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Exposure to Chrysotile Asbestos Associated with Unpacking and Repacking Boxes of Automobile Brake Pads and Shoes

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Industrial hygiene surveys and epidemiologic studies of auto mechanics have shown that these workers are not at an increased risk of asbestos-related disease; however, concerns continue to be raised regarding asbestos exposure from asbestos-containing brakes. Handling new asbestos-containing brake components has recently been suggested as a potential source of asbestos exposure. A simulation study involving the unpacking and repacking of 105 boxes of brakes (for vehicles ca. 1946–80), including 62 boxes of brake pads and 43 boxes of brake shoes, was conducted to examine how this activity might contribute to both short-term and 8-h time-weighted average exposures to asbestos. Breathing zone samples on the lapel of a volunteer worker (n = 80) and area samples at bystander (e.g., 1.5 m from worker) (n = 56), remote area (n = 26) and ambient (n = 10) locations collected during the unpacking and repacking of boxes of asbestos-containing brakes were analyzed by phase contrast microscopy and transmission electron microscopy. Exposure to airborne asbestos was characterized for a variety of parameters including the number of boxes handled, brake type (i.e. pads versus shoes) and the distance from the activity (i.e. worker, bystander and remote area). This study also evaluated the fiber size and morphology distribution according to the International Organization for Standardization analytical method for asbestos. It was observed that (i) airborne asbestos concentrations increased with the number of boxes unpacked and repacked, (ii) handling boxes of brake pads resulted in higher worker asbestos exposures compared to handling boxes of brake shoes, (iii) cleanup and clothes-handling tasks produced less airborne asbestos than handling boxes of brakes and (iv) fiber size and morphology analysis showed that while the majority of fibers were free (e.g. not associated with a cluster or matrix), <30% were respirable and even fewer were of the size range (>20 μm length) considered to pose the greatest risk of asbestos-related disease. It was found that average airborne chrysotile concentrations (30 min) ranged from 0.086 to 0.368 and 0.021 to 0.126 f cc^{-1} for a worker unpacking and repacking 4–20 boxes of brake pads and 4–20 boxes of brake shoes, respectively. Additionally, average airborne asbestos exposures (30 min) at bystander locations ranged from 0.004 to 0.035 and 0.002 to 0.011 f cc^{-1} when 4–20 boxes of brake pads and 4–20 boxes of brake shoes were handled, respectively. These data show that a worker handling a relatively large number of boxes of brakes over short periods of time will not be exposed to airborne asbestos in excess of its historical or current short-term occupational exposure limits.

Keywords: asbestos; automobile brakes; exposure assessment

INTRODUCTION

Over the last 30 years, significant attention has been paid to evaluating asbestos exposures and the potential risk of asbestos-related diseases among garage mechanics (Paustenbach *et al.*, 2004). Such interest stems from decades-long use of chrysotile asbestos in automobile brake pads and shoes. Chrysotile's superior characteristics, such as good tensile strength, durability, flexibility and heat resistance, provided the auto industry with a friction material that could

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withstand extreme temperatures, pressure and stress (Skinner *et al.*, 1988; Sheehy *et al.*, 1989; Paustenbach *et al.*, 2004). These characteristics were particularly necessary for safety, as automobiles throughout the 20th century became larger, heavier and better able to attain greater speeds (Harper, 1998).

Despite the fact that numerous studies have shown that garage mechanics were historically exposed to airborne asbestos levels below contemporaneous and current occupational standards and are not at an increased risk of asbestos-related disease (McDonald and McDonald, 1980; Teta *et al.*, 1983; Spirtas *et al.*, 1985; Spirtas *et al.*, 1994; Woitowitz and Rodelsperger, 1994; Teschke *et al.*, 1997; Agudo *et al.*, 2000; Wong, 2001; Paustenbach *et al.*, 2003; Goodman *et al.*, 2004; Hessel *et al.*, 2004; Paustenbach *et al.*, 2004), concerns continue to be raised regarding the handling of asbestos-containing brake components. Handling new brake components is an aspect of brake repair work that has recently been suggested as a potential source of asbestos exposure and thus a hazard to individuals in work environments where these components are used (Atkinson *et al.*, 2004). Handling new brake components is not limited to brake mechanics; retail automobile parts store and distribution center personnel also face potential exposure to asbestos during the handling of boxes of asbestos brakes (Fig. 1).

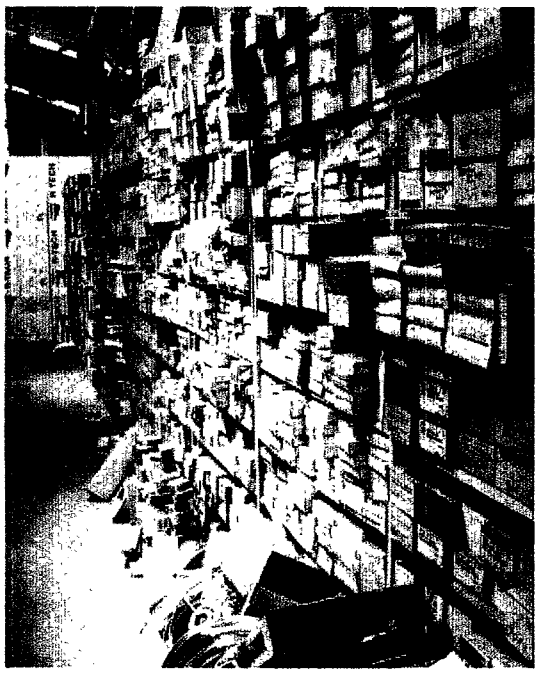


Fig. 1. Photo of brake replacement parts storage area in an automobile parts supply and repair shop. It shows storage area of replacement brake parts in a vintage auto parts facility, where the majority of boxes of brakes were purchased for the simulation study. The volume of brakes that can be stored in a relatively small facility or operation can be substantial.

Residual asbestos fibers might be present inside a new brake box, for example, due to wear during product shipping or as a result of airborne fibers 'settling' into the open box in the packaging facility. These residual fibers may become airborne when the brakes are removed from the box or 'repacked' into the original box or another container.

Several studies have assessed airborne asbestos exposures to automobile and brake mechanics (Paustenbach *et al.*, 2003); however, it is not readily apparent that any of these studies included the handling of new brake components in their short-term or workday exposure estimates. The purpose of the present evaluation was to characterize airborne asbestos exposures associated with typical tasks that might be performed by a mechanic in a repair shop, a counter salesperson in a parts shop or a parts picker in an industrial warehouse in handling of boxes of new asbestos-containing replacement brakes. Given that replacement asbestos brakes are currently available from some parts suppliers, the potential for handling asbestos brakes is not only a historical issue. This study provides exposure information that improves the knowledge of the historic and current potential hazards associated with handling these products.

METHODS

Testing was conducted in two phases. Phase I (27 July 2004) focused on understanding and characterizing the plausible number of boxes that could be unpacked and repacked within a specific period of time, as well as identifying optimal airflow rates and sample times. Using the sampling parameters identified in the first phase, Phase II (5 and 6 November 2005) testing was conducted to increase the sample size of a lower and upper bound box-handling scenario, as well as to evaluate other related tasks (i.e. cleanup and clothes handling) that might be associated with asbestos exposure. In both phases of testing, breathing zone air samples were collected from the worker's lapel. In addition, area samples were collected at bystander (1.5 m from the main activity), remote (7.6–9.1 m from the main activity) and ambient (outside testing facility) locations (Figs. 2 and 3). Protocol for this simulation study was approved by an accredited Institutional Review Board (Essex Institutional Review Board, Inc., Lebanon, NJ, USA).

Description of site conditions

The automobile repair shop where the study was conducted has been previously described in detail (Paustenbach *et al.*, 2006). The shop, which is located in Santa Rosa, CA, is a relatively large garage with an open floor plan, ~30.8 m wide by 14.5 m deep with a 4.6 m ceiling (Fig. 2). To prevent air measurements from being confounded by other

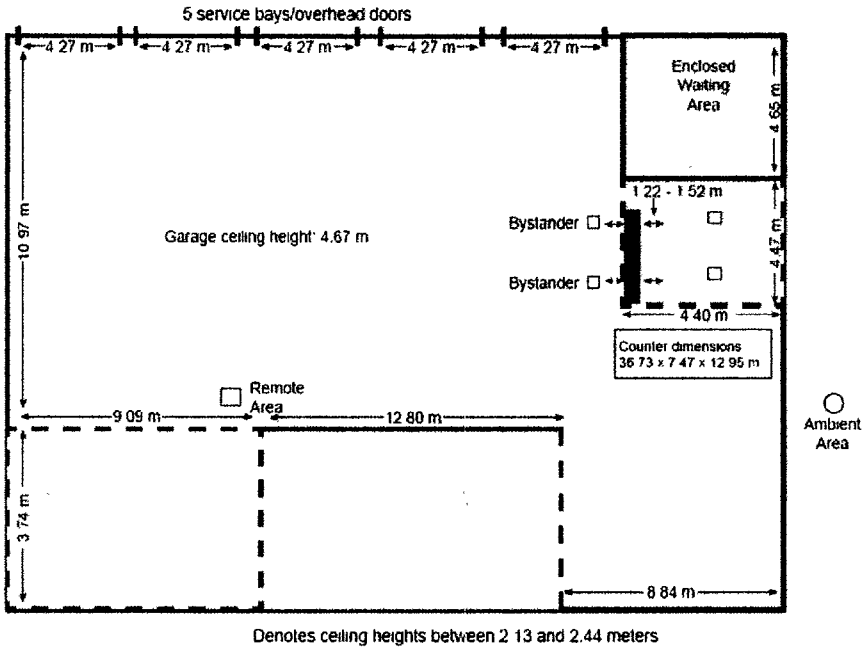


Fig. 2. Diagram of automotive repair shop and locations of area sampling stations.

repair activities in the shop, no other automobile repair work was conducted during the study. Additionally, the shop was not ventilated with heating or air conditioning and all entry and service doors were closed during testing.

Description of boxes of brake pads and shoes

A total of 105 boxes of brakes, including 62 boxes of brake pads and 43 boxes of brake shoes, were identified and purchased from vintage automotive parts suppliers and repair facilities primarily located in Arizona and California. These brake boxes were not opened by investigators prior to testing so that the study's results would mimic a worker opening a new, unused box of replacement brakes. The investigators worked with personnel at the vintage automobile parts suppliers and repair facilities to identify boxes most likely to contain asbestos brake pads and shoes (Fig. 4). Based on the historical knowledge of the parts supplier, the boxes were identified with brand and year of the vehicle for which its replacement brakes were believed to contain asbestos. In addition, the boxes were inspected for information regarding the composition of the brakes (e.g. asbestos warning labels). Replacement brakes identified for the study were made for passenger vehicles and were manufactured prior to the mid-1970s by ~15 different brake manufacturers. Boxes of brakes were typically undisturbed for several years, according to the parts suppliers, and were in good structural condition.

Given the scarcity of unused vintage boxes of asbestos-containing brakes, the same boxes of brakes were used for both Phase I and II testing in the study. After Phase I, the boxes of brakes were shipped round-trip to a location on the East Coast via ground transportation in order to simulate the dust generated from the rubbing of brake parts during shipment. After shipment, these boxes of brakes were not opened until Phase II of testing. In addition, boxes of brakes that were unpacked and repacked on the first day of Phase II testing were not used for the second day of sampling. Each box, then, was unpacked and repacked only once during each phase of testing.

Description of work conditions and exposure scenarios

The study was conducted in an automobile repair shop because it presented a more realistic environment in terms of conditions potentially experienced in a brake repair or auto parts shop. This shop, for example, had a counter of a height (1.1 m) that would typically be encountered in these kinds of settings (e.g. closer to the breathing zone than a standard height table). All box-handling work was performed by a single volunteer and was conducted in a manner consistent to that described by interviewed career automotive mechanics and parts suppliers. These interviews revealed that in a parts supply or repair shop, new replacement brakes would be removed from the box and compared to the old brake component to confirm that the correct part was indeed ordered. In circumstances where the correct part was not

Sampling Sequence of Testing I

		Event 1	Event 2	Ventilation	Background
Worker	Right and left lapel	15-min	15-min		
	Right and left lapel	30-min			
Bystander	Four locations	30-min			30-min
Remote area	Two locations	30-min			

Summary of Testing I Events

Event No.	Brake Type	No. of Boxes Handled	
		15 min	30 min
1	Pad	2	
2	Pad	4	6
3	Pad	8	
4	Pad	12	20
5	Pad	16	
6	Pad	20	36
7	Shoe	2	
8	Shoe	4	6
9	Shoe	8	
10	Shoe	12	20
11	Shoe	17	

Sampling Sequence of Testing II

		Event 1		Ventilation	Background
Worker	Right and left lapel	15-min	15-min		
	Right and left lapel	100-min			
Bystander	Four locations	30-min			30-min
Remote area	Two locations	30-min			

Summary of Testing II Events

Event No.	Brake Type	No. of Boxes Handled	
		15 min	30 min
1	Shoe	4	4
2	Shoe	16	16
3	Pad	4	4
4	Pad	16	16
5	Cleanup		
6	Shoe	4	4
7	Shoe	16	16
8	Pad	4	4
9	Pad	16	16
10	Cleanup		
11	Clothes handling		

Fig. 3. Schematic of sampling regimen of airborne asbestos samples collected at various locations within the shop during the unpacking/repacking of boxes of brake pads and shoes.

identified, this task would have to be duplicated. Thus, during the simulation study, boxes of brakes were stored on a cart within reach of the worker, new replacement brakes were opened, compared to a demonstrative brake, and then repacked in their original boxes. Generally, four brake shoes or brake pads were in each box; however, in some circumstances each brake shoe was packaged in separate boxes.

Airborne asbestos concentrations were characterized for a worker handling between 2 and 20 boxes of brakes within a 15-min time period or 6–36 boxes of brakes within a 30-min time period (Tables 1 and 2). In addition, airborne asbestos concentrations were measured during cleanup of dust that accumulated on the counter and during the handling of clothes worn during the box-handling activities. The clothes-handling task involved shaking and folding cloth coveralls worn by the volunteer during each day of testing to simulate the handling and laundering of potentially contaminated work clothes. More specifically, clean, newly purchased cloth coveralls were worn during the entire duration of testing and were carefully removed by the worker as not to disturb the potentially adhered fibers. Each coverall ($n = 3$) was stored in separate plastic-lined bags until the last day of testing, when the clothes-handling task was conducted. The simulated clothes-handling task involved repeatedly shaking, folding and turning clothes inside out for ~1 to 2 min for each pair of overalls. Although no fibers or debris were visible

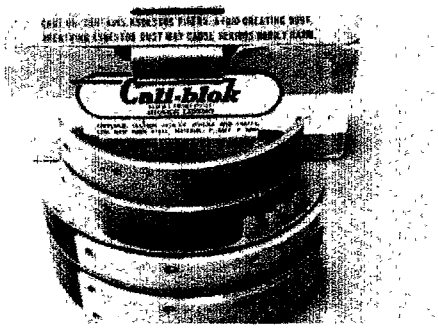


Fig. 4. Photo of example brake shoes included in the exposure simulation study. (**A**) Cali-blok relined shoes manufactured for Hudson (1953–54), IHC (1961–62), Jeep (1946–67) and Willys (1951–55) vehicles. Warnings on this particular brake shoe box included 'Caution: Contains asbestos fibers. Avoid creating dust. Breathing asbestos dust may cause serious bodily harm.' and 'Do not regrind these brake shoes'.

on the coveralls after each day of testing, some particles were observed in the air during the clothes-handling task. Transmission electron microscopy (TEM) analysis of air samples was used to evaluate the proportion of airborne particles that were asbestos versus non-asbestos. Cleanup of dust found on the countertop after testing was performed with dry and wet paper towels and wipes and was subsequently collected for bulk sample analysis via polarized light microscopy (PLM). The debris which had settled onto the countertop appeared to consist mostly of cardboard box fragments and debris. The counter surface was cleaned for an approximate duration of 1–2 min. Air samples collected during clothes handling and cleanup tasks followed the same protocol as that conducted for the box-handling tasks (Fig. 3).

The number of boxes of brakes handled in this study is consistent with the number of brake repair jobs conducted in repair shops as reported in the literature. For example, a typical brake mechanic may conduct between 2 and 40 brake repair jobs per week (Paustenbach *et al.*, 2003) and Hickish and Knight (1970) reported as many as 11 brake jobs being performed in 1 day at a repair shop (Hickish and Knight, 1970). Depending on the brand and the number of replacement brakes contained within each box, potentially four times as many boxes of brakes could be handled because four brake pads or shoes are needed for a complete front or rear brake replacement. The rate of handling boxes of brakes in a repair shop would certainly be limited by the pace of the brake repair work; however, a parts picker in an industrial warehouse would handle a far greater number of boxes than a worker in a repair shop. While a worker may not handle 36 boxes of brakes within a 30-min time period under normal conditions, the study was designed to understand the range of airborne asbestos concentrations associated with a variety of conditions (e.g. handling different number of boxes, tasks and brake type). In addition, conducting the simulation study in such a manner allows one to estimate the contribution of handling a different number of boxes of brakes on a worker's short-term and 8-h time-weighted average (TWA) exposure. While some of the conditions in this study may represent more of a worst-case scenario (e.g. low ventilation and high number of boxes being handled in a given time period), the purpose of handling different number of boxes in our study was 2-fold: (i) to understand how increasing the number of boxes being handled during a given time would influence the airborne asbestos and (ii) to assess the upper bound limits that a person could physically handle boxes of brakes in a given length of time.

Collection and analysis of airborne asbestos samples

All airborne samples for asbestos were collected as previously described (Paustenbach *et al.*, 2006). Airborne asbestos samples were collected using mixed cellulose ester filter membranes (25 mm, 0.45-μm pore size, Zefon International, St Petersburg, FL, USA) using either portable SKC Universal PCXR (SKC-West, Inc., Fullerton, CA, USA), Gilian Gilair (Ashtead Technology Rentals, Hayward, CA, USA) or high-volume Dawson 1300 sampling pumps (Ashtead Technology Rentals, Hayward, CA, USA). Portable SKC or Gilair pumps were used to collect asbestos samples at 2 liters per minute (LPM), whereas high-volume pumps were used to collect samples at airflow rates between 3 and 10 LPM. The sampling flow rates were calibrated with a Bios® DryCal DCLite primary flow calibrator (Bios International Corporation, Butler, NJ, USA) before and after sample collection. Any discrepancies observed between start and stop airflow rates were within 15%. All airborne asbestos samples were collected accordance with National Institute for Occupational Safety and Health (NIOSH) methods 7400 and 7402 (National Institute for Occupational Safety and Health, 1994a,c). Field blanks were collected throughout each day of the sampling and were sent to the analytical laboratory for analysis along with the samples collected during the testing. A total of 15 field blanks were collected and analyzed, none of which showed any detectable asbestos fibers. After collection, all air samples were capped and sealed with tape and placed in sealable plastic bags inside cardboard boxes, along with the corresponding chain-of-custody sheets, for overnight shipment to the analytical laboratory (EMS Laboratories, Inc., Pasadena, CA, USA).

Background samples of airborne asbestos were collected within the shop each day before any asbestos sampling began in the simulation study. Three

Table 1. Worker airborne asbestos concentrations (f cc^{-1}) during unpacking and repacking of asbestos-containing brake pads and shoes

	No. of boxes	Chrysotile content (% by weight)		PCM (NIOSH 7400 method)					TEM (NIOSH 7400 fiber parameters)[a]					PCME (NIOSH 7402 method)		
		Average	Range	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N
Testing I: worker																
Short-term sampling (15 min)																
Pads	2	43	41–45	0.100	0.092–0.108	2	0	0	0.072	0.013–0.131	2	0	0	0.058	0.008–0.108	2
	4	45	39–47	0.123	0.098–0.148	2	0	0	0.049	0.026–0.071	2	0	0	0.065	0.033–0.098	2
	8	33	20–43	0.330	0.260–0.399	2	0	0	0.494	0.294–0.694	2	0	0	0.330	0.260–0.399	2
	12	32	22–41	0.438	0.383–0.492	2	0	0	1.265	1.183–1.347	2	0	0	0.438	0.383–0.492	2
	16	34	24–42	0.657	0.477–0.836	2	0	0	1.762	1.744–1.779	2	0	0	0.657	0.477–0.836	2
	20	27	3–33	0.269	0.043–0.496	2	0	0	1.829	1.528–2.129	2	0	0	0.463	0.429–0.496	2
Shoes	2	45	41–49	0.059	0.054–0.063	2	0	0	0.045	0.032–0.058	2	0	0	0.026	0.023–0.029	2
	4	39	29–51	0.075	0.073–0.077	2	0	0	0.048	0.041–0.054	2	0	0	0.031	0.028–0.034	2
	8	34	5–49	0.102	0.071–0.132	2	0	0	0.124	0.065–0.182	2	0	0	0.072	0.047–0.098	2
	12	38	22–60	0.113	0.080–0.146	2	0	0	0.123	0.094–0.152	2	0	0	0.080	0.058–0.103	2
	17	34	20–47	0.150	0.145–0.154	2	0	0	0.282	0.262–0.302	2	0	0	0.120	0.119–0.122	2
Short-term sampling (30 min)																
Pads	6	44	39–47	0.111	0.073–0.148	2	0	0	0.133	0.132–0.133	2	0	0	0.108	0.070–0.145	2
	20	32	20–43	0.374	0.358–0.389	2	0	0	0.453	0.416–0.489	2	0	0	0.368	0.358–0.378	2
	36	30	3–42	—	—	0	2	0	—	—	0	2	0	—	—	0
Shoes	6	42	29–51	0.044	0.044–0.044	2	0	0	0.050	0.041–0.058	2	0	0	0.028	0.027–0.029	2
	20	36	5–60	0.064	0.060–0.067	2	0	0	0.089	0.066–0.112	2	0	0	0.051	0.046–0.055	2
Testing II: worker																
Short-term sampling (15 min)																
Pads	4	36	24–49	0.193	0.072–0.320	8	0	0	0.369	0.080–0.826	4	0	0	0.171	0.058–0.294	4
	16	36	5–60	0.559	0.062–1.190	8	0	0	1.423	1.000–2.502	4	0	0	0.541	0.057–1.190	4
Shoes	4	35	22–45	0.060	0.033–0.077	8	0	0	0.071	0.024–0.119	4	0	0	0.030	0.024–0.119	4
	16	31	3–47	0.167	0.053–0.261	8	0	0	0.328	0.121–0.600	8	0	0	0.126	0.036–0.193	8
Cleanup				0.017	0.008–0.029	8	0	0	0.012	0.001–0.040	8	0	3	0.004	0.002–0.006	5
Clothes handling				0.037	0.030–0.047	4	0	0	0.009	0.003–0.020	4	0	1	0.011	0.007–0.015	3
Short-term sampling (30 min)[a]																
Pads	4	36	24–49	0.104	0.068–0.140	2	0	0	0.187	0.089–0.284	2	0	0	0.086	0.049–0.122	2
	16	36	5–60	0.297	0.276–0.318	2	0	0	0.750	0.619–0.882	2	0	0	0.284	0.252–0.315	2

Table 1. *Continued*

	No. of boxes	Chrysotile content (% by weight)		PCM (NIOSH 7400 method)					TEM (NIOSH 7400 fiber parameters)[a]					PCME (NIOSH 7402 method)		
		Average	Range	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N
Shoes	4	35	22–45	0.040	0.032–0.049	2	0	0	0.038	0.021–0.055	2	0	0	0.021	0.021–0.021	2
	16	31	3–47	0.167	0.128–0.207	2	0	0	0.328	0.228–0.428	2	0	0	0.126	0.090–0.162	2
Long-term sampling (100 min)																
Pads	4	36	24–49	0.044	0.019–0.082	4	0	0	0.096	0.030–0.201	4	0	0	0.032	0.010–0.070	4
	16	36	5–60	0.180	0.123–0.304	4	0	0	0.325	0.200–0.483	4	0	0	0.157	0.105–0.280	4
Shoes	4	35	22–45	0.028	0.022–0.031	4	0	0	0.027	0.006–0.055	4	0	0	0.012	0.002–0.023	4
	16	31	3–47	0.059	0.021–0.085	4	0	0	0.177	0.100–0.281	4	0	0	0.046	0.017–0.070	4
Cleanup				0.013	0.013–0.013	1	0	0	0.010	0.010–0.010	1	0	0	0.012	0.012–0.012	1

—, Not applicable; N, number of samples; N_{NR}, number of samples not readable by analytical methods; N_{ND}, number of samples below the sensitivity limit; PCME, Phase Contrast Microscopy Equivalent concentration in accordance to the NIOSH 7402 method.

[a]Fibers were counted using TEM with fiber parameters (>0.25 μm diameter, ≥5 μm length and ≥3:1 aspect ratio) outlined by NIOSH 7400 method.

samples were collected at the beginning of each day of Phase I and Phase II testing at an airflow rate of 10 LPM for ~40 min. Three consecutive ambient air samples were collected for ~120 min each testing day, with a sampling rate of 5–10 LPM outside the south wall of the shop away from automobile traffic.

In Phase I testing, two consecutive 15-min (n = 4) and one 30-min (n = 2) sample were collected at airflow rates of 8–10 LPM on both the right and left lapel of the worker during each event (Fig. 3). During Phase II testing, two consecutive 15-min (n = 2) and 100-min (n = 2) samples on both the right and left lapel of the worker were collected at an airflow rate of 8–10 and 2–5 LPM, respectively (Fig. 3). Bystander samples were collected at four locations ~1.5 m from the box-handling activity at breathing zone height (1.5 m) with sampling rates of 8–10 LPM for Phase I testing and 5–10 LPM for Phase II (Fig. 2). Remote area samples for airborne asbestos were also collected during box-handling work, with an airflow rate of 8–10 LPM at breathing zone height (1.5 m) at two locations near the center of the shop (~7.6 to 9.1 m from the worker) (Fig. 2). After each box handling, clothes handling or cleanup event, the shop doors were opened to ventilate the workspace, and four background samples were then collected with an airflow rate of 9–10 LPM prior to the next testing event (Fig. 3).

Fibers were counted according to NIOSH methods 7400 and 7402, which define fibers as being >5 μm in length and having at least a 3:1 aspect ratio and (in the case of 7402) >0.25 μm in diameter (National Institute for Occupational Safety and Health, 1994a,c). All airborne asbestos samples were sent to an accredited laboratory (EMS Laboratories, Inc.) for analysis by phase contrast microscopy (PCM, NIOSH method 7400) and TEM (NIOSH method 7402) (National Institute for Occupational Safety and Health, 1994a,c). For the analysis of air samples by TEM, selected area electron diffraction and energy-dispersive X-ray were used to assess the fiber type via the diffraction pattern and elemental profile of the asbestos fibers, respectively (National Institute for Occupational Safety and Health, 1994b). All sample analysis was performed by EMS Laboratories Inc., which is an accredited laboratory for asbestos analysis by the American Industrial Hygiene Association and the National Voluntary Laboratory Accreditation Program (US Department of Commerce, National Institute for Standards and Technology, Gaithersburg, MD, USA). This laboratory utilizes analysts trained according to NIOSH 582 and adheres to the quality assurance and quality control requirements set forth by Occupational Safety and Health Administration (OSHA) (29 CFR 1910.1001 Appendix A) and the most current version of the NIOSH 7400 method.

Table 2. Area airborne asbestos concentrations (f cc^{-1}) during unpacking and repacking of asbestos-containing brake pads and shoes (testing I and II)

	No. of boxes	Chrysotile Content (% by weight)		PCM (NIOSH 7400 method)					TEM (NIOSH 7400 fiber parameters)[a]					PCME (NIOSH 7402 method)		
		Average	Range	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N
Bystander																
Short-term sampling (30 min)																
Pads	4	36	24–49	0.014	0.007–0.027	8	0	0	0.011	0.003–0.020	8	0	1	0.004	0.002–0.009	7
	6	44	39–47	0.020	0.015–0.024	4	0	0	0.006	0.002–0.013	4	0	0	0.007	0.001–0.016	4
	16	36	5–60	0.018	0.010–0.027	8	0	0	0.039	0.002–0.090	8	0	1	0.010	0.003–0.022	7
	20	32	20–43	0.039	0.025–0.078	4	0	0	0.029	0.015–0.063	4	0	0	0.035	0.016–0.076	4
	36	30	3–42	0.032	0.014–0.062	4	0	0	0.058	0.023–0.130	4	0	0	0.027	0.012–0.060	4
Shoes	4	35	22–45	0.018	0.002–0.035	8	0	0	0.003	0.002–0.008	8	0	6	0.002	0.002–0.003	2
	6	42	29–51	0.006	0.004–0.009	4	0	0	0.003	0.001–0.005	4	0	2	0.002	0.002–0.002	2
	16	31	3–47	0.022	0.001–0.059	12	0	1	0.019	0.003–0.074	12	0	2	0.011	0.003–0.038	9
	20	36	5–60	0.017	0.002–0.030	4	0	0	0.019	0.001–0.052	4	0	1	0.011	0.006–0.020	3
Cleanup				0.011	0.006–0.020	8	0	0	0.005	0.002–0.020	8	0	6	0.002	0.001–0.004	2
Clothes Handling				0.014	0.008–0.022	4	0	0	0.004	0.002–0.008	4	0	3	0.010	0.010–0.010	1
Remote area																
Pads	4	36	24–49	0.015	0.011–0.022	4	0	0	0.009	0.001–0.017	4	0	1	0.006	0.003–0.010	3
	6	44	39–47	0.017	0.017–0.017	2	0	0	0.033	0.014–0.052	2	0	0	0.017	0.017–0.017	2
	16	36	5–60	0.011	0.008–0.016	4	0	0	0.015	0.009–0.024	4	0	0	0.005	0.003–0.007	4
	20	32	20–43	0.016	0.012–0.019	2	0	0	0.012	0.004–0.020	2	0	0	0.008	0.006–0.010	2
	36	30	3–42	0.005	0.003–0.006	2	0	0	0.014	0.013–0.015	2	0	0	0.005	0.003–0.006	2
Shoes	4	35	22–45	0.016	0.010–0.024	4	0	0	0.002	0.001–0.002	4	0	3	0.001	0.001–0.001	1
	6	42	29–51	0.008	0.007–0.008	2	0	0	0.001	0.001–0.001	2	0	1	0.001	0.001–0.001	1
	16	31	3–47	0.007	0.003–0.011	4	0	0	0.003	0.002–0.006	4	0	1	0.001	0.001–0.002	3
	20	36	5–60	0.008	0.007–0.009	2	0	0	0.001	0.001–0.001	2	0	2	—	—	0
Cleanup				0.009	0.007–0.012	4	0	0	0.004	0.002–0.007	4	0	1	0.003	0.001–0.006	3
Clothes handling				0.014	0.013–0.014	2	0	0	0.002	0.002–0.003	2	0	1	0.002	0.002–0.002	1
Background (before testing)																
Day 1				0.001	0.001–0.002	3	0	2	0.001	0.001–0.001	3	0	3	—	—	0
Day 2				0.018	0.012–0.024	2	0	0	0.002	0.002–0.002	2	0	2			0
Day 3				0.009	0.003–0.017	3	0	0	0.002	0.002–0.002	3	0	3	—	—	0

Table 2. *Continued*

	No. of boxes	Chrysotile Content (% by weight)		PCM (NIOSH 7400 method)					TEM (NIOSH 7400 fiber parameters)[a]					PCME (NIOSH 7402 method)		
		Average	Range	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N	N_{NR}	N_{ND}	Average	Range	N
Background (between-testing events)																
Pads	4	36	24–49	0.006	0.002–0.010	8	0	0	0.003	0.002–0.008	8	0	6	0.002	0.002–0.002	2
	6[a]	44	39–47	0.006	0.003–0.010	4	0	0	0.002	0.002–0.002	4	0	4	—	—	—
	16	36	5–60	0.007	0.004–0.009	8	0	0	0.004	0.002–0.015	8	0	4	0.004	0.001–0.008	4
	20[a]	32	20–43	0.007	0.004–0.012	4	0	0	0.005	0.002–0.014	4	0	3	0.002	0.002–0.002	1
	36[a]	30	3–42	0.005	0.004–0.006	4	0	0	0.001	0.001–0.002	4	0	4	—	—	—
Shoes	4	35	22–45	0.012	0.005–0.025	8	0	0	0.002	0.002–0.003	8	0	8	—	—	—
	6[a]	42	29–51	0.005	0.002–0.009	4	0	0	0.002	0.002–0.002	4	0	4	—	—	—
	16	31	3–47	0.007	0.004–0.013	8	0	0	0.002	0.002–0.003	8	0	7	0.001	0.001–0.001	1
	20[a]	36	5–60	0.005	0.003–0.007	4	0	0	0.002	0.001–0.003	4	0	3	0.003	0.003–0.003	1
Ambient																
Day 1				0.002	0.001–0.005	4	0	0	0.001	0.0004–0.001	4	0	4	—	—	0
Day 2				0.001	0.0008–0.001	3	0	0	0.000	0.0003–0.0005	3	0	3	—	—	0
Day 3				0.001	0.0004–0.0007	3	0	0	0.000	0.0003–0.0004	3	0	3	—	—	0

—, Not applicable; N = number of samples; N_{NR}, number of samples not readable by analytical methods; N_{ND}, number of samples below the sensitivity limit; PCME, Phase Contrast Microscopy Equivalent concentration in accordance to the NIOSH 7402 method.

[a]Fibers were counted using TEM with fiber parameters (>0.25 μm diameter, >5 μm length and ≥3:1 aspect ratio) outlined by NIOSH 7400 method.

Fiber size and morphology analysis

Air samples were also analyzed according to the International Organization for Standardization (ISO) method for characterization of type, size and morphology of fibers >5 μm in length (International Organization for Standardization, 1995). Asbestos fiber morphology was quantified by categorizing asbestos fibers of >5 μm in length as free fibers, free fiber bundles, fiber clusters or matrix fibers (including matrix fibers, bundles and dispersed arrangements). In those instances where asbestos fibers were associated with a cluster or matrix, the dimensions of the cluster or matrix structure, as well as those of the individual fibers themselves were recorded. Asbestos fibers were characterized by their morphology, as well as their size, in order to evaluate the potentially respirable proportion of airborne fibers. Long, thin fibers can penetrate the deep lung. Once in the lung, those fibers that can be fully engulfed by macrophages can be removed. Fibers <5μm in length are cleared easily by the lung and present little risk to exposed groups (Agency for Toxic Substances and Disease Registry, 2001, 2003). The US Environmental Protection Agency (US EPA) (US Environmental Protection Agency, 2003) determined that length of the fiber has little impact on the respirability up to a length of ~20 μm but that the deposition of longer fibers is inversely related to the length of longer fibers. While fibers up to 3.5 μm in diameter have been detected in the lungs of asbestos workers, fibers of this dimension may represent the very upper bound limit of respirability (Gross *et al.*, 1971; Morgan and Holmes, 1980; Timbrell, 1980, 1982). A number of studies have shown that nearly all fibers deposited in the pulmonary region of the lung are thinner than 0.7 μm (Harris and Timbrell, 1975; Sussman *et al.*, 1991a,b; Strom and Yu, 1994; Yu *et al.*, 1995). Respirable fibers (free and bundles) were therefore designated as those with diameter of ≤0.7 μm. The deposition of fibers contained within clusters or matrices was assumed to be based on the dimensions of the overall cluster or matrix structure. Depending on the size and shape of these structures, the fiber cluster or matrix may act aerodynamically more as a particle rather than a fiber. Respirability of fiber clusters or matrices was therefore evaluated in two ways: as a respirable fiber of diameter ≤0.7 μm or as a respirable particle with diameter ≤10 μm.

Collection and analysis of bulk asbestos samples

Brake material filings and dust from the counter after the box-handling activities were collected for bulk sample analysis for asbestos. Brake material from brake pads and shoes were manually filed on a separate day and location from the simulation study. Both brake filings and countertop debris were collected in separate sterilized pre-sealed plastic bags and sent to EMS Laboratories, Inc., for analysis by PLM according to NIOSH method 9002 (National Institute for Occupational Safety and Health, 1994b).

Air exchange measurements using tracer gas

Sulfur hexafluoride (SF_6) was used as a tracer gas to estimate the air exchange rate within the garage as previously described (Paustenbach *et al.*, 2006). Measurements of the gas were taken according to American Society for Testing and Materials method E741-00 (American Society for Testing and Materials International, 2001). A steady-state concentration of 1 ppm for SF_6 (Sigma-Aldrich, St Louis, MO, USA) was targeted for the tracer gas analysis. After steady state was reached, SF_6 measurements were taken in 30-s intervals with a MIRAN SapphIRe-XL Analyzer (Thermo-Electron Corporation, Hayward, CA, USA) for ~1 h. The air exchange in the garage was calculated using the concentration decay (optional regression) test method of plotting the natural logarithm of SF_6 concentration over time (American Society for Testing and Materials International, 2001).

Data and statistical analyses

Descriptive statistics were calculated for both PCM and TEM airborne fiber concentration measurements. Analytical sensitivity limits, also referred to as limits of detection, were estimated based on the presumption that one fiber could be counted within 100 microscopic fields for a given volume of air sampled. Results below the analytical sensitivity limit were entered using a value equal to one-half the sensitivity limit. PCM measurements were adjusted for asbestos fiber content according to NIOSH method 7402, which specifies multiplying the ratio of asbestos fibers to total fibers observed in the TEM analysis by the PCM fiber concentration (National Institute for Occupational Safety and Health, 1994c). The ratios of asbestos to total fibers (asbestos and non-asbestos fibers) were based on TEM fiber counts from the same filters the PCM fiber counts were obtained. In this study, the PCM measurements adjusted by the ratio of asbestos versus total fibers were referred to as 'phase contrast microscopy equivalent (PCME)' airborne asbestos concentrations. In cases where the PCM result was below the analytical sensitivity limit, but asbestos fibers were detected in the corresponding TEM measurement, a value of one-half the PCM analytical sensitivity limit was substituted and multiplied by the ratio of asbestos fibers to total fibers observed by TEM. In circumstances where PCM measurements were above the sensitivity limit, but asbestos fibers were not detectable by TEM, a PCME asbestos concentration was not calculated. In addition to using TEM for NIOSH

7202 and ISO, TEM was also used to measure an asbestos fiber concentration using the same fiber parameters utilized by NIOSH 7400.

All statistical analyses were performed using Microsoft Excel. Correlation coefficients (r) were used to assess the association between the number of boxes of brakes handled and airborne asbestos concentrations.

RESULTS

Air exchange measurements using SF_6 as a tracer gas showed rates of 0.83 air exchanges per hour on 27 July 2004 during Phase I testing and 0.39 and 0.66 air exchanges per hour on 5 and 6 November 2005 during Phase II testing. These low exchange rates were expected, considering that no active ventilation system was present in the building, and all doors/windows were kept closed. These air exchange rates were consistent with those reported previously for this building by Paustenbach *et al.* (2006) and are low compared to what would be expected in most auto repair facilities (four to six air exchanges per hour) (American Society of Heating Refrigerating and Air Conditioning Engineers Inc., 1991; Paustenbach *et al.*, 2006).

Asbestos bulk sample analyses

Detailed information regarding the number of boxes of brakes, the type of brakes and the average chrysotile composition of the brakes used in each sampling event is provided in Tables 1 and 2. Bulk sample analysis revealed that the average chrysotile asbestos content in the brake pads and shoes ranged from 27 to 45% for the various simulation events in Phase I testing and ranged from 31 to 36% for events in Phase II testing. Individual measurements of chrysotile asbestos in brake pads and shoes ranged from 3 to 60%. PLM analysis did not indicate the presence of amphibole asbestos fibers in any of the brake pads or shoes. Bulk sample analysis of the dust that accumulated on the countertop during the unpacking and repacking of boxes of brakes indicated average chrysotile asbestos concentrations ranging from 2 to 8%.

Airborne asbestos—short-term exposures

The number and types of asbestos samples collected during each box-handling scenario, as well as the airborne asbestos concentrations as determined by PCM and TEM, are presented in Tables 1 and 2. A total of 214 air samples were collected for different scenarios associated with the unpacking and repacking of boxes of brake pads and shoes, including 80 personal samples (fifty-four 15 min, ten 30 min and sixteen 100 min), 56 bystander samples, 8 indoor background samples prior to any testing, 26 remote area samples, 52 indoor background samples between testing events and 10 outdoor ambient samples. Of the samples collected, only two personal lapel samples could not be analyzed due to particulate interferences and/or excessive loading. Comparisons of right and left lapel samples showed no difference, and because they were viewed as replicate samples, the right and left lapel samples were averaged for each simulation event. Table 3 summarizes the total number of samples collected and the mean and range of PCM and TEM analytical sensitivity limits for each type of sample. While PCM, TEM and PCME airborne fiber concentrations are summarized in Tables 1 and 2, only PCME asbestos concentrations are discussed in the text.

A number of observations can be derived from the study results. First, airborne asbestos concentrations generally increased with the number of boxes handled (Figs 5 and 6). This relationship was linear (Figs 5 and 6) with a strong positive correlation between the mean 15-min worker asbestos concentration and the number of boxes handled for both pads and

Table 3. Estimated analytical sensitivity limits (f cc^{-1}) for asbestos for each type of sample collected during various box handling activities (testing I and II)

	PCM (NIOSH 7400 method)			TEM (NIOSH 7400 fiber parameters)[a]		
	N	Average	Range	*N*	Average	Range
Worker—15 min	54	0.003	0.002–0.004	54	0.008	0.001–0.024
Worker—30 min	10	0.001	0.001–0.001	10	0.003	0.001–0.005
Worker—100 min	17	0.002	0.001–0.003	17	0.004	0.002–0.007
Bystander	68	0.002	0.001–0.003	68	0.003	0.002–0.005
Background between testing events	56	0.002	0.001–0.003	56	0.004	0.003–0.005
Background before testing	8	0.001	0.001–0.002	8	0.002	0.001–0.004
Remote area	32	0.001	0.001–0.002	32	0.003	0.001–0.021
Ambient	10	0.001	0.0003–0.001	10	0.001	0.001–0.002

N, number of samples.
[a]Fibers were counted using TEM with fiber parameters (>0.25 μm diameter, ≥5 μm length and ≥3:1 aspect ratio) outlined by NIOSH 7400 method.

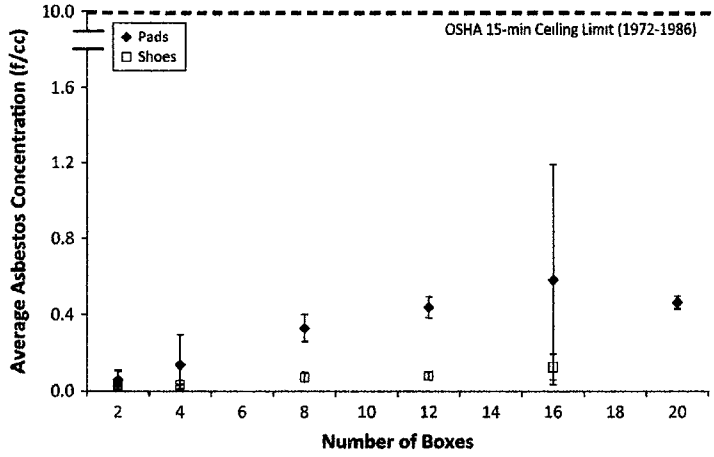


Fig. 5. Airborne asbestos concentrations (15-min PCME) for worker handling different numbers of boxes of brake pads and shoes.

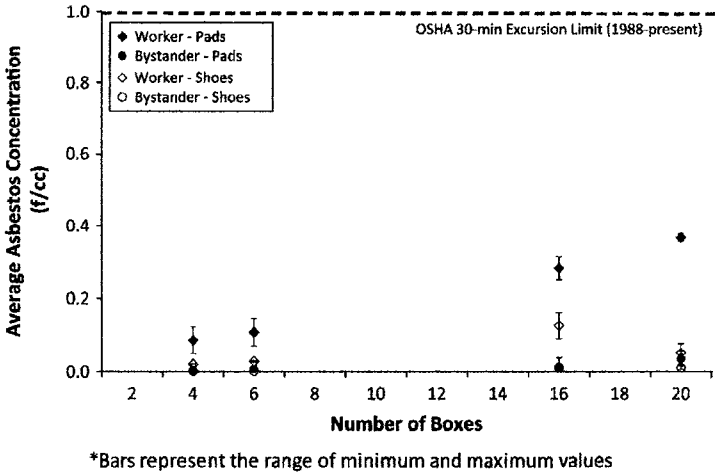


Fig. 6. Comparison of airborne asbestos concentrations (30-min PCME) for worker and bystander samples during the handling of different numbers of boxes of brake pads and shoes.

shoes (brake pads $r = 0.91$ and brake shoes $r = 0.98$). For worker samples collected over a 30-min time period, a strong association existed between the number of boxes of brake pads and the airborne asbestos concentrations ($r = 0.99$), but not with the number of boxes of brake shoes ($r = 0.61$). This trend was more apparent in the personal samples than in the area samples collected at bystander locations (Table 1, Fig. 6). The number of boxes handled appeared to be associated with increasing bystander PCME concentrations for brake shoes, as well as brake pads. No such trend was observed at remote area locations, 25–30 ft from box-handling activity.

Second, the type of brake material in each box influenced airborne asbestos concentrations. Although the brake pad and shoe asbestos content was similar, it was consistently observed that handling brake pad boxes resulted in higher airborne asbestos concentrations within the breathing zone of the worker than handling brake shoe boxes. Specifically, it was observed that boxes of brake pads produced two to seven times higher airborne asbestos concentrations (PCME) in a 15- or 30-min time period for the worker compared to the concentrations created by boxes of brake shoes (Table 1, Figs 5 and 6).

Third, airborne asbestos concentrations in the worker's breathing zone were greater than those observed at the bystander locations (Table 2, Fig. 6) and airborne asbestos concentrations at bystander locations were higher than those observed at remote area locations. For example, average 30-min samples collected on the lapel of the worker ranged from 0.086 to 0.368 f cc^{-1} (PCME) for handling 4–20 boxes of brake pads and 0.021 to 0.126 f cc^{-1} (PCME) for the same number of boxes of brake shoes (Table 2, Fig. 4). At the bystander sampling locations for the same number of boxes of brakes, average PCME airborne asbestos concentrations were observed at 0.004–0.035 f cc^{-1} for brake pads and 0.002–0.011 f cc^{-1} for brake shoes. No difference

was apparent between bystander (brake pads average 0.004 f cc^{-1}; brake shoes average 0.002 f cc^{-1}) and remote (brake pads average 0.006 f cc^{-1} and brake shoes average 0.001 f cc^{-1} areas when only four boxes of brakes pads were handled. Higher airborne asbestos concentrations, however, were observed at bystander (brake pads average 0.010 f cc^{-1} and brake shoes 0.011 f cc^{-1}) locations compared to remote area (brake pads average 0.005 f cc^{-1} and brake shoes average 0.001 f cc^{-1}) locations when 16 boxes of brakes were unpacked and repacked. Although remote area airborne asbestos concentrations were higher during the handling of brake pad boxes compared to brake shoes, the samples collected in the remote area locations were not greatly influenced by the various box-handling tasks. Comparisons demonstrated similar airborne asbestos concentrations for the remote area samples (range of averages 0.001–0.017 f cc^{-1}) collected during the box-handling tasks when compared to the background samples (range of averages 0.001–0.004 f cc^{-1}) collected in between the testing events.

While it is not surprising that the airborne asbestos measurements from the worker's lapel were greater than those observed at bystander sample locations, it is worth noting that asbestos concentrations decreased quickly and significantly in the breathing zone of the worker after box-handling activities ceased. Most boxes of brakes (all but two brake shoe boxes in Phase II testing) were handled within the first 15 min. Therefore, the second 15-min sample represents the concentration of airborne asbestos that remains in the air after box-handling activities cease. Comparison of the first and second 15-min samples showed a decrease in airborne asbestos concentrations for the handling of brake pad boxes, but not for brake shoe boxes. Specifically, average airborne asbestos concentrations decreased from 0.356 to 0.021 f cc^{-1} after unpacking and repacking of brake pads ceased, and concentrations decreased from 0.030 to 0.013 f cc^{-1} after unpacking and repacking of brake shoe boxes ceased.

Fourth, personal airborne asbestos concentrations during box-handling tasks were higher than those measured during cleanup and clothes-handling tasks. Cleanup of dust which had accumulated on the work countertop and handling of clothes which had been worn while boxes were unpacked and repacked showed airborne asbestos concentrations of 0.004 and 0.011 f cc^{-1} for the worker and 0.002 and 0.010 f cc^{-1} for the bystander locations, respectively. Comparisons showed that worker exposures resulting from clothes-handling activities (average 0.011 f cc^{-1}) were similar to measurements collected during cleanup (average 0.004 f cc^{-1}); both activities were comparable to bystander (clothes-handling average 0.010 f cc^{-1} and cleanup average 0.002 f cc^{-1}) and remote area (clothes-handling average 0.002 f cc^{-1} and cleanup average 0.003 f cc^{-1}) concentrations measured during box-handling activities.

Fifth, background airborne asbestos concentrations measured between testing events compared to those measured prior to the study showed that results from each testing event were independent. Background measurements collected prior to any testing did not show any detectable asbestos fibers by TEM. Of the 52 background samples collected in between box-handling testing events, only nine showed a measurable concentrations of asbestos. The samples in which asbestos fibers were detected resulted in average PCME airborne asbestos concentrations ranging from 0.001 to 0.004 f cc^{-1}. Given that asbestos measurements between testing events were low or below the sensitivity limit (e.g. 83% were <0.001–0.008 f cc^{-1}), concentrations of asbestos from one testing event did not impact the results of successive testing events.

Ambient contributions to background asbestos concentrations were also characterized. Although average PCM airborne fiber concentrations for ambient air samples ranged from 0.001 to 0.002 f cc^{-1}, no asbestos fibers were detected by TEM. The observed PCM concentrations were slightly less than the ambient air concentrations reported by Paustenbach *et al.* (2006) and, in general, were consistent with background concentrations reported by the Agency for Toxic Substances and Disease Registry and US EPA for typical US cities (Agency for Toxic Substances and Disease Registry, 2001; US Environmental Protection Agency, 2003; Paustenbach *et al.*, 2006).

Airborne asbestos—8-h TWA exposures

Measurements collected during box-handling, clothes-handling and cleanup events were used to estimate 8-h TWA exposures for a worker handling 4, 16 and 40 boxes of brakes in a workday. In Phase II testing, long-term samples were collected in consecutive 100-min intervals, which encompassed the testing event (~30 min), ventilation period (~30 min) and background characterization (~30 min). Air concentrations during the cessation of these tasks were assumed to be equivalent to remote area asbestos concentrations (collected during testing events). Based on the 100-min samples collected during the box-handling activities, 8-h TWA asbestos exposures for workers handling 4, 16 or 40 boxes of brakes over a workday were estimated to be below the current OSHA PEL for asbestos. Eight-hour TWAs for workers handling 4 or 16 boxes of asbestos-containing brakes ranged from 0.002 to 0.021 f cc^{-1}, approximately one-quarter to four-hundredths below the OSHA PEL of 0.1 f cc^{-1} for asbestos. Eight-hour TWA worker exposures handling up to 40 boxes of brakes in a workday was 0.063 f cc^{-1}, nearly one-half of the current OSHA PEL.

Fiber size and morphology

Fiber size and morphology were assessed in the personal worker samples collected during box-handling, cleanup and clothes-handling activities from Phase II testing. Results showed that 50–59% of the fibers counted for the different activities were free fibers or bundles, 9–33% were fiber clusters and 16–31% were associated with a matrix (Table 4). Assuming, though, that only fibers <0.7 μm in diameter can reach the deep lungs, then only 30% of the total fibers were respirable considering the fiber size and morphology characteristics. It was also observed that <7% (specifically 0–7%) of the total fibers counted within this size range were respirable and had a fiber length >20 μm. If the criterion for respirability was extended to 3 μm in diameter, 33–56% of the asbestos fibers (free or bundles) would therefore be considered respirable. The majority of fibers associated with a cluster or a matrix were too large to be considered as respirable fibers, whereas 0–27% could be classified as respirable particles.

DISCUSSION

This study was conducted to assess possible exposures to airborne asbestos during unpacking and repacking of boxes of asbestos-containing brake pads and shoes (for vehicles ca. 1946–80), as well as to understand potential asbestos exposures associated with other related activities such as cleanup and clothes handling. In addition to those already discussed, there are a few other observations that can be made from this simulation study. Not surprisingly, for example, we observed that there were physical limitations to the number of boxes that could be handled within a certain time period. We found that handling ~16 to 20 boxes in 15 or 30 min represented a maximum physical limit.

It was interesting to observe higher airborne asbestos concentrations associated with the handling of brake pad boxes compared to brake shoe boxes. Due to the curvature of the brake shoe and the fact that these parts were often packed tightly, it is possible that the boxes of brake shoes produced less airborne asbestos because there was less of an opportunity for the brake parts to rub against one another during shipment. In addition, it is noteworthy that the shipment of the boxes prior to the commencement of Phase II testing appeared to produce dust to such an extent that the airborne asbestos concentrations measured in Phase II were similar to those produced from comparable events in Phase I. The difference in air exchange rates between days of testing also did not appear to have an effect on worker or bystander exposures, thus emphasizing that activities have the greatest impact on exposures in the near field.

The handling and cleaning of contaminated work clothing worn in some occupational environments have been suggested as a possible source of para-occupational or 'take-home' chemical exposure. Studies that have reported exposure through this possible secondary exposure pathway include industries where beryllium, lead or even asbestos (e.g. insulation workers) exposures in the workplace were excessive. For example, Eisenbud *et al.* (1949) found mean

Table 4. Size and morphology distribution of fibers detected in personal workers samples collected during various box handling activities

Fiber structure classification	*N*	Total fibers (%)	Percent fibers (%) classified as fiber or particle with dimensions					
			<0.7 μm width		<3 μm width		<10 μm width	
			>5 μm length	>20 μm length	>5 μm length	>20 μm length	>5 μm length	>20 μm length
Box-handling activities								
Total fibers	1128	—	—	—	—	—	—	—
Free fiber/bundle	667	59.1	35.1	4.7	55.9	8.6	—	—
Fiber clusters	109	9.7	0.0	0.0	2.0	0.8	7.0	2.7
Matrix disperse	352	31.2	0.7	0.0	4.6	0.8	23.4	4.2
Cleanup activities								
Total fibers	15	—	—	—	—	—	—	—
Free fiber/bundle	8	53.3	33.3	6.7	53.3	6.7	—	—
Fiber clusters	4	26.7	0.0	0.0	6.7	0.0	26.7	0.0
Matrix disperse	3	20.0	0.0	0.0	0.0	0.0	20.0	6.7
Clothes-handling activities								
Total fibers	6	—	—	—	—	—	—	—
Free fiber/bundle	3	50.0	33.3	0.0	33.3	0.0	—	—
Fiber clusters	2	33.3	0.0	0.0	0.0	0.0	0.0	0.0
Matrix disperse	1	16.7	0.0	0.0	0.0	0.0	16.7	0.0

air concentrations of 500 μg beryllium m^{-3} when the clothing of beryllium manufacturing workers was shaken out. Piacitelli *et al.* (1997) found elevated lead concentrations in the vehicles and homes of lead-exposed construction workers. Some persons, who live in the homes of workers, exposed to free asbestos fibers developed asbestos-related disease (Lieben and Pistawka, 1967; Anderson *et al.*, 1976; Li *et al.*, 1978; Anderson *et al.*, 1979; Epler *et al.*, 1980; McDonald and McDonald, 1980; Joubert *et al.*, 1991; Magnani *et al.*, 1993). Generally, workers in asbestos manufacturing, mining, and shipyard industries are exposed to very high airborne concentrations of asbestos and come in direct contact with large amounts of bulk asbestos and, in the majority of cases, amphibole asbestos. The 'take-home' exposure of other household members (so-called secondary exposure or para-occupational exposure) is thought to occur as a result of bringing very dusty work clothing into the home, which was usually contaminated due to daily contact to bulk or raw asbestos. Although all exposures associated with handling work clothes worn during box-handling activities were extremely low, it was felt that this issue deserved greater characterization as it has implications for both historical and current asbestos exposures of a group of individuals not previously studied.

While we were interested in exposures distant (bystander and remote) from the primary activity, it was not intended as a part of the sample design to characterize exposures associated with settled asbestos on work surfaces, but rather associated with the box-handling activity itself. The fact that asbestos was found in the settled dust on the countertop as a result of handling boxes of brakes, however, illustrates how such work might contribute to the presence of asbestos on nearby work surfaces. It should be noted that the dust which settled on the counter surface was present only in the immediate vicinity to the box-handling activities and consisted of ~5% asbestos as compared to ~30% in the original brake material. If the settled dust was not properly cleaned after work activities, theoretically there could be a potential for dispersal to locations distant from the original work activity. In regards to results associated with the box-handling activities, it is likely that closing up the facility resulted in higher worker and bystander exposures than if the facility was fully ventilated. It is also possible that some fibers remain in the air after the work activities ceased. However, our results show that airborne fibers detected in the 15 min following the cessation of box-handling activities were significantly reduced compared to those generated during the box-handling activities and approached background concentrations as measured in between the testing events.

It has been well established that the precision of airborne fiber concentrations by counting fibers on a membrane filters is dependent on the fiber density and proportion of filter surface area (e.g. microscope fields) examined with statistical uncertainties generally being inversely proportional to the fiber density (Ogden 1982; Johnston *et al.*, 1982; Cherrie *et al.*, 1986; Lange *et al.*, 1996). Some researchers have suggested that the variations of low asbestos count data are attributed to a psychological incentive for analysts to search harder for fibers on low-density samples (Cherrie *et al.*, 1986). It has been reported that the accuracy is not greatly improved for counts beyond 50 fibers and thus has been recommended that at least 50 fibers be counted and the number of fields be only limited where the airborne fiber concentrations are so low that the accuracy is no longer important (Ogden 1982). These concepts have been incorporated into the current NIOSH method for asbestos (National Institute for Occupational Safety and Health, 1994a), where 100 fibers or 100 microscope fields, whichever criterion is met first, are counted. For the majority of the worker samples collected in this simulation study, >50 fibers were counted within the prescribed 100 microscope fields, whereas far fewer fibers (<10–20 fibers) were observed in samples collected in bystander or remote area locations. The confidence limits would, as a result, be expected to be narrower for personal compared to those for area airborne asbestos concentrations. This trend has been supported in the literature by comparisons of personal and area asbestos fiber concentrations measured during asbestos insulation, tile and transite abatement operations, which showed that airborne asbestos concentrations were not normally distributed and area measurements were more variable compared to personal fiber measurements (Lange *et al.*, 1996).

In our study, however, the range or variability of asbestos fiber concentrations within a given event and location (e.g. worker and bystander) appeared relatively narrow with the exception of handling 16 boxes of brake pads (Fig. 5). The range of asbestos concentrations across scenarios (e.g. brake type, worker versus bystander) also appeared relatively constant. Possible reasons for this limited variability within or across events or sample locations potentially include (i) the controlled repetitive conditions under which the simulated tasks were performed, (ii) similarity of airborne concentrations across similar spatial distances (e.g. right and left lapel and concentric area samples) and (iii) consistent sample analysis under one laboratory and by similarly trained and certified microscopists. Despite these observations, asbestos counts at low concentrations are generally not normally distributed and variance usually depends on the airborne concentration, precluding the use of statistical comparisons that rely on normality and symmetrical distributions. With this in mind, data were presented in

a descriptive manner and statistical comparisons were not attempted.

The data collected in this simulation study are believed to capture the plausible range of box-handling scenarios (i.e. number of boxes, type of brakes and distance from activity) for a brake mechanic, auto parts supplier or warehouse parts picker, in addition to evaluating potential exposure associated with handling work clothes or performing clean-up activities. In summary, the short-term airborne asbestos concentrations measured for both a worker unpacking and repacking of boxes of asbestos-containing brakes, as well as a bystander working in the vicinity of such activity were below both the current OSHA excursion limit for asbestos and all previous US occupational asbestos standards. The industrial hygiene data presented here should therefore prove useful for retrospective and current exposure assessments of individuals and hazard assessments of work activities which involve the handling of asbestos-containing brakes in a variety of workplace settings.

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