed number of pump strokes after each fixed area was sprayed in a predetermined pattern by following a grid work of string placed over the carpet before the beginning of each experiment. The tank was periodically agitated to help keep the asbestos fibers suspended. Dehumidifiers were placed in the room overnight to aid in drying the carpet. The following day a 200-lb steel lawn roller was rolled over the carpet surface to simulate the effects of normal foot traffic in working the asbestos into the carpet.

Carpet Cleaning Technique

The carpet was vacuumed or wet-cleaned for a period of approximately 65 min to allow the collection of a sufficient volume of air samples to obtain an analytical sensitivity of 0.005 s/cm³ of air. The carpet was cleaned in two directions, the second at a 90-degree angle to the first.

Table 1. For each experiment, a single estimated concentration before and after cleaning was obtained by taking the arithmetic mean of the three individual estimates. This gave

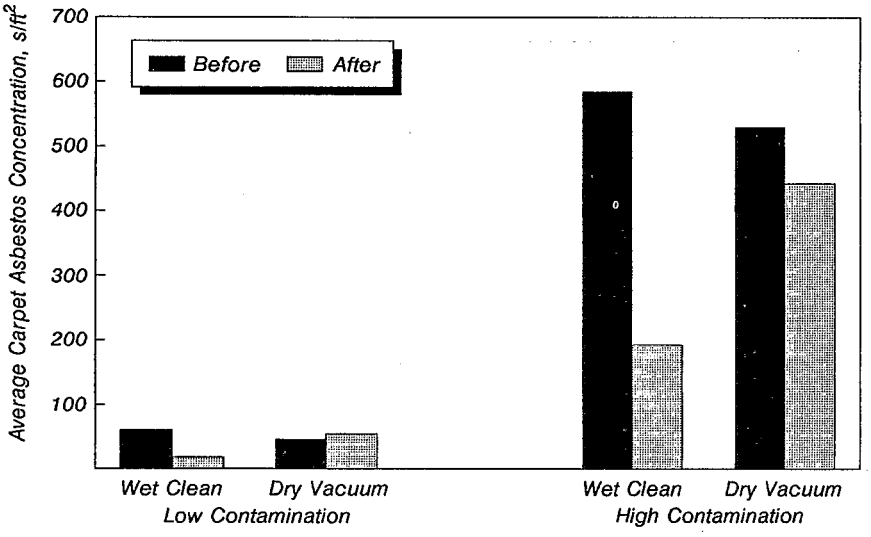

Figure 1. *Average asbestos carpet contamination before and after cleaning.*

Table 1. *Summary Statistics for Asbestos Concentrations in Carpet Before and After Cleaning*

Approximate Contamination Level, s/ft²	*HEPA-Filtered Cleaner*	*Number of Data Points**	*Geometric Mean, million s/ft²*	*95% Confidence Interval*
100 Million:				
Before cleaning	*Hot-water extraction*	*6*	*62*	*(39, 101)*
	Dry-vacuum	*6*	*47*	*(37, 59)*
After cleaning	*Hot -water extraction*	*6*	*18*	*(8, 43)*
	Dry-vacuum	*6*	*56*	*(38, 83)*
1 Billion:				
Before cleaning	*Hot-water extraction*	*6*	*589*	*(397, 873)*
	Dry-vacuum	*6*	*535*	*(356, 803)*
After cleaning	*Hot-water extraction*	*6*	*196*	*(85, 449)*
	Dry-vacuum	*6*	*447*	*(240, 832)*

**Each data point represents the average of three carpet samples.*

Results and Discussion

Carpet Samples

Figure 1 illustrates the average (geometric mean) concentrations of asbestos structures in the carpet before and after cleaning. The 95% confidence intervals for the geometric mean concentrations are given in Table 1. For each experiment, a single estimated concentration before and after cleaning was obtained by taking the arithmetic mean of the three individual estimates. This gave 24 pairs of concentrations, one for each experiment.

Results of a three-factor ANOVA indicated no significant difference between the results from Experiments 1 through 16 and Experiments 17 through 24 (p=0.7). The difference between the two sets of experiments was that the carpet in Experiments 17 through 24

Table 2. Estimated Asbestos Concentration in Carpet After Cleaning as a Proportion of the Concentration Before Cleaning

Approximate Contamination Level, s/ft²	HEPA-Filtered Cleaner	Concentration After Cleaning as a Proportion of Concentration Before Cleaning	95% Confidence Interval
100 Million	Hot-water extraction	0.29	(0.16, 0.51)
	Dry-vacuum	1.19	(0.68, 2.11)
1 Billion	Hot-water extraction	0.33	(0.19, 0.59)
	Dry-vacuum	0.84	(0.47, 1.48)

was first dry-vacuumed, then wet-cleaned, and then dry-vacuumed again before contamination. The data from all 24 experiments were treated equally and reanalyzed by using a two-factor ANOVA.

The type of cleaning method had a significant effect ($p<0.001$) on the difference between the asbestos concentrations before and after cleaning. The level of asbestos contamination in the carpet, however, had no significant effect ($p=0.622$). The estimated asbestos concentration in the carpet after cleaning, expressed as a proportion of the asbestos concentration before cleaning, is given in Table 2, together with a 95% confidence interval.

The asbestos concentration in the carpet after wet-cleaning was approximately 0.3 of the asbestos concentration before cleaning in both the high and low contamination levels. The upper 95% confidence limit (Table 2) at each contamination level is less than 1, which indicates that this reduction is statistically significant.

The asbestos concentration in the carpet after dry-vacuuming was 1.2 and 0.8 times the asbestos concentration before cleaning in the low- and high-contamination levels, respectively. The 95% confidence intervals for both estimates include 1, which indicates that the data do not provide statistically significant evidence of either an increase or a decrease in asbestos concentration after dry-vacuuming.

The TEM analysis of the 144 carpet samples before and after cleaning yielded a total of 8,101 asbestos structures. Of these, 8,080 (99.7%) were chrysotile and 21 (0.3%) were amphibole. The structure morphology distribution for the particles in the carpet samples is summarized in Table 3.

For carpet contaminated with 100 million s/ft², larger residual particles were consistently observed in the carpet after dry-vacuuming than after wet-cleaning. Fiber lengths of the residual asbestos in the carpet after dry-vacuuming and wet-cleaning carpet contaminated with 1 billion s/ft² were comparable. The reason for the difference in results between the two contamination levels is unknown.

Air Samples

Airborne asbestos concentrations were determined before and during carpet cleaning in Experiments 1 through 16 to study the effect of the cleaning method and contamination loading on fiber reentrainment during carpet cleaning. For each experiment, three work-area samples were collected before and during the carpet cleaning. Figure 2 shows the average airborne asbestos concentrations measured before and during cleaning for each cleaning method and carpet contamination loading. The samples collected before cleaning were obtained after the carpet was contaminated to determine the baseline concentration in the test room.

The type of cleaning method had no significant effect ($p=0.58$) on the difference between the airborne asbestos concentrations before and during cleaning. Similarly, the level of asbestos contamination in the carpet had no significant effect on fiber reentrainment ($p=0.09$). Overall, however, the mean airborne asbestos concentration was significantly higher during carpet cleaning than just before cleaning ($p<0.001$). A 95% confidence interval for the mean airborne asbestos concentration during carpet cleaning as a proportion of the airborne concentration before cleaning showed that the mean airborne asbestos concentration was between two and four times greater during carpet cleaning.

Asbestos fibers in the air during carpet cleaning activities tended to be smaller in length than the asbestos fibers remaining in the carpet after cleaning. Overall, approximately 17% of the asbestos fibers found in the carpet were less than 1.0 μm in length, whereas approximately 85% of the fibers observed in the air were greater than 1.0 μm.

Conclusions

Wet-cleaning significantly reduced the asbestos concentration in the carpet by approximately 70%. There was no significant change in asbestos concentration after dry-vacuuming.

Both dry-vacuuming and wet-cleaning of carpet resulted in a statistically significant increase in airborne asbestos concentration. Airborne asbestos concentrations were increased two to four times during carpet cleaning. The level of asbestos contamination in the carpet and the type of cleaning method used had no significant effect on the difference between the airborne asbestos concentration before and during cleaning. Although these data showed significant increases in airborne asbestos concentrations during cleaning activities in a controlled study under simulated conditions, it is not known if such increases will occur in real-world custodial operations. Obviously, the possibility raises a cause for concern.

Microvacuuming of carpet tended to recover significantly less asbestos than the bulk-carpet sonic extraction technique. The mean asbestos recovery from carpet contaminated with 1 billion s/ft² was 23 million s/ft² with microvacuuming and 794 million s/ft² with sonic extraction. The CV for the microvacuuming technique (166%) was four times larger than the CV for the sonic ex-

Table 3. Structure Morphology Distribution in Carpet Samples Collected Before and After Carpet Cleaning

Structure Type	Number of Bundles	Number of Clusters	Number of Fibers	Number of Matrices	Total
Chrysotile	1,763	66	5,893	358	8,080
Amphibole	2	0	18	1	21
Total	1,765	66	5,911	359	8,101

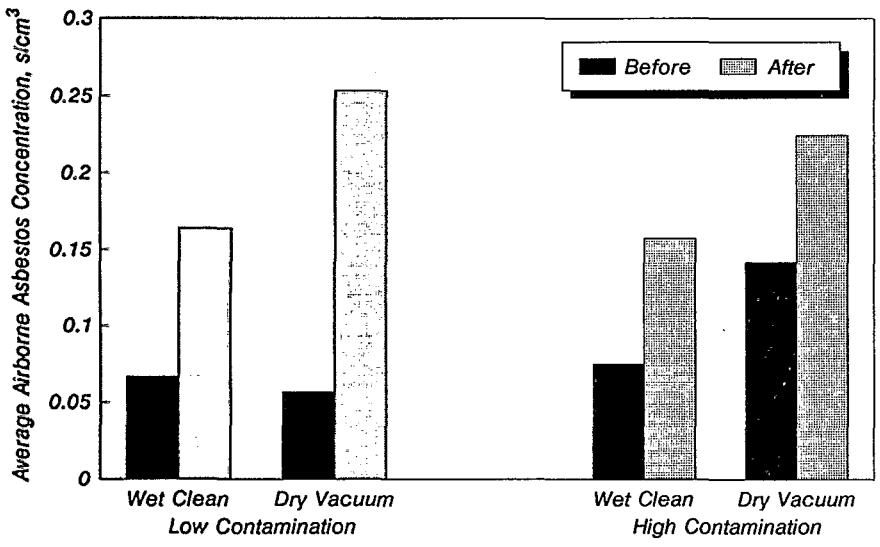

Figure 2. Average airborne asbestos concentrations before and during carpet cleaning.

traction technique (43%), which indicates that the former technique is less precise.

Recommendations

The removal effectiveness demonstrated by these two methods is limited to the specific equipment and work practices used during this study. Further research should be conducted to examine the performance of different HEPA-filtered dry and wet carpet cleaners (i.e., performance as a function of horsepower, static water lift, and operating air volume and velocity). Further study also should be conducted to examine other cleaning methodologies, such as repeated carpet cleaning.

This research suggests that normal custodial cleaning of asbestos-contaminated carpet may result in elevated airborne asbestos concentrations. Further research is needed to determine actual exposure risk to custodial workers performing these activities in buildings containing friable asbestos-containing materials.

The full report was submitted in fulfillment of Contract No. 68-03-4006, Work Assignment No. 2-10, by PEI Associates, Inc., under the sponsorship of the U.S. Environmental Protection Agency.

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***William C. Cain** and **Thomas J. Powers** are the EPA Project Officers (see below).*
The complete report, entitled "Evaluation of Two Cleaning Methods for Removal of Asbestos Fibers from Carpet," (Order No. PB 91-125 740/AS; Cost: $17.00, subject to change) will be available only from:
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