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Exposure to Airborne Asbestos in Buildings

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The concentration of airborne asbestos in buildings and its implication for the health of building occupants is a major public health issue. A total of 2892 air samples from 315 public, commercial, residential, school, and university buildings has been analyzed by transmission electron microscopy. The buildings that were surveyed were the subject of litigation related to suits alleging the general building occupants were exposed to a potential health hazard as a result of exposure to the presence of asbestos containing materials (ACM). The average concentration of all asbestos structures was 0.02 structures/ml (s/ml) and the average concentration of asbestos ≥ 5 μm long was 0.00013 fibers/ml (f/ml). The concentration of asbestos was higher in schools than in other buildings. In 48% of indoor samples and 75% of outdoor samples, no asbestos fibers were detected. The observed airborne concentration in 74% of the indoor samples and 96% of the outdoor samples is below the Asbestos Hazard Emergency Response Act clearance level of 0.01 s/ml. Finally, using those fibers which could be seen optically, all indoor samples and all outdoor samples are below the Occupational Safety and Health Administration permissible exposure level of 0.1 f/ml for fibers ≥ 5 μm in length. These results provide substantive verification of the findings of the U.S. Environmental Protection Agency public building study which found very low ambient concentrations of asbestos fibers in buildings with ACM, irrespective of the condition of the material in the buildings.

1.0. INTRODUCTION

Asbestos is a fibrous material long recognized as having extraordinary flexibility, strength, and durability. Asbestos fibers were identified before 1940 as being associated with occupational disease. The exposure of workers in the textile, insulation, mining, friction products, and cement industries has been intensely studied during the last two decades (Nicholson, 1986; Crump, 1986). These studies have established that the working lifetime exposure to asbestos fibers longer than 5 μm posed a significant health risk to workers in these industries at the historically elevated exposure concentrations. While the actual exposures required, the duration, and the effect of fibers shorter than 5 μm in length have been the subject of intense debate (Crump, 1986; HEI-AR, 1991), it has become widely accepted that long fibers are significantly more hazardous than short fibers (Stanton *et al.*, 1981) and that the amphibole asbestos

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forms (crocidolite and amosite) are of greater significance in producing mesothelioma than chrysotile (Mossman *et al.*, 1990). In contrast, chrysotile accounted for the vast majority of asbestos used in the United States and short chrysotile fibers predominate in building materials.

The possible risk to human health resulting from the presence of asbestos containing materials (ACM) in buildings has prompted widespread public and governmental concern. Coupled with the U.S. Environmental Protection Agency's Asbestos Hazard Emergency Response Act (AHERA) regulation and ban on the manufacturing of ACM, this has spawned a large industry involved in removing asbestos from buildings. Many lawsuits have been filed seeking recovery of the associated costs of removal of ACM. These suits claim that occupants of the buildings are potentially exposed to hazardous airborne levels of asbestos resulting from spontaneous emission of asbestos fibers from the in-place building product or disturbance of the product during routine housekeeping, maintenance, or renovation. They further claim that a responsible party such as the manufacturer of the product, the builder, and/or the architect should compensate the owner for recommending, selling, or installing a defective or unsafe product.

A number of defendants and building owners have sponsored testing of the air in buildings as a means of establishing the airborne concentrations of asbestos in buildings under conditions of normal occupancy. Comparisons of these data to historical exposures of workers in the asbestos products industry can be used to estimate the level of risk to the occupant (Hughes *et al.*, 1987; Mossman *et al.*, 1990). The present study reports the results of this air testing in 315 buildings and compares the results with other similar studies.

Studies of airborne asbestos levels in occupational situations in which a relatively high level of airborne asbestos was likely to be present have typically employed phase contrast microscopy (PCM) rather than transmission electron microscopy (TEM). However, PCM is now considered generally unsuitable for quantifying ambient airborne asbestos levels, for two reasons. First, PCM has resolving power sufficient only to identify structures thicker than about 0.25 μm, whereas asbestos fibers may have a thickness of <0.1 μm. (As will be shown later, over 97% of the asbestos fibers identified in the present study were thinner than 0.2 μm.) Consequently, PCM will miss very thin fibers. Second, as used, PCM cannot distinguish between asbestos and nonasbestos fibers. This is less of a problem in occupational settings involving use of considerable amounts of asbestos, since in such settings the airborne fibers are likely to be asbestos (Dement *et al.*, 1990). However, in ambient settings involving the presence of ACM, the majority of fibers identified by PCM are generally nonasbestos (HEI-AR, 1991; Keyes *et al.*, 1985; USEPA, 1990).

Two types of analytical methods based on TEM have been employed. Direct methods analyze structures in their original deposited position. Indirect methods involve ashing of filters and resuspension of the deposited material in water. This process has been found to alter the original concentration and size distribution of airborne fibers (Chesson *et al.*, 1990b). Only data derived from direct methods of analysis will be reported or reviewed in this paper.

Until recently there was a paucity of data on environmental concentrations of asbestos, both indoors and outdoors. Most of the data used in arriving at policy decisions regarding ACM in buildings were collected using indirect procedures. Even so, it was apparent from these data that levels in buildings of asbestos fibers longer than 5 μm were far below the levels of past occupational exposures associated with asbestos-related disease.

2.0. SOURCES OF DATA

The air samples described in this report were collected by consultants for defendants in preparation for litigation from buildings in which asbestos removal was alleged to be necessary because of the risk to occupant health. Buildings were not sampled if removal activities had already been carried out or if defendents were denied access to the buildings. Also, some buildings were not sampled because of time or cost constraints. Typically a number of samples were collected outdoors and from indoor areas representing different activity levels, and from these, five indoor or personal, two outdoor, and one blank sample were analyzed from each building. The samples, from 315 different buildings nationwide, were collected over a 5-year period and represent all of those analyzed by RJ Lee Group for defendents in building litigation. A portion of this work involving 71 school buildings has previously been reported (Corn *et al.*, 1991).

2.1. Building Survey

Building survey and air sampling, both inside and outside the buildings, were conducted by a team composed of a certified industrial hygienist, who acted as team leader, and three or more assistants. Buildings selected for surveying were the subject of litigation and were referred to the survey team by attorneys for defendants when the attorneys received notice of imminent asbestos abatement or some other reason why sampling should be scheduled. The actual sampling sites within the recommended buildings were selected by the survey teams on-site on the basis of location, use, and other factors described below. All buildings were classified as schools (both public and private elementary and secondary buildings), universities (postsecondary educational buildings), commercial buildings (buildings generally limited to businesses or for-profit activities), or public buildings (hospitals, libraries, governmental offices, etc.).

When a survey team was not able to sample every building at a given location in the time allowed, the buildings were ranked on the amount of ACM alleged to be present, the owner's allegations of which buildings were in greatest need of abatement, and similar factors. The buildings were then surveyed in order of highest rank as time permitted.

The general construction materials visible inside the building were noted, with particular attention paid to the presence, type, and condition of materials alleged to contain asbestos. Potential asbestos containing materials were identified and bulk samples of this material were collected. The condition of both the ACM and the building in general was determined. Sources of dust or other air contaminants were identified.

The grounds and community surrounding the building were also surveyed. Observations were made regarding geographical terrain and ground surface materials, particularly the presence of clay or asphalt. Also noted were parking lots, chimney stacks, and high activity areas (e.g., sports or play, bus loading or unloading points, and construction activity).

2.2. *Air Sampling*

Air sampling was conducted to determine the airborne fiber concentrations in occupied buildings. Sampling was conducted both in areas where ACM was present and in areas where ACM was absent. The survey teams noted whether the occupancy levels were high, medium, or low. These ratings were judgmental in nature and depended upon actual usage at the time of the survey. Sampling was also conducted outside the buildings to allow comparison between outdoor and indoor fiber levels.

In school buildings, high activity levels generally included gymnasiums, cafeterias, and auditoriums. Moderate activity areas included classrooms and staff quarters, while low activity areas included libraries and study areas. For public and commercial buildings, high activity areas included restaurants, auditoriums, copy centers, and meeting rooms. Low activity areas included libraries, study areas, and individual office space. Additionally, factors such as concentration of people, time duration of occupancy, and exertion levels were considered. Air sample locations were selected based on these factors and on availability of the location. All personal samples collected in this program were collected by the survey team members who wore personal air samplers during the time they were observing the static air sampling pumps. In non-school buildings, the samples were grouped into those from common areas, such as hallways, lobbies, or from offices.

Air sampling equipment adhered to the requirements of National Institute of Occupational Safety and Health (NIOSH) Method 7400 (NIOSH, 1989) and the Asbestos Hazard Emergency Response Act (AHERA) (USEPA, 1987). Normally pumps were operated at a flow rate of 2 to 3 liters per minute. Each sample volume was kept within the range of 600 to 2500 liters, with a recognized optimum of about 2000 liters. Sampling was conducted over a 2-day period and during normal building use to obtain representative conditions. The samples were collected on two types of filters, cellulose ester membrane (both 0.8 and 0.45 μm pore size, 25 mm diameter) and polycarbonate filters (0.4 μm pore size, backed with a 5.0 μm cellulose ester filter). Both types of filters were mounted in a new cassette with a 2-in. conductive extension.

2.3. *Sample Analytical Procedures*

The measurement of asbestos concentration from samples by TEM consists of sample preparation, asbestos fiber identification, reporting, and quality assurance. Techniques for each of these phases have been developed by a number of groups over a period of years. The methods used closely parallel those of Lee *et al.* (1977), Yamate *et al.* (1984), and the AHERA (USEPA, 1987).

2.4. *Sample Preparation*

All sample information was initially verified against a chain of custody documents upon receipt at the laboratory. The outside of the cassettes were cleaned with a wet wipe to remove any contamination. All sample preparation procedures were conducted in a clean area that was under positive air flow from a high efficiency particulate arrestance filtered air stream. The direct transfer method of preparation was used because it maintains the collected particulate in essentially the same condition as when deposited on the filter. Sample preparation was performed using standard operating procedures (Lee *et al.*, 1977; USEPA, 1987; Yamate *et al.*, 1984). Any time the preparation area was in use there was a laboratory blank exposed to monitor for possible contamination. This laboratory blank was processed as a control sample check.

The cassettes were carefully opened after first removing the plugs. A portion of the filter was cut, attached to a clean glass slide, and transferred to a covered petri dish containing a few milliliters of acetone absorbed in filter paper. The remainder of the filter was archived. The sample strip was next transferred to a carbon evaporator unit which had a rotating table. A carbon film of about 40 nm was evaporated onto the rotating sample strips. Because the filter material itself is too dense for an electron beam to penetrate during analysis, the filter material was carefully dissolved away by a slow washing with solvent vapor. The carbon-coated piece of filter was then transferred onto a 200-mesh electron microscope grid in a closed chamber with the solvent. The filter was dissolved by a wicking action, leaving the particulate entrapped in the carbon film. Multiple grid preparations were made for each sample and then dried and stored in a secure place until analysis.

2.5. *Sample Analysis*

The samples that were analyzed from the collected sets were chosen by either the laboratory or an industrial hygienist. Typically one outdoor sample and five indoor samples were chosen from each building. Samples that were selected were randomly chosen based on sample location (at least one indoor sample from different locations in a building) and volume sampled (at least 1000 liters or about 500 min of sample time).

Prepared samples were analyzed using a transmission electron microscope. Energy dispersive X-ray analysis was performed using a detector mounted to the TEM column. The equipment was aligned, calibrated, and maintained in accordance with appropriate quality assurance standards.

The initial step of sample analysis was to evaluate the quality of the preparation by examining the grid at low magnification (less than 600×) to assure that at least 50% of the available grid openings were covered with the sample containing film. Additionally, grids were evaluated to determine if the carbon film was intact and transparent to allow proper imaging of the particulates. The sample was also evaluated for the evenness and extent of the particle distribution. Grids from samples with more than 25% of the area covered by particulates were not used since close particle spacing may lead to interference from the nearby materials.

Following the qualification of the grids, random grid openings (usually 10) were selected equally from two grids and systematically scanned at 15,000 to 20,000× with overlapping traverses of the open area. Structures with an aspect ratio of greater than 3 to 1 length to width were identified morphologically. Bundles, clusters, and matrices were classified according to the USEPA Level II (Yamate *et al.*, 1984) protocol.

The number, length, width, aspect ratio, and type of all particles having a length: width ratio $\geq$3:1 were recorded. Particles meeting this criterion were classified as chrysotile, amphibole, or nonasbestos following the definitions developed by Yamate (Yamate *et al.*, 1984). A combination of morphology, energy dispersive X-ray analysis and selected area electron diffraction (SAED) was used in making identifications.

Approximately one of every five SAED patterns of chrysotile were recorded on each sample to validate the identification by the analyst. The diffraction pattern from each particle classified by the analyst as amphibole was recorded and verified. All amphiboles were reported as asbestos, even though, in general, the amphiboles observed were not asbestiform. Structures having a morphology, X-ray spectrum, or SAED pattern inconsistent with either chrysotile or amphibole were classified as nonasbestos. Typically the nonasbestos structures observed included gypsum, clays, iron oxides, and calcite.

All data were recorded in a database. The stored information included mineral type, length, width, aspect ratio, structure type, and the file numbers of X-ray spectra and SAED patterns.

2.6. *Statistical Analysis*

For each individual sample, the total structures per unit air volume (s/ml) was calculated, along with the concentration for fibers $\geqslant 5\ \mu m$ (f/ml) and the concentration for structures $\geqslant 5\ \mu m$ with a width of at least $0.25\ \mu m$. The last category is referred to as "optically equivalent" structures and represent the fraction of structures that would be identified by phase contrast microscopy. In addition to structure concentration, mass concentration (ng/m^3) was also determined based on the number and size of identified structures. For data evaluation purposes, all samples with no asbestos structures counted were treated as 0 s/ml and not as a "less than" detection limit.

For each building, air concentrations calculated from indoor stationary samples are averaged. Summary averages and percentiles of these building averages are presented. These summary values are presented by building type (commercial, public, residential, school, and university). Averages and percentiles of outdoor samples and personal samples are based on individual samples rather than building averages.

A one-tailed Mantel–Haenszel test (Mantel, 1963) is used to test for concentrations higher indoors than outdoors in various types of buildings. These analyses employ buildings as a blocking factor, so that direct comparisons are made only between indoor and outdoor samples from the same building. The significance level of the tests are computed by randomly reassigning samples to indoors or outdoors within blocks (buildings) and recalculating the test statistic for each random reassignment. The significance level reported is the percentage of times in which the test statistic based on a random reassignment of samples to indoors and outdoors equalled or exceeded the test statistic derived from the actual data. Ten thousand random reassignments were used for each of the test results reported. The Kruskal–Wallis test (Feldman *et al.*, 1987), applied to building averages, is used to test for differences among indoor concentrations among different building types. These tests have been used previously with asbestos sampling data (Chesson *et al.*, 1990a; Crump *et al.*, 1989). Standard statistical approaches based on normality assumptions are apt to give poor approximations to significance levels because asbestos sample data are generally highly skewed.

3.0. RESULTS OF THIS STUDY

A total of 2892 samples from 315 buildings are included in this study. These include 921 samples from 177 schools, 426 samples from 78 university buildings, 213 samples from 28 commercial buildings, 123 samples from 32 public buildings, and 10 samples from 1 residential building. There are a total of 1693 indoor samples (exclusive of personal samples), 759 outdoor samples, 106 personal samples, and 334 blanks. The samples from the schools include data reported earlier (Corn *et al.*, 1991) from 71 schools, while the university samples include data reported in a brief correspondence (Crump, 1990).

The average analytical sensitivity is 0.00341 ± 0.00008 s/ml for 1693 indoor samples. This value varied based upon the amount of air sampled and the number of grid openings counted. A total of 1,429,099 liters of air was sampled for outdoor samples, 3,070,438 liters were collected for indoor samples, and 188,605 liters were collected for personal samples.

The average concentration of asbestos structures for all indoor samples was 0.02485 s/ml (Table 1); for asbestos ⩾5 μm, the concentration averaged 0.00013 f/ml. The corresponding averages for outdoor samples were 0.00188 s/ml and 0.00005 f/ml, respectively, and those for personal samples were 0.00866 s/ml and 0.00012 f/ml, respectively. AHERA concentration of fibers averaged 0.01193 s/ml for indoor samples, 0.00134 s/ml for outdoor samples, and 0.00465 s/ml for personal samples. Table 1 lists the results for the several categories of buildings and sample types.

Table 2 shows the average concentration of optically equivalent fibers to be 0.00008 f/ml for indoor samples, 0.00002 f/ml for outdoor samples, and 0.00009 f/ml for personal samples. The weighted ratio (by number of buildings) for indoor samples of the average s/ml to the average ng/m^3 is 115 ng/m^3/s/ml.

There are significant differences in the concentration of total asbestos structures among building types ($P = 0.0001$) for all structures, but not for fibers ⩾5 μm ($P = 0.261$). Additionally, there is no difference in the concentration of fibers ⩾5 μm between indoor and outdoor samples for commercial ($P = 0.63$), public ($P = 0.62$), or university ($P = 0.35$) buildings, but a higher level indoors was found for school buildings ($P = 0.003$). All buildings types show a higher concentration indoors than outdoors when considering all structures: public, $P \leqslant 0.0001$; university, $P = 0.0002$; commercial, $P = 0.044$; and school, $P \leqslant 0.0001$.

Table 3 summarizes the 90th percentile information by building type. In the school building data, 90% of the samples contained asbestos contamination levels less than

TABLE 1

SUMMARY OF BUILDINGS SAMPLED AND MEAN ASBESTOS-IN-AIR CONCENTRATION FOR ALL ASBESTOS STRUCTURES, AHERA STRUCTURES, AND ASBESTOS FIBERS ⩾ 5 μm

			Structures/ml		Fibers (⩾5 μm)/ml		AHERA[a] (s/ml)	
Building type	No. buildings	No. samples	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
School[b]	177	921	0.04015	0.12758	0.00018	0.00039	0.01894	0.05492
University[b]	78	426	0.00865	0.01938	0.00008	0.00031	0.00467	0.00953
Commercial[b]	28	213	0.00162	0.00202	0.00003	0.00011	0.00125	0.00170
Public[b]	32	123	0.00538	0.00631	0.00016	0.00056	0.00288	0.00325
Outdoor[c]		759	0.00188	0.00854	0.00005	0.00040	0.00134	0.00680
Residential[c]	1	10	0.00486	0.00443	0.00000	0.00000	0.00179	0.00231
Personal[c]		106	0.00866	0.01769	0.00012	0.00060	0.00465	0.00901

[a] Fibers having a length of at least 0.5 μm and at least five times the width (used in AHERA regulations to define when schools are sufficiently free of asbestos following abatement).

[b] Average of building averages.

[c] Average of individual samples.

TABLE 2

SUMMARY OF BUILDINGS SAMPLED AND MEAN ASBESTOS-IN-AIR CONCENTRATION FOR OPTICALLY EQUIVALENT FIBERS AND MASS CONCENTRATION FOR ALL STRUCTURES

Building type	No. buildings	No. samples	Optical equivalent[a] (f/ml) Average	Optical equivalent[a] (f/ml) Standard deviation	All structures (ng/m^3) Average	All structures (ng/m^3) Standard deviation
School[b]	177	921	0.00011	0.00031	3.93	11.55
University[b]	78	426	0.00007	0.00029	0.95	3.16
Commercial[b]	28	213	0.00002	0.00010	2.94	11.74
Public[b]	32	123	0.00007	0.00044	2.07	13.28
Outdoor[c]		759	0.00002	0.00026	0.50	7.31
Residential[c]	1	10	0.00000	0.00000	0.36	0.83
Personal[c]		106	0.00009	0.00051	0.68	3.67

[a] Fibers at least 5 μm long and with a diameter of at least 0.25 μm (fibers projected to be counted by phase contrast microscopy).
[b] Average of building averages.
[c] Average of individual samples.

0.08 s/ml of asbestos (or 9.18 ng/m^3). Similarly, 90% of the samples from school buildings had concentrations of asbestos ≥5 μm less than 0.00071 f/ml.

Table 4 summarizes the median (50th percentile) information by building type. The majority of samples showed no fibers longer than 5 μm.

Figures 1 and 2 contain graphs of cumulative concentrations for all asbestos structures and for structures ≥5 μm in length. A sufficient number of school samples have been analyzed and the distribution of average asbestos concentrations in school buildings, as shown in Fig. 1, approximates a log-normal distribution as expected.

When the individual outdoor samples are categorized by type of building with which they are associated, the average asbestos s/ml values are as follows: school outdoor,

TABLE 3

NINETIETH PERCENTILE CONCENTRATIONS OF ASBESTOS-IN-AIR FOR SELECTED SAMPLE SETS

Building type	No. buildings	Structures/ ml	Fibers (≥5 μm)/ml	ng/m^3	AHERA[a] (s/ml)	Optical[b] (f/ml)
School[c]	177	0.08134	0.00071	9.183	0.04227	0.00056
University[c]	78	0.02543	0.00000	1.162	0.01357	0.00000
Commercial[c]	28	0.00476	0.00000	4.288	0.00302	0.00000
Public[c]	32	0.01551	0.00054	6.443	0.00841	0.00015
Outdoor[d]	759	0.00437	0.00000	0.100	0.00000	0.00000
Peronal[d]	106	0.02368	0.00000	0.397	0.00000	0.00000

[a] Fibers having a length of at least 0.5 μm and at least five times the width (used in AHERA regulations to define when schools are sufficiently free of asbestos following abatement).
[b] Fibers at least 5 μm long and with a diameter of at least 0.25 μm (fibers projected to be counted by phase contrast microscopy).
[c] Percentile of building averages.
[d] Percentile of individual samples.

TABLE 4

MEDIAN CONCENTRATIONS OF ASBESTOS-IN-AIR FOR SELECTED SAMPLE SETS

Building type	No. buildings	Structures/ml	Fibers (≥5 μm)/ml	ng/m³	AHERA[a] (s/ml)	Optical[b] (f/ml)
School[c]	177	0.01017	0.00000	0.363	0.00608	0.00000
University[c]	78	0.00165	0.00000	0.033	0.00131	0.00000
Commercial[c]	28	0.00101	0.00000	0.011	0.00072	0.00000
Public[c]	32	0.00335	0.00000	0.051	0.00175	0.00000
Outdoor[d]	759	0.00000	0.00000	0.000	0.00000	0.00000
Personal[d]	106	0.00316	0.00000	0.009	0.00000	0.00000

[a] Fibers having a length of at least 0.5 μm and at least five times the width (used in AHERA regulations to define when schools are sufficiently free of asbestos following abatement).
[b] Fibers at least 5 μm long and with a diameter of at least 0.25 μm (fibers projected to be counted by phase contrast microscopy).
[c] Percentile of building averages.
[d] Percentile of individual samples.

0.00183 s/ml; university outdoor, 0.00281 s/ml; commercial outdoor, 0.00104 s/ml; and public outdoor, 0.00098 s/ml. These concentrations are not significantly different ($P = 0.0675$).

Similarly, when personal samples are separated into the different building categories, the average asbestos content of the samples is: school personal 0.00956 s/ml; university personal 0.02072 s/ml; commercial personal 0.00132 s/ml; and public personal 0.00145 s/ml. These concentrations were significantly different ($P = 0.0047$).

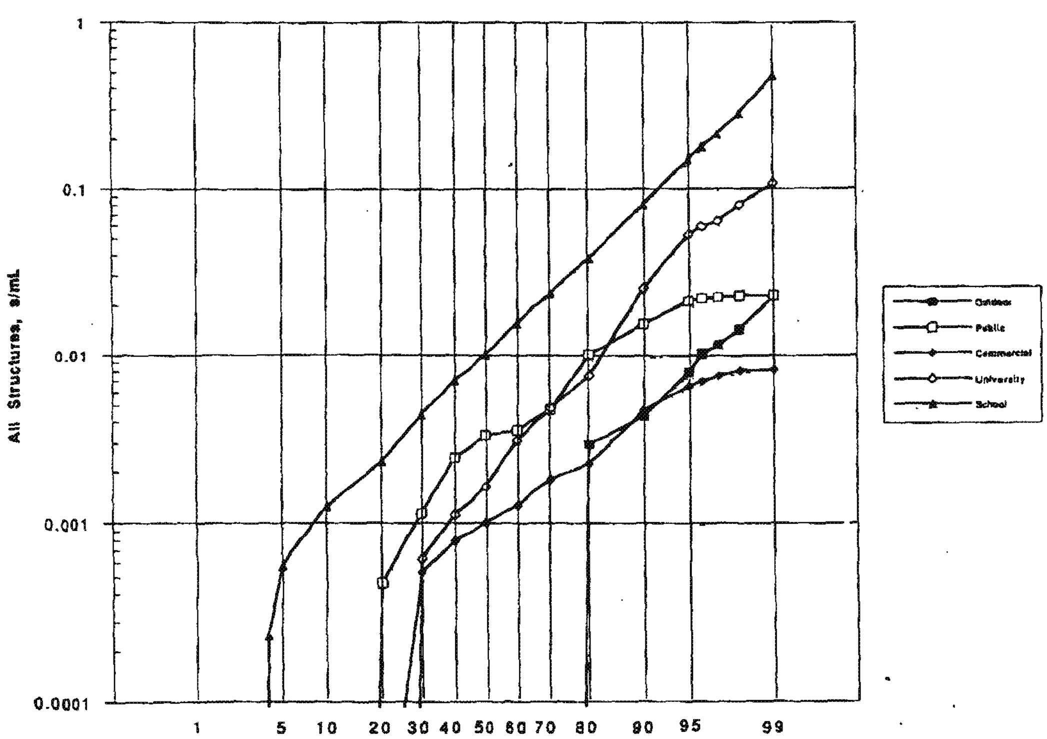

FIG. 1. Percentile distribution of building averages for all asbestos structures (s/ml).

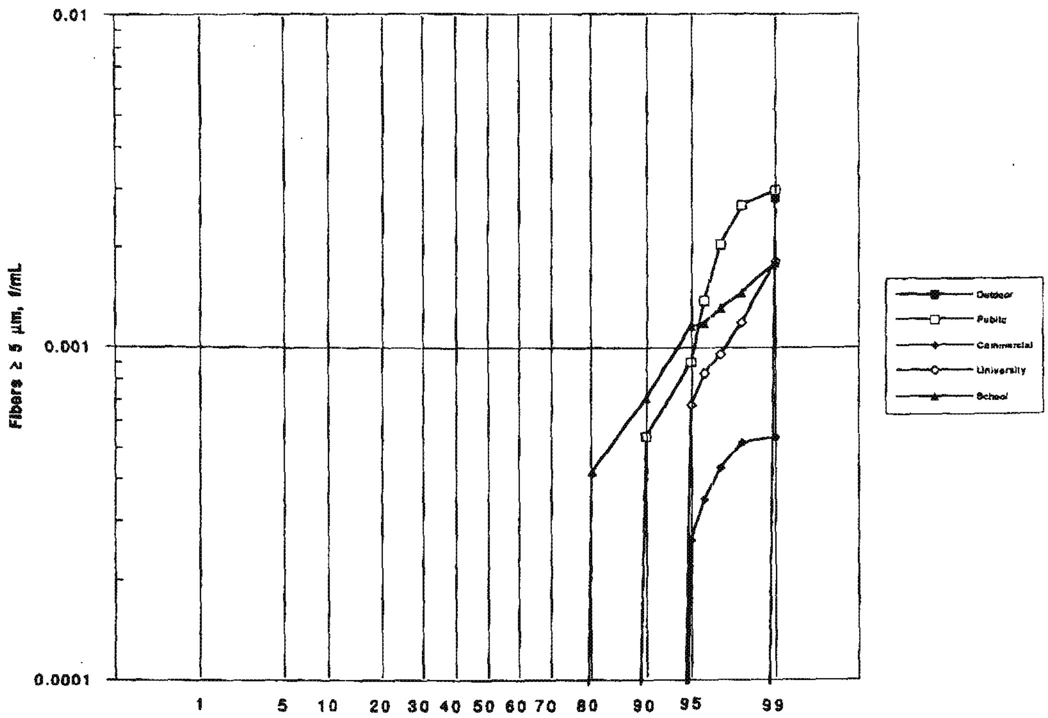

FIG. 2. Percentile distribution of building averages for asbestos fibers ⩾5 μm (fibers/ml).

Table 5 shows the joint length and width distributions for chrysotile and amphiboles. Most of the chrysotile fibers were very thin (97% less than 0.2 μm in diameter) and short (85% less than 1 μm long). Only 2% of the fibers were amphiboles. The amphibole fibers were longer and thicker than the chrysotile fibers.

4.0. DISCUSSION

No attempt was made in this paper to determine if airborne asbestos levels were correlated with various possible determinants of airborne asbestos levels, such as type and condition of ACM, type of air flow, etc. However, no such correlations were found in the earlier report (Corn *et al.*, 1991) of a subset of the data obtained from schools.

Although the present study reports on 921 samples from 177 school buildings, whereas the earlier school study reported only 328 samples from 71 schools, the results from the two studies are similar. While a somewhat higher concentration of total asbestos structures was found in the group of 921 school samples (0.04 s/ml) than in the 328 samples reported by Corn *et al.* (1991) (0.02 s/ml), the concentration of fibers ⩾5 μm in length was somewhat smaller in the larger sample (0.00018 f/ml versus 0.00023 f/ml).

In the earlier paper on a subset of the data from schools (Corn *et al.*, 1991), the presence of ACM was documented by analysis of bulk samples in all but one of 70 schools studied. Although a similar bulk sample analysis was not conducted for all the samples in the larger study, based on the results of Corn *et al.* and the fact that all of the buildings involved were alleged in legal proceedings to contain ACM, it seems highly likely that most, if not all, of the buildings in the present study likewise contained ACM.

TABLE 5

WIDTH AND LENGTH DISTRIBUTIONS OF ASBESTOS STRUCTURES, EXPRESSED AS A PERCENTAGE OF TOTAL STRUCTURES

	Width				
Length (μm)	<0.2 μm	0.2–0.39 μm	0.4–0.79 μm	≥0.8 μm	Total
	Chrysotile (10,299 structures)				
<0.5	44.89	0.04	0.00	0.00	44.93
0.5–0.99	40.02	0.18	0.07	0.00	40.28
1.0–1.99	10.45	0.84	0.13	0.00	11.42
2.0–4.99	1.76	0.54	0.34	0.07	2.71
5.0–9.99	0.15	0.12	0.06	0.09	0.41
≥10	0.10	0.04	0.06	0.07	0.26
	97.36	1.77	0.65	0.22	100.00
	Amphibole (263 structures)				
<0.5	6.08	0.00	0.00	0.00	6.08
0.5–0.99	29.28	5.32	0.00	0.00	34.60
1.0–1.99	15.97	14.45	1.90	0.00	32.32
2.0–4.99	2.66	6.84	7.22	3.04	19.77
5.0–9.99	0.38	2.28	1.90	1.14	5.70
≥10	0.00	0.00	0.76	0.76	1.52
	54.37	28.90	11.79	4.94	100.00

There have been a number of studies on indoor air quality that have used methods comparable to those used in the present study (including analysis by direct TEM) to monitor indoor exposures. Table 6 provides a summary of the exposures referenced

TABLE 6

SUMMARY OF CONCENTRATIONS OF FIBERS ≥5 μm FROM A WORLD HEALTH ORGANIZATION STUDY[a]

Location	No. samples	Range (fibers/ml)
Canada		
Residential near asbestos mines	3	0.0002–0.0018
South Africa		
Downwind of mill	6	0.0024–0.6000
Residence of asbestos workers	6	0.002–0.011
Residential near asbestos mines	6	0.0002–0.0008
Outdoor	5	<0.0001–0.0002
Austria		
Outdoor	5	<0.0001–0.0046
Germany		
Sporting halls	45	0.0001–0.0011
Schools	5	0.0001–0.011
Public buildings	5	0.0001–0.010
Homes	3	0.0001–0.006
Outdoor	7	0.0002–0.005

[a] World Health Organization (1986).

TABLE 7

SUMMARY OF CONCENTRATIONS OF FIBERS ≥5 μm FROM A HEALTH EFFECTS INSTITUTE-ASBESTOS RESEARCH STUDY[a]

Study[b]	Samples	Buildings	Average (fibers/ml)	
			All samples	Selected samples[c]
Public and commercial				
GSA	297	43	0.00005	0.00005
McCrone	328	1	0.00004	0.00004
Burdett	70	8	0.00025	0.00025
Chatfield	33	2	0.00335	0.00000
Schools and universities				
Chatfield—university	7	2	0.00422	0.00111
Pinchin	63	19	0.00042	0.00042
McCrone	269	19	0.00022	0.00022
Burdett	40	5	0.00043	0.00010
Chatfield—school	14	3	0.00059	0.00059

[a] Health Effects Institute-Asbestos Research (1991).
[b] These studies may be found in the HEI-AR report.
[c] Selected samples representing non-normal conditions were eliminated from the average.

in a World Health Organization study (1986) on asbestos and other naturally occurring fibers. Table 7 contains a summary of data from studies recently reviewed by Health Effects Institute-Asbestos Research (1991). Figure 3 shows a comparison of the results contained in these studies with the data presented herein.

The results shown in Fig. 3 and contained in Table 7 indicate that average U.S. asbestos concentrations are generally lower than those reported from other countries.

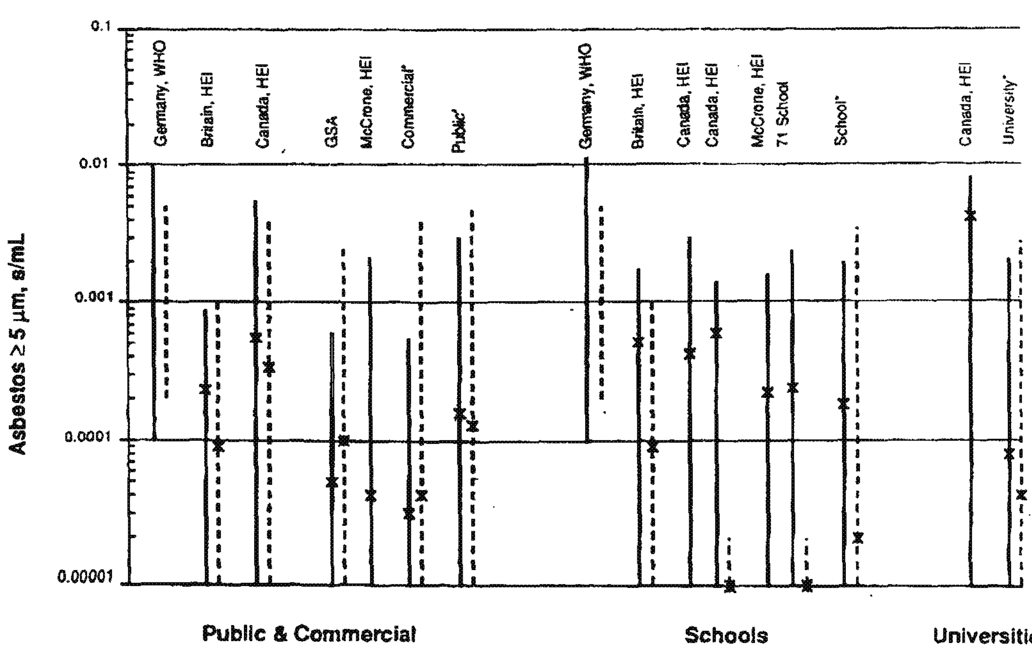

FIG. 3. Comparison of average exposures for fibers ≥5 μm from WHO, HEI-AR, and this study (fibers/ml). Solid lines indicate indoor air samples; dashed lines indicate outdoor samples; (X) indicates the mean of the distribution; (*) indicates sample results from this study.

While there are buildings in the United States which have asbestos levels as high as those of other countries, average concentrations in the United States are 10 to 100 times less than those found in Britain, Germany, or Canada. This is true for both indoor samples (solid lines) and outdoor samples (dashed lines).

One of the more notable of these studies was the USEPA investigation (Chesson *et al.*, 1990a; Crump *et al.*, 1989) of 49 government buildings in the United States. A total of 43 of these buildings contained ACM, 37 of which contained ACM in disrepair. The levels found in these 43 buildings (average of 0.00005 f/ml for fibers $\geq 5\ \mu m$) were indistinguishable from outdoor levels.

In addition to these data reported in the literature, several groups of samples that were also analyzed by direct TEM and appeared as part of court records are summarized in Table 8. These studies include samples collected on behalf of building owners by industrial hygiene firms to assess the air in buildings for possible elevated asbestos concentrations and also studies sponsored by plaintiffs in lawsuits. Table 8 contains all of the samples from these sources that were collected under ambient conditions and analyzed by direct TEM procedures.

The bank building samples were collected at a West Virginia commercial building by two hygiene firms between February 1986 and July 1989. The samples were prepared using a modified NIOSH 7402 procedure and analyzed following USEPA Level II methods. These data presented in Table 8 comprise only indoor ambient samples. In addition, eight personal samples were taken during installation of computer cables and other electrical service to various rooms in the building and three personal samples were collected as part of a simulation on entering return plenums.

The school samples were collected from a Pennsylvania school between October 1985 and June 1989. Most of these samples were collected in a plenum with asbestos containing dust. The samples were prepared and analyzed following USEPA Level II procedures.

The courthouse was sampled by the building owner between August 1987 and October 1988. The samples, analyzed by two different firms, were prepared using a modified NIOSH 7402 procedure and analyzed following USEPA Level II methods. The samples contained in Table 8 are all ambient samples collected using nonaggressive sampling techniques and were analyzed by direct TEM procedures. Several of the ambient samples were too heavily loaded for direct preparation and are not included in Table 8. In addition to ambient monitoring, a "decontamination program" was

TABLE 8

ASBESTOS-IN-AIR CONCENTRATIONS OF SAMPLES ANALYZED USING DIRECT TEM METHODOLOGY FOR STUDIES APPEARING AS PART OF COURT RECORDS, EXPRESSED AS RANGE AND MEAN VALUES

Site description	No. of samples	Concentration (structures/ml) Range	Concentration (structures/ml) Mean	Fibers ($\geq 5\ \mu m$)/ml Mean
Bank building	5	0–0.0134	0.0076	0.0
School	50	0–0.0040	0.0004	0.0
Courthouse, 1987	65	0–0.0080	0.0012	Not given
Courthouse, 1988	36	0–0.0880	0.0064	0.00093
Office building	10	0–0.0016	0.0002	0.0

undertaken during 1988 to clean desks, chairs, lamps, etc. These data are not included in the table. Also not included are samples collected using aggressive sampling techniques and personal samples taken from public employees during routine occupational activities (moving boxes and other O & M activities).

An office building in the southern United States was in various stages of an asbestos abatement program when these samples were taken in April 1989. The samples included in Table 8 are from unabated areas of the building. The samples were prepared using a modified NIOSH 7402 procedure and analyzed following USEPA Level II methods.

Overall, the data in Tables 6, 7, and 8 summarized from other sources are consistent with the sample results presented in the present paper. All of these samples combined encompass nearly 3000 indoor samples collected by government agencies, individual researchers, building owners, defendants in lawsuits, and plaintiffs in lawsuits. They present a consistent picture of uniformly low ambient concentrations.

These data can be compared to the regulatory limits imposed by the federal government. The USEPA (1987) has established a concentration of 0.01 s/ml (for all asbestos structures longer than 0.5 μm), below which a building is considered clean. This level is invoked after performing asbestos abatement activities and prior to reoccupancy. At least five air samples must be collected and each sample air volume must exceed 1200 liters. Permissible individual exposure limits have been promulgated by OSHA (USDOL, 1989) and Mine Safety and Health Administration (MSHA) (USDOI, 1989) for a working lifetime for construction workers and miners, respectively. The OSHA action level is 0.1 f/ml of air calculated as an 8-hr time-weighted average. (A permissible exposure limit of 0.1 f/ml and an action level of 0.05 f/ml have been proposed by OSHA for fibers $\geq$5 μm. All administrative requirements of the rule are waived for workplaces associated with airborne asbestos exposures below the action level.) OSHA also has an excursion limit of 1 f/ml, averaged over a sampling time of 30 min. MSHA has determined similar limits of 2 f/ml for 8 hr and has an excursion limit of 10 f/ml as determined over a minimum sampling time of 15 min.

The data reported herein indicate that average ambient levels in buildings containing ACM are far below (typically on the order of 1000-fold less) federal action levels. It should also be kept in mind that the action levels themselves are considerably below any levels that have been shown to cause disease in humans. Further, the data presented herein indicate that many of the indoor locations sampled have airborne fiber levels that are below the 0.01 USEPA clearance level.

The structures found in buildings are much smaller and coarser than those found in occupational settings. The percentage of all asbestos fibers longer than 10 μm in samples reported herein was 0.29%. This percentage is 10 to 40 times less than that observed by Dement and Harris (1979) for textile manufacturing (10.4%) and 50 to 70 times less than that reported for amosite insulation workers (18.1%).

REFERENCES

CHESSON, J., HATFIELD, J., SCHULTZ, B., DUTROW, E., AND BLAKE, J. (1990a). Airborne asbestos in public buildings. *Environ. Res.* **51**, 100–107.

CHESSON, J., AND HATFIELD, J. (1990b). *Comparison of Airborne Asbestos Levels Determined by Transmission Electron Microscopy (TEM) Using Direct and Indirect Transfer Techniques.* Report EPA 560/5-89-004. U.S. Environmental Protection Agency, Washington, DC.

CORN, M., CRUMP, K., FARRAR, D. B., LEE, R. J., AND MCFEE, D. R. (1991). Airborne concentrations of asbestos in 71 school buildings. *Regul. Toxicol. Pharmacol.* **13**, 99–114.

CRUMP, K. S. (1986). *Asbestos Potency Assessment for EPA Hearing.* Prepared for the Asbestos Information Association and presented at USEPA hearings (June 1986).

CRUMP, K. S., AND FARRAR, D. B. (1989). Statistical analysis of data on airborne asbestos levels collected in an EPA survey of public buildings. *Regul. Toxicol. Pharmacol.* **10**, 51–62.

CRUMP, K. S. (1990). Letter. *Science* **248**, 799.

DEMENT, J. M., AND HARRIS, R. L. (1979). *Estimates of Pulmonary and Gastrointestinal Deposition for Occupational Fiber Exposures.* DHEW publication No. 79-135. National Institute of Occupational Safety and Health, Washington, DC.

DEMENT, J. M. AND KALLENBURG, K. M. (1990). Comparison of phase contrast and electron microscopic methods for evaluation of occupational asbestos exposures. *Appl. Occup. Environ. Hyg.* **5**, 242–247.

FELDMAN, D. S., JR., GAGNON, G., HOFMANN, R., AND SIMPSON, J. (1987). *StatView II,* Version 1.03. Abacus Concepts, Berkeley, CA.

Health Effects Institute–Asbestos Research (HEI–AR) (1991). *Asbestos in Public and Commercial Buildings: A Literature Review and Synthesis of Current Knowledge.* Cambridge, MA.

HUGHES, J., WEILL, H., AND HAMMAD, Y. Y. (1987). Mortality of workers employed in two asbestos cement manufacturing plants. *Br. J. Ind. Med.* **44**, 161–174.

KEYES, D. L., PRICE, B. P., AND CHESSON, J. (1985). *Guidance for Controlling Asbestos-Containing Materials in Buildings.* Report EPA 560/5-85-024. U.S. Environmental Protection Agency, Washington, DC.

LEE, R. J., LALLY, J. S., AND FISHER, R. M. (1977). Identification and counting of mineral fragments. In *Proceedings of Workshop on Asbestos: Definitions and Measurement Methods* (C. C. Garavatt, P. D. LaFleur, and K. F. J. Heinrich, Eds). Special Publication 506. National Bureau of Standards, Washington, DC.

MANTEL, N. (1963). Chi-square tests with one degree of freedom: Extensions of the Mantel–Haenszel procedure. *J. Am. Stat. Assoc.* **58**, 690–700.

MOSSMAN, B. T., BIGNON, J., CORN, M., SEATON, A., AND GEE, J. B. L. (1990). Asbestos: Scientific developments and implications for public policy. *Science* **247**, 294–301.

NICHOLSON, W. J. (Ed.) (1986) *Airborne Asbestos Health Assessment Update.* Report EPA/600/8-84/003F. U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office, Washington, DC.

National Institute of Occupational Safety and Health (NIOSH) (1989). Fibers. In *NIOSH Manual of Analytical Methods* (P. M., Eller, Ed.). Method 7400. NIOSH, Washington, DC. (issued 2/15/84, revised 5/15/89).

STANTON, M. F., LAYARD, M., TEGERIS, A., MILLER, E., MAY, M., MORGAN, E., AND SMITH, A. (1981). Relation of particle dimension to carcinogenicity in amphibole asbestoses and other fibrous minerals. *J. Natl. Cancer Inst.* **67**, 965–975.

U.S. Department of the Interior, Mine Safety and Health Administration (USDOI) (1989). 30 CFR Part 56.5001.b. U.S. Department of the Interior, Washington, DC.

U.S. Department of Labor, Occupational Safety and Health Administration (USDOL) (1989). 29 CFR Part 1926.58.c. U.S. Department of Labor, Washington, DC.

U.S. Environmental Protection Agency (USEPA) (1987). *Asbestos Hazard Emergency Response Act,* 40 CFR Part 763, Appendix A to Subpart E. USEPA, Washington, DC.

U.S. Environmental Protection Agency (USEPA) (1990). *Environmental Asbestos Assessment Manual, Superfund Method for the Determination of Asbestos in Ambient Air,* Part 2, *Technical Background Document.* Report EPA/540/2-90/005b. USEPA, Washington, DC.

World Health Organization (1986). *Asbestos and Other Natural Mineral Fibres.* Environmental Health Criteria 53. World Health Organization, Geneva.

YAMATE, G., AGARWAL, S. C., AND GIBBONS, R. D. (1984). *Methodology for the Measurement of Airborne Asbestos by Electron Microscopy.* Contract 68-02-3266. U.S. Environmental Protection Agency, Washington, DC.