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Airborne Asbestos Concentrations Associated with Heavy Equipment Brake Removal

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Asbestos-containing brake linings were used in heavy-duty construction equipment such as tractors, backhoes, and bulldozers prior to the 1980s. While several published studies have evaluated exposures to mechanics during brake repair work, most have focused on automobiles and light trucks, not on heavy agricultural or construction vehicles. The purpose of this study is to characterize the airborne concentration of asbestos to workers and bystanders from brake wear debris during brake removal from 12 loader/backhoes and tractors manufactured between 1960 and 1980. Asbestos content in brake lining (average 20% chrysotile by polarized light microscopy) and brake wear debris [average 0.49% chrysotile by transmission electron microscopy (TEM)] was also quantified. Breathing zone samples on the lapel of mechanics (n = 44) and area samples at bystander (n = 34), remote (n = 22), and ambient (n = 12) locations were collected during 12 brake changes and analyzed using phase contrast microscopy (PCM) [National Institute for Occupational Safety and Health (NIOSH) 7400] and TEM (NIOSH 7402). In addition, the fiber distribution by size and morphology was evaluated according to the International Organization for Standardization method for asbestos. Applying the ratio of asbestos fibers:total fibers (including non-asbestos) as determined by TEM to the PCM results, the average airborne chrysotile concentrations (PCM equivalent) were 0.024 f/cc for the mechanic and 0.009 f/cc for persons standing 1.2–3.1 m from the activity during the period of exposure (~0.5 to 1 h). Considering the time involved in the activity, and assuming three brake jobs per shift, these results would convert to an average 8-h time-weighted average of 0.009 f/cc for a mechanic and 0.006 f/cc for a bystander. The results indicate that (i) the airborne concentrations for worker and bystander samples were significantly less than the current occupational exposure limit of 0.1 f/cc; (ii) ~2% of respirable fibers were >20 μm in length; and (iii) ~95% of chrysotile in the brake linings degraded in the friction process. The industrial hygiene data presented here should be useful for conducting retrospective and current exposure assessments of individuals, as well as hazard assessments of work activities that involve repairing and replacing asbestos-containing brakes in heavy construction equipment.

Keywords: asbestos; brakes; heavy equipment; industrial hygiene

INTRODUCTION

Once thought to be a ‘miracle’ mineral, asbestos gained widespread use beginning in the early 1900s, and has been reportedly incorporated in some 3000 different products because of its low cost and desirable qualities, such as heat and fire resistance, wear and friction characteristics, tensile strength, heat, electrical and sound insulation, adsorption capacity, and resistance to chemical and biological attack [Agency for Toxic Substances and Disease Registry (ATSDR), 2001]. For these reasons, asbestos, specifically chrysotile, was used for many decades by the automobile, heavy equipment, crane, railroad, and airline industries as a component of brakes. Chrysotile’s frictional characteristics, such as good tensile strength, durability, flexibility, and heat resistance, provided the auto industry with a friction material that could withstand extreme temperatures, pressure, and stress (Skinner *et al.*, 1988; Paustenbach *et al.*, 2004; Maines, 2005). These characteristics were particularly necessary for safety, as automobiles throughout the 20th century became larger, heavier, and faster (Harper, 1998).

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Because of regulatory and societal concerns about the health effects caused by its exposure, asbestos use in the USA has precipitously declined since the mid-1970s (ATSDR, 2001; Maines, 2005; dos Santos Antao *et al.*, 2009; Kelly and Matos, 2009). Over the last 30 years, significant attention has been paid to evaluating asbestos exposures and the potential risk of asbestos-related diseases among automobile garage mechanics (Paustenbach *et al.*, 2004). Chrysotile asbestos was also used as a friction material in heavy construction equipment, but potential asbestos exposures to mechanics repairing brakes on such equipment has been less well studied and understood (Boelter *et al.*, 2007).

Although the asbestos content in automobile brakes is generally between 30 and 50% (Lynch, 1968; Anderson *et al.*, 1973; Madl *et al.*, 2008), heat and pressure, such as that exerted during vehicle braking, can cause chrysotile asbestos to degrade to non-fibrous amorphous decomposition products, as well as form other non-fibrous minerals, such as forsterite and olivine (Jacko *et al.*, 1973; Candela *et al.*, 2007). The dehydration or retention of water in chrysotile decomposition products has been shown to influence the extent to which forsterite is formed under heat and pressure (Candela *et al.*, 2007). It has been suggested, however, that friction during mechanical braking disaggregates mineral bundles in the brake lining, which liberates water and results primarily in amorphous, non-fibrous, magnesium silicate degradation products (Candela *et al.*, 2007). Because the elemental ratios and X-ray diffraction (XRD) patterns of chrysotile and these degradation products are similar, transmission electron microscopy (TEM) is often necessary to identify fibrous structures of chrysotile at low bulk concentrations. Using microscopy, historical studies have shown that brake wear debris collected from an automobile dynamometer or drum brakes contains on average between 0.02 and 4.5% asbestos, with the majority of wear debris samples containing <1% chrysotile (Hickish and Knight, 1970; Luxon, 1970; Anderson *et al.*, 1973; Jacko *et al.*, 1973; Rohl *et al.*, 1977; Rowson, 1978; Williams and Muhlbaier, 1982; Cha *et al.*, 1983; Sheehy *et al.*, 1989). While these studies do not directly measure forsterite or other degradation products in brake wear debris, the breakdown of chrysotile is inferred by comparing asbestos content in the lining to that in brake emissions or accumulated dust in the brake assembly.

Although it has been assumed that the forces that convert chrysotile in automotive brakes are at work during the use of heavy equipment (e.g. dozers, backhoes, and graders), little work has been conducted to confirm the degradation of chrysotile to forsterite or an amorphous form. This matter is of particular interest, since it is not well understood how the different speeds or weights of heavy construction equipment, compared to passenger automobiles, can influence the frictional mechanisms, and thus, by extension, the conversion to forsterite or other non-asbestos amorphous materials. Understanding this matter will inform hygienists as to whether workers conducting brake repairs on heavy construction equipment during the period between the 1950s and the 1980s or in modern times, were exposed to appreciable concentrations of asbestos.

Only one published study has evaluated potential asbestos exposures to mechanics repairing heavy construction equipment brakes (Boelter *et al.*, 2007). In this paper, personal short-term (30 min) and long-term [8-h time-weighted average (TWA)] samples for airborne asbestos were collected during repair activities involving the replacement of asbestos-containing products (i.e. engine gaskets, brake, and clutch linings) in a dozer, grader, and two loaders. Area samples were also analyzed to characterize potential exposures to a bystander nearby these activities. The asbestos-containing products removed from the construction equipment, as well as brake wear debris were analyzed for asbestos content. While this study filled an important data gap, it did not address directly whether chrysotile asbestos was degraded to a similar extent as that observed with passenger automobiles, and it only characterized a limited number of equipment representing a wide array of types and brake assembly configurations (e.g. disc, drum, and band). Complete enclosure of a brake system, size of asbestos-containing friction lining, location, and access configuration in relation to the mechanic's breathing zone, as well as method of maintenance work are all likely to influence occupational exposures to airborne asbestos during brake repair activities. With these factors in mind and without additional information, it was uncertain how the information presented in Boelter *et al.* (2007) might compare to results from other types of heavy construction equipment.

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 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, 1979; Li *et al.*, 1978; Epler *et al.*, 1980; McDonald and McDonald, 1980; Joubert *et al.*, 1991; Magnani *et al.*, 1993).

Historically, workers in asbestos manufacturing, mining, and shipyard industries were exposed to very high airborne concentrations of asbestos and came 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 into the home very dusty work clothing that may have been contaminated due to daily contact with bulk or raw asbestos. Although exposures associated with handling work clothes worn during brake repair work were expected to be extremely low, we 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.

Since a broader range of data would increase the confidence in the preliminary study, we evaluated a number of vehicles for the purpose of understanding the extent of potential conversion of chrysotile asbestos in brake linings to forsterite and amorphous materials. We also characterized worker and bystander exposures to airborne asbestos during brake removal in various types of heavy construction equipment and assessed the potential of take-home exposures from clothing worn during the brake removal activities. In this study, worker and environmental exposures were evaluated during the maintenance of 12 pieces of heavy construction equipment with similar brake assembly configurations. Because of the relatively large number of pieces of equipment tested with similar brake assemblies, the influence of the extent of equipment use (e.g. hours of operation), methods of brake removal used by different mechanics, oily versus dry brake assemblies, and type of equipment (loader backhoe and tractor) on the variability of the airborne asbestos measurements could be assessed. In addition, short-term samples were collected and 8-h TWA exposures were calculated to compare with historical and current occupational exposure limits for asbestos. The fiber size and morphology distributions were also measured to characterize the proportion of respirable airborne fibers, free or associated with a matrix, released during brake removal activities. It is anticipated that this information will not only provide useful information regarding potential historical exposures experienced by mechanics conducting brake repair work on heavy construction equipment, but will also provide a basis for correlating this information to the exposures and health experience of automobile mechanics.

METHODS

Description of backhoe/tractor brake assemblies

Table 1 provides a summary of the type of vehicles evaluated in the study, as well as the years during which the equipment was manufactured, total hours of operation, and the facility in which the brake repair work was performed. Each of these vehicles contained a left and right drum and disc brake assembly (Fig. 1), each of which possessed an inner and outer drum lining and two band linings comprised friction material. Equipment that potentially had asbestos-containing linings was selected for the study based on the age of the equipment and repair maintenance records provided by the equipment owners. A total of 12 pieces of equipment (two tractors and 10 loader backhoes) manufactured between 1960 and 1980 and operated between 943 and 6741 h were included in this study. It should be noted that the hours of operation for each piece of equipment may not necessarily reflect the total number of hours on the brakes; however, measurements of lining thickness for each brake assembly showed significant brake wear. It was not determined until after the testing through bulk sample analysis whether the equipment contained asbestos brake linings. In fact, all vehicles tested did have asbestos in the friction materials.

Description of test site and study conditions

Brake repairs were performed at two heavy-duty equipment service centers on six different days over a period of 17 months (April 2005 to September 2006); 5 days were spent at one center located in Stockton, CA, and the other day at a center in Big Rock, IL (Table 1). These service centers were selected because they were (and continue to be) active repair facilities for heavy-duty construction equipment, including tractors and backhoe loaders. The weather conditions in Stockton were generally sunny and clear, with temperatures ranging from 21 to 27°C during the 5 days of testing. The Big Rock testing took place during cloudy conditions, with temperatures ~15.6°C.

All work was performed by two currently employed mechanics (one in Stockton and one in Big Rock), who had between 15 and 30 years of professional experience repairing heavy-duty construction and agricultural equipment. The mechanics performed the brake removal in the same manner they had reportedly used throughout their careers. The service shop in Stockton, CA, was relatively large, with four service bay doors and approximate dimensions of 30 m wide by 14.9 m deep, with a ceiling height of 6.1 m (Fig. 2). The facility in Big Rock, IL, was less than half the size of the service center in Stockton, CA, with only one service bay door and approximate dimensions of 14.3 m wide by 11.9 m deep with a 6.1-m ceiling (Fig. 3). All service bay and entry doors were closed while the brake removal was being conducted. In addition, neither repair shops were equipped with any active heating, air conditioning, or ventilation systems.

Prior to conducting the study, permission from a medical institutional review board (IRB) was

Table 1. Summary of equipment tested and bulk sample asbestos concentrations of brake linings and wear debris

Equipment	Date	Equipment type	Hours	Model type	Site	Air exchange (ACH)	Average thickness (mm) by assembly		Brake linings															Brake wear debris
							Left	Right	XRD (% weight chrysotile)					PLM (% area chrysotile)					TEM (% weight chrysotile)					Decomposition
									n	*n* (ND)	Avg	SD	Range	*n*	*n* (ND)	Avg	SD	Range	*n*	*n* (ND)	Avg	SD	Range	%
Eq1	13 April 2005	580C	4360	Backhoe	Stockton	—	4.33	4.31	8	0	32	4	25–37	8	0	40	8	24–54	2	0	0.150	0.071	0.1–0.2	99.5
Eq2	14 September 2005	580C	1232	Backhoe	Stockton	0.6	4.46	4.26	8	0	19	3	15–22	8	0	26	8	20–35	2	0	0.009	0.001	0.008–0.009	100.0
Eq3	16 September 2005	580	1562	Tractor	Big Rock	0.6	4.76	4.73	8	0	23	3	19–28	8	0	28	5	20–35	2	0	0.075	0.021	0.06–0.09	99.7
Eq4	16 September 2005	430	943	Tractor	Big Rock	0.6	4.11	4.42	8	0	29	4	24–36	8	0	33	10	15–40	2	0	0.450	0.354	0.2–0.7	98.5
Eq5[a]	14 November 2005	580C	6230	Backhoe	Stockton	0.66	2.57	3.15	8	1	14	6	1–19	8	1	15	8	0.5–25	2	2	0.050	0.000	0.05–0.05	99.6
Eq6[a]	14 November 2005	580C	3600	Backhoe	Stockton	0.66	4.09	4.42	8	4	8	9	1–25	8	5	8	12	0.05–30	2	2	0.050	0.000	0.05–0.05	99.4
Eq7	14 November 2005	580C	6741	Backhoe	Stockton	0.66	3.41	4.36	8	0	17	3	14–22	8	0	19	2	15–20	2	1	0.825	1.096	0.05–1.6	95.1
Eq8[b]	14 June 2006	580C	3264	Backhoe	Stockton	1.55	4.04	4.13	8	0	27	7	18–39	8	0	17	6	10–27	2	0	0.700	0.141	0.6–0.8	97.4
Eq9[b]	14 June 2006	580CK	2744	Backhoe	Stockton	1.55	4.43	4.56	6	2	15	12	1–29	6	0	15	12	0.5–28	2	0	3.015	4.221	0.03–6	79.2
Eq10	20 September 2006	580C	2743	Backhoe	Stockton	1.28	4.62	3.76	8	2	20	13	1–36	8	2	25	25	0.5–70	2	0	0.085	0.021	0.07–0.1	99.6
Eq11	20 September 2006	580B	4188	Backhoe	Stockton	1.28	4.46	4.36	8	0	19	4	12–25	8	0	16	6	6–25	2	0	0.035	0.021	0.02–0.05	99.8
Eq12	20 September 2006	580C	5320	Backhoe	Stockton	1.28	4.31	2.18	8	5	1	0	1–2	8	4	1	1	0.5–3	4	0	0.435	0.422	0.04–0.8	65.2
Eq1–Eq12									**12**		**19**	**3.8**	**1–39**	**12**		**20**	**6.1**	**0.05–70**	**12**		**0.49**	**1.20**	**0.008–6**	**94.4**

ND, non-detectable; Avg, average; SD, standard deviation; ACH, air exchanges per hour. Non-detectable samples were entered as one-half the sensitivity limit. Figures in bold represent average and range for all equipment.

[a] Asbestos was not detected in both band and drum lining on right assembly.

[b] No right drum lining was present.

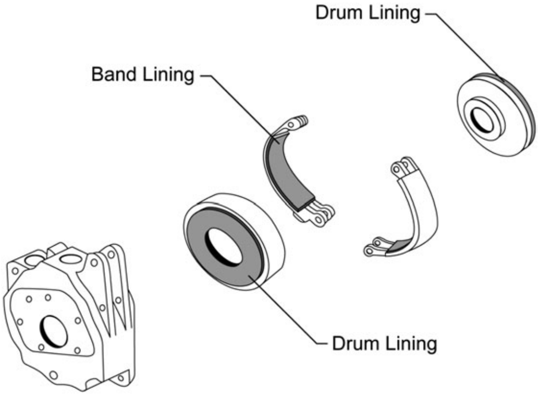


Fig. 1. Heavy equipment dry brake systems diagram.

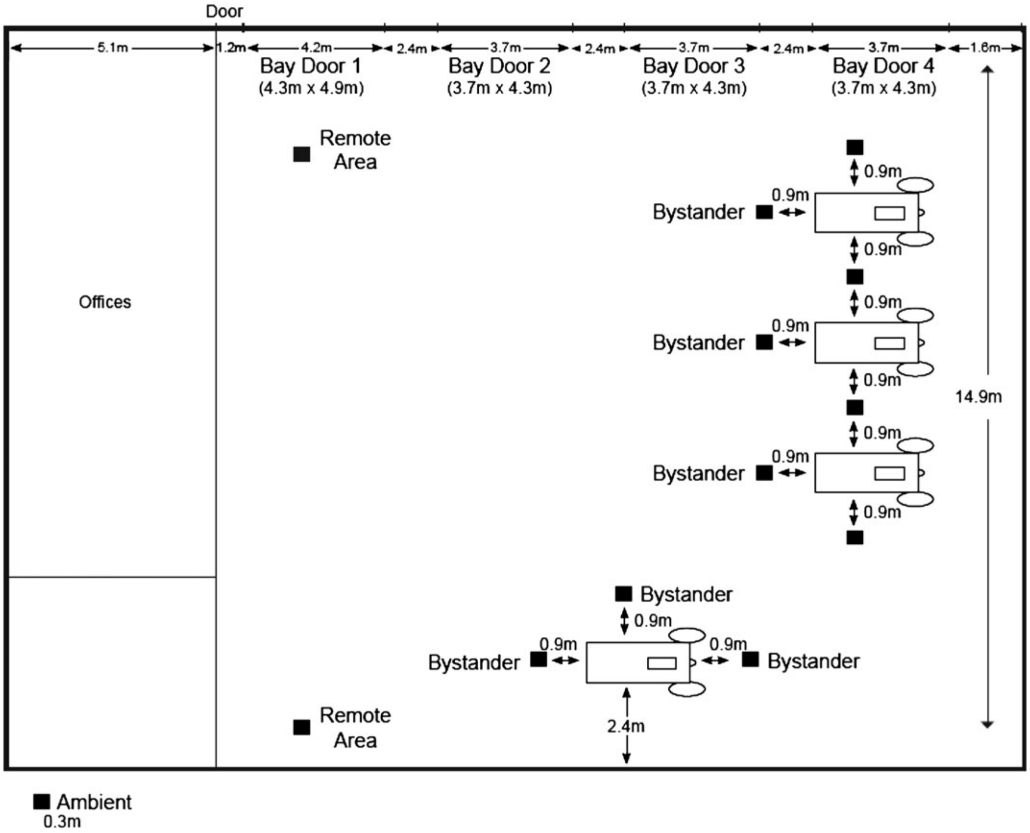


Fig. 2. Diagram of equipment repair facility (Stockton, CA) and locations of area sampling stations.

requested and obtained (Essex Institutional Review Board, Inc., Lebanon, NJ, USA). This IRB complies with the federal regulations of the National Institute of Health, the Office of Human Research Protection (45 CFR 46), and the Food and Drug Administration (21 CFR 50, 56). It is also accredited by the National Committee for Quality Assurance, formerly The Partnership for Human Research Protection.

Description of exposure scenarios

Airborne asbestos concentrations were measured during brake removal and disassembly activities related to all 12 pieces of equipment. Clothes handling tasks, such as shaking and folding of coveralls worn during maintenance of 11 pieces of equipment, were also studied. Before any brake work was performed, mechanics were fitted with new coveralls. These coveralls were collected after the mechanic completed work on each piece of equipment and were later tested to evaluate the exposure of persons during the handling of these potentially contaminated work clothes. Each coverall (n = 11) was stored in separate plastic-lined bags until the last day of testing, when the clothes handling task was conducted.

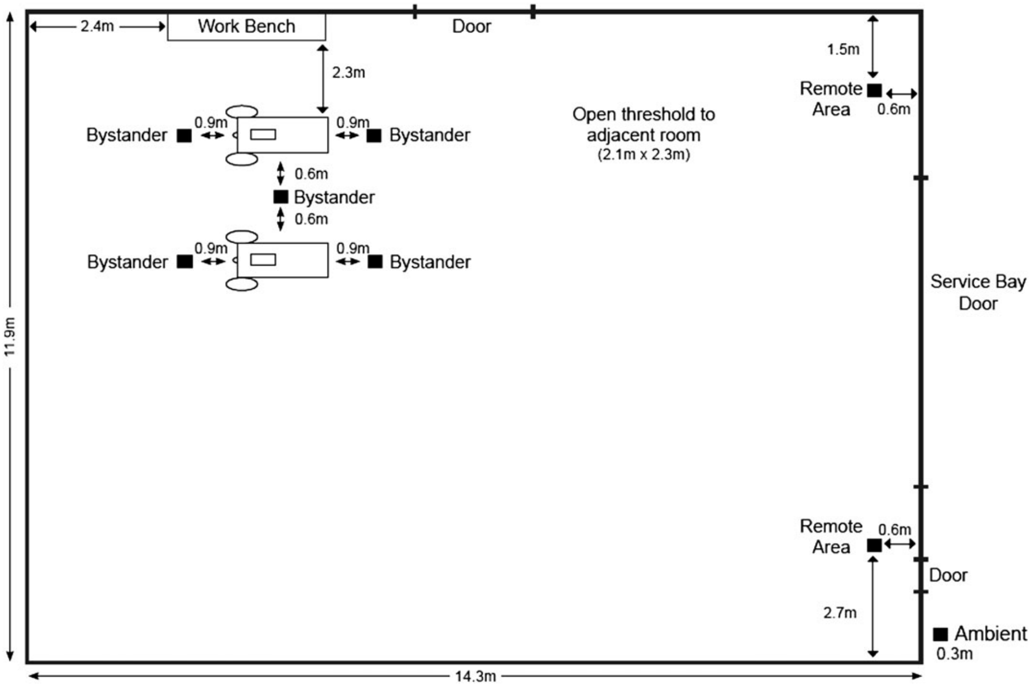


Fig. 3. Diagram of equipment repair facility (Big Rock, IL) and locations of area sampling stations.

The simulated clothes handling task involved repeatedly shaking, folding, and turning clothes inside out for ∼1 to 2 min for each pair of overalls by a volunteer to simulate the handling and laundering. Although no fibers or debris were visible on the coveralls, some particles were observed in the air during the clothes handling task. TEM analysis of air samples was used to evaluate the proportion of asbestos versus non-asbestos airborne particles released during shaking.

The brake removal process was similar for all pieces of equipment, with slight differences only in the work practices exhibited by each mechanic. The mechanics worked on each piece of equipment one at a time. To disassemble the brakes, the external brake housing was first removed from the tractor or loader backhoe using a manual or power wrench to loosen bolts holding the housing in place. On four occasions (Eq1, Eq9, Eq10, and Eq12), a blowtorch had to be applied to facilitate loosening of the external housing bolts. Once the external housing was removed, the entire brake assembly was removed from the vehicle. At this point, the mechanic at the Stockton facility would blow out the assembly and work area with compressed air and then repeat the entire process for the second brake housing. Once both complete assemblies were removed, he performed bench work, which entailed disassembling the drum linings from both brake assemblies. Using a slightly different order than the Stockton mechanic, the mechanic in Big Rock, IL, completed the entire brake removal process on the first assembly before beginning the process on the second one. More specifically, once the brake assembly was removed from the external housing, the brake assembly was moved to a workbench, and the drum linings were removed from the face plates in preparation of shipment to a specialized shop for refacing. After one complete brake assembly was disassembled and the linings removed, the mechanic from Big Rock would repeat the same process for the second housing and then blow out both brake housings at the end of the brake removal job.

While performing the bench work, the Stockton and Big Rock mechanics used different methods to separate the friction linings from the drum facings. Specifically, the Stockton mechanic used a hammer and punch to remove the rivets that attached the lining to the drum face, whereas the Big Rock mechanic used a power drill. It is noteworthy that four of the 12 pieces of equipment tested contained at least one brake assembly that was saturated in oil that had leaked from an adjacent reservoir. In these circumstances, these assemblies were wiped clean before the linings were removed. In general, the Stockton mechanic took ∼30 min to remove and disassemble the linings from two brake housings from one piece of equipment, whereas the Big Rock mechanic took ∼45 to 60 min to perform the same job.

Sampling and analytical methods

All airborne samples for asbestos were collected in accordance with federally established criteria. Airborne asbestos and other particulates were collected onto mixed cellulose ester membranes (25 mm, 0.45 μm pore size; Zefon International, St Petersburg, FL, USA), with either portable SKC Universal (SKC-West, Inc., Fullerton, CA, USA) or high-volume Dawson 1300 sampling pumps (Ashtead Technology Rentals, Hayward, CA, USA). The sampling pumps were calibrated with a Bios DryCal DCLite primary flow calibrator (Bios International Corporation, Butler, NJ, USA) before and after each sampling event. The temperature inside the garage was noted (Springfield PreciseTemp, Wind and Weather Instruments, Fort Bragg, CA, USA) during the collection of each air sample. Asbestos sample collection equipment, materials, and procedures were consistent with National Institute for Occupational Safety and Health (NIOSH) Methods 7400 and 7402.

Before any brake removal activities began, background samples for airborne asbestos were collected in three different locations in the service centers. Personal samples from workers' lapels, bystander area samples within 1.2–3.1 m of the work activities, remote area samples at more distant locations (9–15 m) from the work activities, and ambient samples for airborne asbestos were collected during tractor brake or backhoe brake removal and disassembly. Figures 2 and 3 illustrate the location of the bystander, remote area, and ambient airborne asbestos samples collected in relation to the work activities at both the Stockton and the Big Rock facilities. Consecutive 30-min samples were collected at an airflow rate ranging from 1 to 10 l min^{-1} on the right and left lapel of the worker during the brake removal activities. To characterize potential bystander exposures to asbestos, air samples were collected at breathing zone height (1.5 m) at three different locations ~1.2 to 3.1 m from the vehicle. Bystander samples were collected at an airflow rate of 5–11 l min^{-1} during brake removal activities on each vehicle (30–60 min). Background samples of ambient air (outside the shop, 90–180 min) and remote area (inside the shop, 30–60 min) were also collected for airborne asbestos at an airflow rate of ~10 l min^{-1} during the brake removal activities. At least two field blanks were collected during each day of the above-described testing.

All airborne asbestos samples, including personal, area, background, and ambient samples, were sent to an accredited laboratory (EMS Laboratories, Pasadena, CA, USA) for asbestos analysis by phase contrast microscopy (PCM, NIOSH Method 7400) and TEM (NIOSH Method 7402) (NIOSH, 1994a,c). EMS Laboratories is an asbestos analysis laboratory accredited 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) and utilizes analysts trained according to NIOSH 582 who adhere to the quality assurance and quality control requirements set forth by Occupational Safety and Health Administration (OSHA) (OSHA, 1994) and the most current version of the NIOSH 7400 Method. 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 (NIOSH, 1994c). Fibers were counted according to the NIOSH Methods 7400 and 7402, which define fibers as being >5 μm in length and 0.25 μm in diameter and having at least a 3:1 aspect ratio (NIOSH, 1994a,c). Air samples were also analyzed according to the International Organization for Standardization (ISO) method for characterization of fiber type, size, and morphology of fibers >5 μm in length (ISO, 1995).

Fiber size and morphology analysis

Because OSHA specifies PCM analysis (with or without TEM analysis) for evaluating occupational exposures to airborne asbestos, most studies utilize NIOSH Method 7400. However, PCM analysis under NIOSH Method 7400 does not differentiate asbestos fibers from other structurally similar non-asbestos fibers, so OSHA has indicated that TEM analysis (NIOSH Method 7402) can be used to quantify the ratio of asbestos fibers to total fibers (OSHA, 1994). While NIOSH Methods 7400 and 7402 are still used today to determine workplace compliance with the OSHA permissible exposure limit (PEL) for asbestos, these methods are limited in their ability to account for fiber morphology (e.g. presence of a resin) that might influence the respirability or the health hazard of airborne fibers.

While not widely used, the ISO Standard method allows for characterization of both fiber size and type, as well as for determination of the fiber size distribution of airborne asbestos and differentiation of free fibers from fibers associated with a non-respirable matrix (ISO, 1995). This method (in addition to the NIOSH methods) was used in this study because the data can then be employed in future dose–response and risk assessment models (while the NIOSH methods are most appropriate for comparing to the OSHA PEL) (OSHA, 1994).

Using the ISO methodology, asbestos fibers were classified according to fiber size and morphology. Asbestos fiber morphology was quantified by categorizing asbestos fibers that were >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 comprised within the cluster or matrix, were recorded. Asbestos fibers were characterized by their morphology and size to evaluate the proportion of airborne fibers that were potentially respirable. While fibers up to 3.5 μm in diameter have been detected in the lungs of workers, and while 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 studies have shown that most fibers that are deposited in the pulmonary region of the lung are thinner than 0.7 µm, and almost all are thinner than 1 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 diameters of $\leq$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 behave aerodynamically more like a particle than as a fiber. Nonetheless, respirability of fiber clusters or matrices was evaluated in two ways, as a respirable fiber of diameter $\leq$0.7 µm or a respirable particle with diameter $\leq$10 µm.

In addition, fibers >20 µm in length were considered in the size distribution analysis. There is data that suggests that asbestos fibers of this length or greater pose the greatest risk, whereas those <5 µm do not. Stanton *et al.* conducted a series of animal exposure experiments with asbestos and non-asbestos fibers and ultimately concluded that fibers $\leq$8 µm in length have little or no mesotheliogenic potential (Stanton, 1973; Stanton *et al.*, 1977, 1981). Berman *et al.* (1995) evaluated data from 13 rat inhalation bioassays in which the animals were exposed to nine different types of asbestos dusts and concluded that structures contributing to lung tumor risk appeared to be long ($\geq$5 µm) and thin (0.4 µm) fibers (Berman *et al.*, 1995). Berman further noted that potency appeared to increase with increasing length, with structures longer than 40 µm being ~500 times more potent than those between 5 and 40 µm in length. These researchers suggested that structures <5 µm in length did not contribute to lung tumor risk. Modeling results reported by Miller *et al.* (1999) indicated that the concentration of fibers longer than 20 µm and thinner than 1 µm in diameter is most influential in determining the tumorigenic potential of fibers (Miller *et al.*, 1999). In addition, the US Environmental Protection Agency (US EPA) contracted the preparation of a technical support document for a protocol to assess asbestos-related risk (Berman and Crump, 2003). Based on the modeling results presented in the technical support document, the authors concluded that the best estimate of risk for both lung cancer and mesothelioma for fibers between 5 and 10 µm in length is one-three-hundredth of the risk assigned to fibers longer than 10 µm. Further, the best estimate of the potency of fibers shorter than 5 µm was zero for mesothelioma and lung cancer. The authors also explained that 'results from [their] review of the supporting literature suggest that the optimum cutoff for increased potency occurs at a length that is closer to 20 µm than 10 µm'.

Collection and analysis of bulk asbestos samples

For each piece of equipment, filings of the brake material from each assembly (two drum linings and two band linings) and samples of brake wear debris (one from each assembly) were collected for bulk sample asbestos analysis. Both types of bulk material were analyzed by EMS Laboratories, using polarized light microscopy (PLM) according to NIOSH Method 9002 (NIOSH, 1994b) and XRD according to NIOSH Method 9000 (NIOSH, 1994d). Because the asbestos concentration in brake wear debris was anticipated to be below the detection limit for PLM or XRD (~1%), a modified approach based on the US EPA methods for detecting asbestos in bulk samples and drinking water was utilized (Chatfield and Dillon, 1983; Perkins and Harvey, 1993). More specifically, this approach involved ashing the sample to remove organic material using a muffle furnace, suspending the ashed sample in water, filtering an aliquot of the water suspension, transferring the filtered sample onto a TEM grid, and characterizing dimensions of fibers according to those measured under NIOSH 7400/7402.

Air exchange measurements using tracer gas

Sulfur hexafluoride (SF_6) was used as a tracer gas to estimate the air exchange rate within the service centers. Briefly, measurements of the gas were taken according to American Society for Testing and Materials (ASTM) Method E741-00 (ASTM, 2001), and air exchange measurements using this method were collected during each day of testing. A steady state concentration of 1 p.p.m. for SF_6 (Sigma–Aldrich, St Louis, MO) was targeted as the initial room concentration for the tracer gas analysis. Tedlar bags (Fisher Scientific, Hampton, NH, USA) filled with SF_6 were then released in the garage with all doors closed. Fans on either end of the garage were used to facilitate the gas dispersion. After steady state was reached, fans were turned off, and SF_6 measurements were taken in 30-s intervals with a MIRAN SapphIRe-XL Analyzer (Thermo-Electron Corporation, Waltham, MA, USA; Ashtead Technology Rentals) for ~1 h. The air exchange in the garage was calculated using the concentration decay (optional regression) test method by plotting the natural logarithm of SF_6 concentration over time (ASTM, 2001).

Data and statistical analysis

For the purposes of statistical analyses, results below the analytical sensitivity limit were inputed using a value equal to one-half the sensitivity limit. Analytical sensitivity limits were estimated based on the presumption that one fiber could be counted within 100 microscopic fields and divided by the volume of air sampled. PCM measurements were adjusted for asbestos fiber content according to the method outlined in NIOSH Method 7402, which specifies multiplying the ratio of asbestos fibers to total fibers observed in the TEM analysis by the PCM fiber concentration (NIOSH, 1994c). The ratios of asbestos to total fibers (asbestos and non-asbestos fibers) were based on TEM fiber counts for the same filters, from which the PCM fiber counts were obtained. The PCM measurements adjusted by the ratio of asbestos versus total fibers are referred to as 'PCM-equivalent' (PCME) airborne asbestos concentrations. 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.

Descriptive statistics were performed on PCM, TEM, and PCME measurements of airborne fiber concentrations collected during the removal of asbestos-containing brake assemblies from tractors and loader backhoes, and also during the clothes handling activities. Results were analyzed by sample location (worker, bystander, remote area, and background), by testing location (Stockton and Big Rock), and by assembly oiliness, when applicable. Eight-hour TWA asbestos exposures during brake removal were also calculated based on the PCME measurements for both the worker and the bystander, based on the assumption that three brake jobs could be conducted in a single workday and the remaining time the worker would be exposed to background concentrations. For example, 90 min of brake removal activities (representing work on three pieces of equipment) at a concentration of 0.024 f/cc and a 390-min exposure to background at a concentration of 0.005 f/cc would result in an 8-h TWA of 0.009 f/cc.

Air concentration data were determined to be lognormally distributed based on probability plots. One-way analysis of variance and pairwise comparisons based on the Tukey's test for each group were conducted for natural log-transformed air concentration data of worker, bystander, and remote area samples. Two-sample *t*-test of the log-transformed worker data was conducted with respect to dry versus oily brake assemblies based on unequal variances. Power calculations of the above comparisons were estimated to be 100%. A Pearson and Spearman (non-parametric) analysis was performed to evaluate whether airborne chrysotile concentrations for the worker (untransformed and natural log transformed) were influenced or correlated with the asbestos content in the brake lining or brake wear debris and whether the asbestos content in the brake wear debris was influenced by the extent of wear (e.g. lining thickness) or the original asbestos content in the brake lining.

RESULTS

All equipment contained at least one brake assembly with asbestos-containing linings. The thickness of the brake linings ranged from completely worn to the metal support to 5.94 mm, and their asbestos content is presented in Table 1. In summary, the asbestos content of the brake lining averaged 19% chrysotile by weight (range: 1–39%) as measured by XRD and 20% chrysotile by area (range: 0.5–70%) as measured by PLM (Table 2). Table 1 also presents the asbestos content measured in the break wear debris. The average asbestos content found in these samples was 0.49% of chrysotile asbestos (range: 0.008–6%). All heavy equipment showed brake wear debris with <1% chrysotile asbestos, with the exception of Equipment 9, which had brake debris in one assembly containing 6% asbestos. It should be noted that this assembly was also missing both drum linings. These results indicate that nearly all (average of 94.4%, range 58–100%) the chrysotile in the brake linings degraded or was converted to an amorphous material. Specifically, for 10 of the 12 pieces of equipment, over 95% of the chrysotile in the brake linings was degraded to non-fibrous particles in the brake wear debris. Interestingly, there were no correlations found between the asbestos content in the brake lining and brake wear debris, suggesting that the asbestos content in the brake lining does not influence the amount of asbestos remaining in the brake wear debris after degradation processes.

Air sampling results are reported in Tables 2 and 3. Table 2 presents the short-term (30 min) and brake removal airborne asbestos concentrations measured by PCM, TEM, and PCME for the worker, bystander, remote, and background locations by facility. The average airborne chrysotile concentrations as measured by PCM, TEM, and PCME were 0.053, 0.087, and 0.024 f/cc, respectively, for the Stockton mechanic and 0.338, 0.012, and 0.010 f/cc measured by PCM, TEM, and PCME, respectively, for the Big Rock mechanic (Table 2). The overall worker average airborne asbestos concentrations by analytical method are presented and compared to the OSHA 30-min asbestos excursion limit in Fig. 4. No correlations were found between concentrations of airborne asbestos for the worker (PCME, 30 min) and the asbestos content in the brake lining or wear debris; this lack of correlation is likely attributed to the low asbestos concentrations in the air samples and in the brake wear debris.

The results of the clothes handling activity are also presented in Table 2. The average airborne asbestos concentrations measured on the volunteer (handling

Table 2. Summary of air sampling results: brake removal and clothes handling by PCM, TEM, and PCME (30 min) by worker, bystander, remote, and background, as well as location

Sample type/activity/location	Equipment	Asbestos fiber concentrations (f/cc)																	
		PCM							TEM							PCME^a			
		n	*n* (ND)	*n* (NR)	Avg	GM	SD	Range	*n*	*n* (ND)	*n* (NR)	Avg	GM	SD	Range	*n*	Avg	SD	Range
Worker																			
Brake and bench work																			
Stockton	Eq1	3	0	0	0.056	0.038	0.059	0.013–0.123	3	1	0	0.009	0.009	0.004	0.005–0.013	2	0.038	0.055	0.013–0.101
	Eq2	3	0	0	0.156	0.120	0.103	0.037–0.220	3	0	1	0.055	0.053	0.021	0.040–0.070	2	0.036	0.018	0.023–0.048
	Eq5	4	0	1	0.038	0.027	0.027	0.007–0.059	4	0	2	0.300	0.300	0.000	0.300–0.300	2	0.044	0.005	0.040–0.048
	Eq6	4	0	0	0.024	0.024	0.004	0.021–0.029	4	1	1	0.048	0.040	0.029	0.015–0.070	2	0.009	0.008	0.012–0.016
	Eq7	4	0	0	0.016	0.015	0.007	0.011–0.026	4	1	0	0.015	0.011	0.011	0.003–0.030	3	0.003	0.003	0.001–0.008
	Eq8	4	0	0	0.075	0.071	0.028	0.042–0.103	4	0	0	0.225	0.200	0.126	0.100–0.400	4	0.042	0.034	0.035–0.090
	Eq9	4	0	0	0.058	0.057	0.011	0.046–0.071	4	0	0	0.048	0.039	0.036	0.020–0.100	4	0.033	0.012	0.018–0.043
	Eq10	4	0	0	0.029	0.027	0.015	0.021–0.052	4	1	0	0.031	0.022	0.023	0.004–0.060	3	0.009	0.008	0.004–0.018
	Eq11	4	0	0	0.028	0.026	0.013	0.017–0.046	4	0	0	0.125	0.089	0.120	0.030–0.300	4	0.018	0.014	0.006–0.038
	Eq12	4	0	0	0.050	0.047	0.023	0.036–0.084	4	1	0	0.011	0.009	0.007	0.003–0.020	3	0.003	0.002	0.003–0.006
	Eq1–Eq2, Eq5–Eq12	**10**			**0.053**	**0.045**	**0.029**	**0.007–0.220**	**10**			**0.087**	**0.077**	**0.038**	**0.003–0.400**	**10**	**0.024**	**0.016**	**0.001–0.090**
Big Rock	Eq3	4	0	0	0.256	0.230	0.130	0.110–0.425	4	4	0	0.003	0.003	0.001	0.002–0.004	—	—	—	—
	Eq4	4	0	0	0.419	0.354	0.236	0.131–0.622	4	0	3	0.020	0.020	—	0.020	1	0.010	—	0.010
	Eq3–Eq4	**2**			**0.338**	**0.292**	**0.183**	**0.110–0.622**	**2**			**0.012**	**0.011**	**0.001**	**0.002–0.004**	**1**	**0.010**	**—**	**0.010**
Clothes handling		**4**	**0**	**0**	**0.231**	**0.199**	**0.125**	**0.080–0.360**	**2**	**2**	**0**	**0.011**	**0.007**	**0.010**	**0.002–0.020**	**2**	**0.036**	**0.0**	**0.032–0.039**
Bystander																			
Brake and bench work																			
Stockton	Eq1	0	—	—	—		—	—	0	—	—	—	—	—	—	—	—	—	—
	Eq2	3	0	0	0.029	0.029	0.006	0.024–0.035	3	1	0	0.007	0.005	0.005	0.002–0.010	2	0.006	0.001	0.008–0.009
	Eq5	3	0	1	0.007	0.007	0.002	0.006–0.008	3	0	3	—	—	—	—	—	—	—	—
	Eq6	3	0	0	0.014	0.012	0.010	0.007–0.025	3	3	0	0.002	0.002	0.001	0.002–0.003	—	—	—	—
	Eq7	3	0	0	0.009	0.009	0.002	0.007–0.010	3	3	0	0.002	0.001	0.001	0.001–0.002	—	—	—	—
	Eq8	3	0	0	0.021	0.019	0.012	0.008–0.032	3	1	0	0.010	0.008	0.009	0.004–0.020	2	0.017	0.008	0.012–0.023
	Eq9	3	0	0	0.013	0.013	0.004	0.009–0.016	3	2	0	0.003	0.003	0.001	0.002–0.004	1	0.008	0.000	0.008
	Eq10	3	0	0	0.012	0.010	0.008	0.007–0.021	3	3	0	0.003	0.002	0.001	0.002–0.004	—	—	—	—
	Eq11	3	0	0	0.019	0.015	0.015	0.007–0.036	3	1	0	0.011	0.008	0.009	0.003–0.020	2	0.005	0.005	0.006–0.010

Table 2. *Continued*

Sample type/activity/location	Equipment	Asbestos fiber concentrations (f/cc)																	
		PCM							TEM							PCME^a			
		n	*n* (ND)	*n* (NR)	Avg	GM	SD	Range	*n*	*n* (ND)	*n* (NR)	Avg	GM	SD	Range	*n*	Avg	SD	Range
	Eq12	2	0	0	0.004	0.003	0.005	0.001–0.008	2	2	0	0.004	0.003	0.001	0.002–0.003	—	—	—	—
	Eq1–Eq2, Eq5–Eq12	**9**			**0.014**	**0.013**	**0.007**	**0.001–0.036**	**9**			**0.005**	**0.004**	**0.003**	**0.001–0.020**	**4**	**0.009**	**0.004**	**0.006–0.023**
Big Rock	Eq3	5	0	0	0.015	0.014	0.007	0.007–0.026	5	5	0	0.003	0.002	0.001	0.002–0.004	—	—	—	—
	Eq4	3	0	0	0.055	0.054	0.005	0.049–0.059	3	2	0	0.002	0.001	0.001	0.001–0.002	1	0.002	—	0.002
	Eq3–Eq4	**2**			**0.035**	**0.034**	**0.006**	**0.007–0.059**	**2**			**0.002**	**0.002**	**0.001**	**0.001–0.004**	**1**	**0.002**	**—**	**0.002**
Clothes handling		**2**	**0**	**0**	**0.093**	**0.080**	**0.066**	**0.046–0.140**	**2**	**0**	**0**	**0.012**	**0.008**	**0.012**	**0.003–0.020**	**2**	**0.010**	**0.011**	**0.003–0.018**
Remote area																			
Brake and bench work																			
Stockton	Eq1	0	—	—	—		—	—	0	—	—	—		—	—	—	—	—	—
	Eq2	2	0	0	0.004	0.004	0.001	0.004–0.005	2	2	0	0.002	0.002	0.000	0.002–0.002	—	—	—	—
	Eq5	2	0	0	0.005	0.004	0.002	0.003–0.006	2	1	0	0.002	0.002	0.000	0.002–0.002	1	0.001	0.000	0.001
	Eq6	2	0	0	0.004	0.004	0.000	0.004–0.004	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq7	2	0	0	0.005	0.005	0.002	0.003–0.007	2	2	0	0.001	0.001	0.000	0.001	—	—	—	—
	Eq8	2	0	0	0.009	0.009	0.003	0.007–0.011	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq9	2	0	0	0.006	0.006	0.000	0.006–0.006	2	1	0	0.002	0.002	0.001	0.002–0.003	1	0.002	0.000	0.002
	Eq10	2	0	0	0.005	0.004	0.004	0.002–0.007	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq11	2	0	0	0.008	0.008	0.002	0.007–0.010	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq12	2	0	0	0.008	0.008	0.000	0.008	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq1–Eq2, Eq5–Eq12	**10**			**0.006**	**0.006**	**0.002**	**0.002–0.011**	**10**			**0.002**	**0.002**	**0.000**	**0.001–0.003**	**2**	**0.001**	**0.000**	**0.001–0.002**
Big Rock	Eq3	2	0	0	0.010	0.010	0.001	0.010–0.011	2	2	0	0.001	0.001	0.000	0.001	—	—	—	—
	Eq4	2	0	0	0.035	0.035	0.002	0.033–0.036	2	2	0	0.001	0.001	0.000	0.001	—	—	—	—
	Eq3–Eq4	**2**			**0.022**	**0.022**	**0.001**	**0.010–0.036**	**2**			**0.001**	**0.001**	**0.000**	**0.001–0.001**	**—**	**—**	**—**	**—**
Clothes handling		**2**	**0**	**0**	**0.040**	**0.037**	**0.021**	**0.025–0.055**	**2**	**2**	**0**	**0.001**	**0.001**	**0.000**	**0.001–0.002**	**0**	**—**	**—**	**—**
Background																			
Brake and bench work																			
Stockton	Eq1	0	—	—	—		—	—	0	—	—	—		—	—	—	—	—	—
	Eq2	2	0	0	0.023	0.023	0.006	0.019–0.027	2	1	0	0.003	0.002	0.002	0.001–0.004	1	0.005	0.000	0.005

Table 2. *Continued*

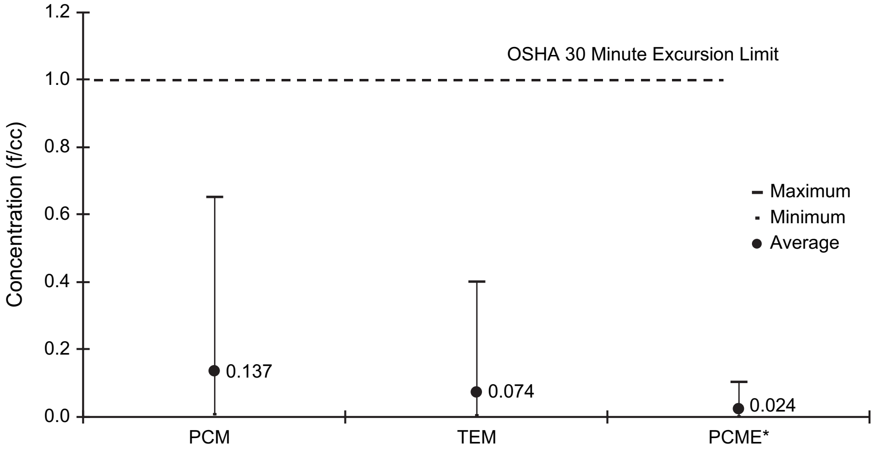
Sample type/activity/location	Equipment	Asbestos fiber concentrations (f/cc)																	
		PCM							TEM							PCME[a]			
		n	*n* (ND)	*n* (NR)	Avg	GM	SD	Range	*n*	*n* (ND)	*n* (NR)	Avg	GM	SD	Range	*n*	Avg	SD	Range
	Eq5	3	0	0	0.010	0.007	0.008	0.003–0.019	3	2	1	0.001	0.001	0.000	0.001	—	—	—	—
	Eq6	3	0	0	0.007	0.006	0.002	0.004–0.008	3	3	0	0.002	0.002	0.001	0.002–0.003	—	—	—	—
	Eq7	3	0	0	0.008	0.005	0.008	0.002–0.017	3	3	0	0.002	0.002	0.001	0.002–0.003	—	—	—	—
	Eq8	3	0	0	0.006	0.005	0.002	0.003–0.007	3	3	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq9	3	0	0	0.008	0.008	0.001	0.007–0.009	3	3	0	0.001	0.001	0.000	0.001–0.002	—	—	—	—
	Eq10	3	0	0	0.007	0.006	0.005	0.002–0.012	3	3	0	0.002	0.002	0.000	0.015	—	—	—	—
	Eq11	3	0	0	0.007	0.006	0.001	0.006–0.007	3	3	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq12	3	0	0	0.008	0.008	0.001	0.006–0.009	3	3	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq1–Eq2, Eq5–Eq12	**10**			**0.009**	**0.008**	**0.004**	**0.002–0.027**	**10**			**0.002**	**0.002**	**0.000**	**0.001–0.004**	**1**	**0.005**	**—**	**0.005**
Big Rock	Eq3	2	0	0	0.008	0.008	0.000	0.008	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq4	2	0	0	0.021	0.021	0.019	0.007–0.035	2	2	0	0.002	0.002	0.000	0.002	—	—	—	—
	Eq3–Eq4	**2**			**0.015**	**0.015**	**0.010**	**0.007–0.035**	**2**			**0.002**	**0.002**	**0.000**	**0.002**	**—**	**—**	**—**	**—**
Ambient																			
Brake and bench work																			
Stockton	Eq1	0	—	—	—		—	—	0	—	—	—		—	—	—	—	—	—
	Eq2	1	0	0	0.001	0.001	—	0.001	1	1	0	0.0004	0.0004	—	0.0004	—	—	—	—
	Eq5–Eq7	3	0	0	0.002	0.002	0.002	0.001–0.005	3	3	0	0.0004	0.0004	0.0001	0.0004–0.0005	—	—	—	—
	Eq8–Eq9	3	0	0	0.002	0.002	0.002	0.001–0.004	3	1	0	0.001	0.001	0.0001	0.0005–0.0007	2	0.0004	0.0000	0.0004
	Eq10–Eq12	3	0	0	0.003	0.003	0.001	0.003–0.004	3	1	0	0.001	0.001	0.0001	0.0008–0.0010	2	0.0002	0.0000	0.0001–0.0002
	Eq1, Eq5–Eq12	**4**			**0.002**	**0.002**	**0.001**	**0.001–0.005**	**4**			**0.001**	**0.001**	**0.000**	**0.0004–0.0010**	**2**	**0.0003**	**—**	**0.0001–0.0004**
Big Rock	Eq3	1	0	0	0.001	0.001	—	0.001	1	1	0	0.0003	0.0003	—	0.0003	—	—	—	—
	Eq4	1	0	0	0.001	0.001	—	0.001	1	1	0	0.0005	0.0005	—	0.0005	—	—	—	—
	Eq3–Eq4	**1**			**0.001**	**0.001**	**—**	**0.001**	**1**			**0.0004**	**0.0004**	**—**	**0.0003–0.0005**	**—**	**—**	**—**	**—**

PCME, PCM concentration multiplied by the ratio of asbestos fibers to total fibers measured by TEM; *n*, number of samples; NR, number of samples not readable; ND, number of samples in which asbestos was not detected; Avg, average; SD, standard deviation; GM, geometric mean; —, not applicable.

[a] Based on samples in which asbestos fibers were detected by TEM.

Table 3. Summary of fiber size and morphology of airborne asbestos fibers collected on the worker during brake removal

Fiber structure classification	*n*	Total fibers (%)	Percent fibers (%) classified as fiber or particle with dimensions of					
			Respirable fiber				Respirable particle	
			<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 (%)
Total fibers	261	—	—	—	—	—	—	—
Free fiber/bundle	95	36	18	2	35	2	—	—
Fiber clusters	8	3	2	0	2	1	3	1
Matrix disperse	158	61	0	0	7	0	36	9



* Based on samples in which asbestos fibers were detected by TEM.

Fig. 4. Comparison of worker asbestos concentrations (f/cc, 30 min) by analytical methods (PCM, TEM, and PCME).

the clothes) were 0.231, 0.011, and 0.036 f/cc when measured by PCM, TEM, and PCME, respectively. Likewise, at the bystander location, average asbestos concentrations of 0.093, 0.012, and 0.010 f/cc were measured using PCM, TEM, and PCME, respectively (sampling times were 30 min in duration and collected during the anticipated peak times of exposure).

Figure 5 presents the average asbestos concentrations as measured by PCME for the worker, bystander, remote, and background locations, as compared to the current OSHA 30-min excursion limit for asbestos. Asbestos was not detected in more than half of the samples collected at the bystander locations (even though <1.2 m from the work activity) as determined by TEM, and average airborne asbestos concentrations at the bystander locations were generally less than half of those measured for the mechanic. Airborne concentrations were 0.014 f/cc (PCM), 0.005 f/cc (TEM), and 0.009 f/cc (PCME) at bystander locations at the Stockton facility and 0.035 f/cc (PCM), 0.002 f/cc (TEM), and 0.002 f/cc (PCME) at bystander locations at the Big Rock facility (Table 2). Airborne asbestos concentrations found at the remote and background locations were even lower than those found at the bystander locations. It is interesting to note, however, that actinolite (one fiber) was detected in two ambient air samples and one worker sample, although this finding is not surprising since actinolite is commonly found in ambient air (Lee and Van Orden, 2008).

Because four pieces of equipment (Eq3, Eq4, Eq6, and Eq7) had at least one assembly saturated in oil, airborne asbestos concentrations found on the worker removing those brakes were compared to the concentrations found while removing dry brake assemblies. The resulting average asbestos concentration during oily brake removal (0.009 f/cc) was less than one-fourth the concentration of dry brake removal (0.043 f/cc), as measured by PCME. These findings were statistically significant ($P = 0.001$) by a two-sample *t*-test of the log-transformed worker data.

Estimated 8-h TWA asbestos exposures were calculated for the worker and the bystander. Considering the time involved in the brake removal activity, and assuming three brake removal jobs are conducted per shift, the resulting average 8-h TWA was estimated to be 0.009 f/cc for a mechanic and 0.006 f/cc for a bystander. Therefore, 8-h TWA asbestos exposures for mechanics performing brake removal on heavy

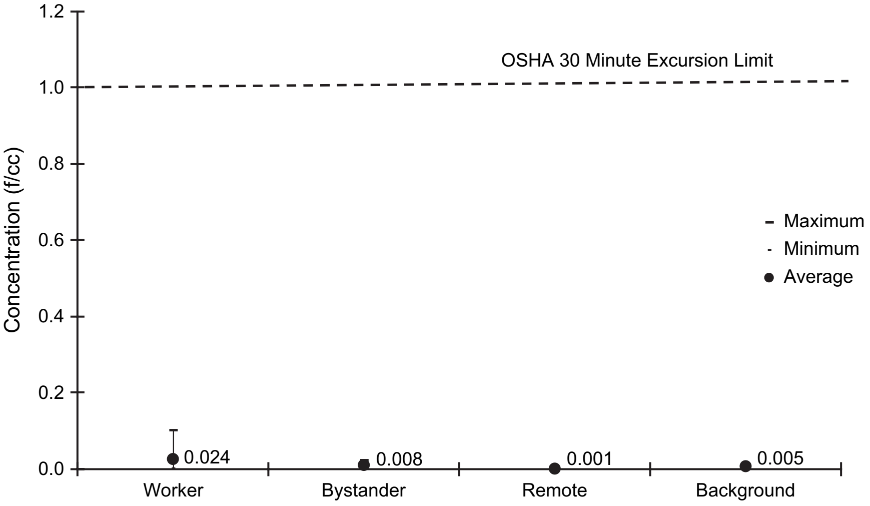


Fig. 5. Comparison of worker, bystander, remote area, and background airborne asbestos concentrations (f/cc, PCME, 30 min).

equipment and those standing nearby this work are not likely to exceed the current OSHA PEL of 0.1 f/cc.

Table 3 presents a summary of fiber size and morphology of the airborne asbestos fibers collected on the worker. Within the worker samples, there were 261 total asbestos fibers counted using the ISO methodology. Of these, only 36% were free fibers or bundles, 18% were free fibers or bundles with diameter <0.7 μm (length > 5 μm) and only 2% were free fibers or bundles with diameter <0.7 μm and length >20 μm. The remaining fibers were either in clusters (3%) or attached to a matrix (61%). Only 3% of the fibers, however, were part of a cluster that may be respirable (<10 μm in width), and 36% of fibers were part of a matrix that may be respirable. Figure 6 is an image of fiber clusters collected in worker samples and exemplifies fibers that are part of a much larger matrix.

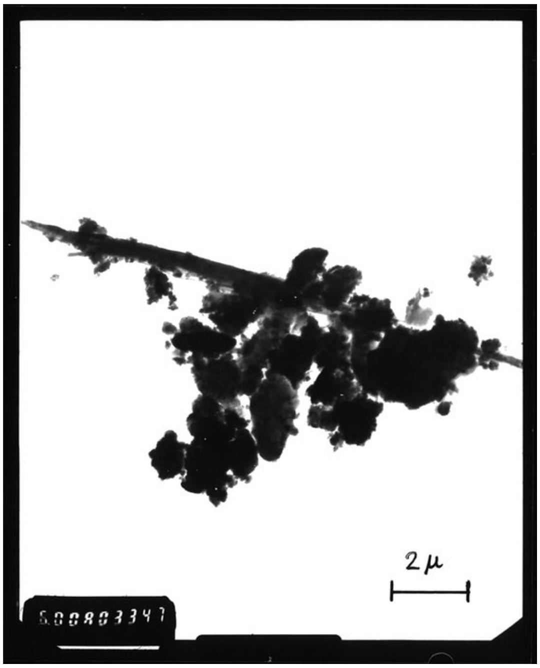


Fig. 6. TEM image of a fiber cluster collected during a short-term worker sample performing brake removal on Equipment 6, courtesy of EMS Laboratories.

DISCUSSION

This study assessed possible exposures to airborne asbestos during removal and disassembly of asbestos-containing brakes from heavy construction equipment manufactured during the 1960–1980 time frame. The data collected in this simulation study are believed to capture the plausible range of variables that might influence exposures during brake removal and disassembly from heavy construction equipment, as well as the potential exposure associated with handling work clothes. The work activities were conducted under low ventilation conditions (e.g. no active local or general ventilation and low building air exchange), by mechanics with varying years of experience and techniques at different maintenance service centers, and on different heavy construction equipment (tractors and backhoes) with similar brake assembly configurations, but representing a range of equipment use (e.g. hours and brake lining wear). The results collected from this study provide information not only on airborne asbestos exposures experienced by mechanics removing asbestos-containing brakes from heavy construction equipment and by persons nearby these activities, but also on the extent to which chrysotile asbestos degrades into non-fibrous particles during braking of heavy construction equipment, the influence that dry versus oily brake assemblies has on airborne asbestos exposures, and the size and morphological distribution and potential respirability of airborne chrysotile fibers generated during the brake removal activities.

Although most of the brake removal work was conducted at the Stockton, CA, service center (10 backhoes) and not at the Big Rock, IL, facility (2 tractors), worker exposures resulting from brake removal and disassembly at these two facilities, mechanics, and types of equipment appeared to be similar. The most striking effect on airborne asbestos concentrations measured on the workers' lapel was the internal dryness of the brake housing (i.e. whether it was saturated with oil), with dry assemblies resulting in worker exposures of 0.043 f/cc (range: 0.01–0.13 f/cc) and oily assemblies resulting in worker exposures of 0.009 f/cc (range: 0.003–0.016 f/cc). No correlation was apparent using regression analyses for the amount of asbestos present in the brake wear debris when compared to the asbestos content in the drum and band linings or to the extent to which the linings were worn (e.g. lining thickness). It is possible that this lack of correlation reflects the already low chrysotile asbestos concentrations present in the brake wear debris (0.49%), inability of these fibers to become airborne during manipulation and compressed air blowout of the brake assembly, and/or similar surface area dynamics during the mechanical action of the braking process that is independent of the asbestos content.

The precision of airborne fiber concentrations 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 (Johnston *et al.*, 1982; Ogden, 1982; Cherrie and Johnston, 1986; Lange *et al.*, 1996). It has been reported that the accuracy is not greatly improved for counts beyond 50 fibers, and thus it has been recommended that at least 50 fibers be counted and the number of fields only be limited when 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 (NIOSH, 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 worker samples compared to those for area airborne asbestos concentrations. Based on the data collected in this study, however, it was determined that the data represented a power of 100% at a 95% confidence level to detect a difference between worker, bystander, and remote area measurements, as well as worker exposures handling dry versus oily brake assemblies. Based on standard *t*-tests comparisons, worker exposures were found to be significantly higher than those measured at bystander or remote area locations ($P < 0.0001$), and worker exposures while removing brakes from dry assemblies were statistically greater than those associated with oily assemblies ($P = 0.001$).

Although Boelter *et al.* (2007) evaluated airborne asbestos levels during repair of heavy construction machinery, they did not restrict their study to just brake work (Boelter *et al.*, 2007). Boelter *et al.* (2007) evaluated asbestos air concentrations during 'in-frame maintenance and repair activities, which included aggressive techniques that resulted in visible dust from work involving friction products and gaskets'. Further, the work performed during this study included dismantling, cleaning, and reassembling engines and clutches. Because a narrow range of work tasks were involved with brake removal, only a subset of asbestos measurements from the Boelter *et al.* (2007) study can be directly compared to our study. It was observed that airborne asbestos concentrations observed during brake removal and disassembly were equal to or less than those of comparable work activities reported by Boelter *et al.* (2007). Work involving band brake removal, rivets and friction lining removal from brake band or brake shoe and disc brake assembly removal resulted in average 30-min airborne asbestos concentrations ranging from 0.044 to 0.045 f/cc (PCME) in the Boelter *et al.* (2007) study. The average airborne asbestos concentration for similar activities in our study was 0.016 f/cc (range: 0.001–0.090 f/cc) (PCME). Boelter *et al.* collected and analyzed debris from the brake assembly of each piece of equipment and reported non-detectable or <1% asbestos levels for every sample. Because PLM was utilized as the method for bulk sample analysis of brake wear debris, and because concentrations below 1% are not detectable, this approach did not allow for precisely quantifying the extent to which chrysotile is degraded during braking.

While we did not specifically measure forsterite concentrations in brake wear debris, indirectly we can determine how much chrysotile is degraded by measuring the chrysotile content in the friction lining and in the brake wear debris residing in the brake housing. With TEM analysis, we were able to quantify the amount of chrysotile in the brake wear debris (average 0.49%, range 0.008–6%) and determine that 95% of chrysotile in the brake lining is degraded to non-fibrous, non-asbestos particles in the friction process. These findings are comparable to those reported for passenger automobiles, with reported averages being between 0.02 and 4.5% asbestos, with the majority of wear debris samples containing <1% chrysotile (Hickish and Knight, 1970; Luxon, 1970; Anderson *et al.*, 1973; Jacko *et al.*, 1973; Rohl *et al.*, 1977;

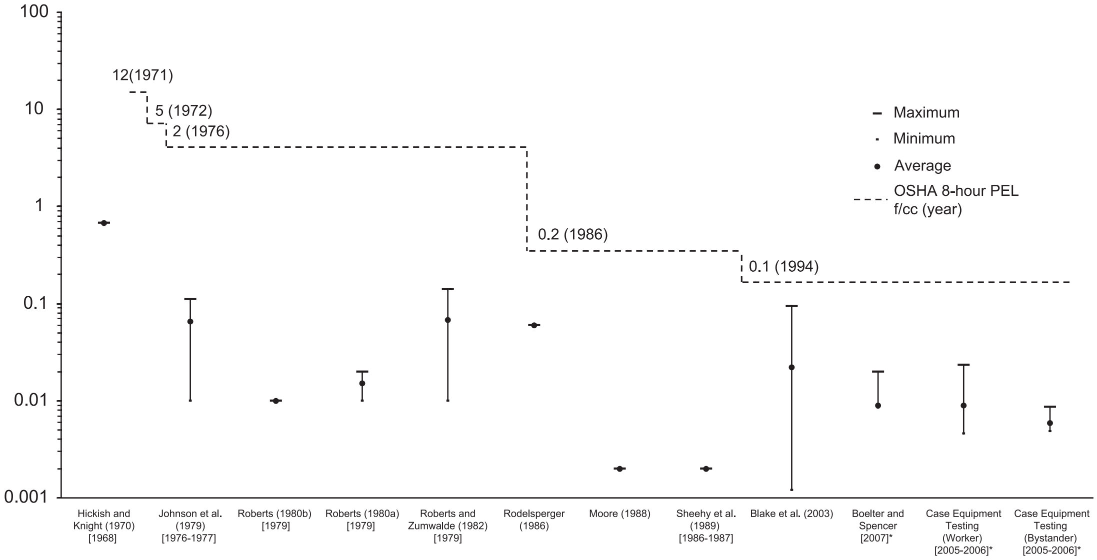
Rowson, 1978; Williams and Muhlbaier, 1982; Cha *et al.*, 1983; Sheehy *et al.*, 1989). We acknowledge that the degraded chrysotile may not, in fact, be chemically equivalent to forsterite, and that it may be some other non-asbestos amorphous material (Langer, 2003; Candela *et al.*, 2007). It is also acknowledged that the material that is called chrysotile in this analysis may not possess the biologic activity of chrysotile asbestos because of dehydroxylation and other stresses, as has been suggested by Langer (2003).

Few studies have characterized the size distribution and morphological characteristics of asbestos fibers associated with handling asbestos-containing friction materials (Atkinson *et al.*, 2004; Jiang *et al.*, 2008; Madl *et al.*, 2008), and other studies have evaluated the size and type of asbestos fibers retained within the lungs of mechanics (Churg and Wiggs, 1986; Dodson *et al.*, 1991; Roggli *et al.*, 2002). In the former set of studies, however, fiber characteristics were associated with directly handling replacement asbestos-containing automobile brakes, and in the latter group of studies, the source of the fibers retained within the lungs can only be qualitatively associated with employment history. To the best of our knowledge, no studies have evaluated the size distribution and morphological characteristics of asbestos fibers in brake wear debris released during the disassembly of brakes, and, in particular, in heavy equipment brakes. We found that 61% of the airborne asbestos fibers were associated with a matrix or resin that can significantly influence the potential respirability of these fibers; of the fibers associated with a matrix, only 9% were potentially respirable (using cutoff of particle diameter of 10 μm) and had fiber lengths >20 μm. Of the free fibers or bundles (not associated with a matrix), only 2% of airborne fibers were respirable (cutoff of fiber diameter of 3 μm and fiber length >20 μm). Thus, even with the low concentrations of airborne asbestos fibers released during heavy construction equipment brake removal and disassembly, only a small percentage of these fibers were likely to be respirable.

The exposure and epidemiologic literature for automobile mechanics can provide a useful benchmark for exposures measured in this study. In a recent assessment of all the published and unpublished industrial hygiene data collected during asbestos brake repair by vehicle mechanics, nearly 200 brake job and 8-h TWA airborne asbestos samples were analyzed (Paustenbach *et al.*, 2003). In this assessment, which encompassed measurements collected in seven different countries over the last 30 years, average 8-h TWA concentrations of 0.04 f/cc for airborne asbestos were found with individual measurements ranging from <0.002 to 0.68 f/cc reported for brake mechanics servicing light trucks and passenger vehicles (Paustenbach *et al.*, 2003). This value (0.04 f/cc) is identical to that identified by US EPA in the survey that they conducted in 1984 (Weil *et al.*, 1985). The values are also not dissimilar from the analysis of >200 short-term samples recently reported by Richter *et al.* (2008).

In addition, since 1975, six epidemiologic case–control studies and two meta-analyses have evaluated the risk of asbestos-related disease among mechanics (McDonald and McDonald, 1980; Teta *et al.*, 1983; Spirtas *et al.*, 1985, 1994; Woitowitz and Rodelsperger, 1994; Teschke *et al.*, 1997; Agudo *et al.*, 2000; Wong, 2001; Hessel *et al.*, 2004). These studies have consistently found no increased risk of mesothelioma in brake mechanics. Studies that specifically evaluated mechanics involved in brake lining installation and repair also showed a relative risk consistently <1.0 (Spirtas *et al.*, 1985; Woitowitz and Rodelsperger, 1994; Teschke *et al.*, 1997; Hessel *et al.*, 2004). It has been noted that the risk of mesothelioma in brake mechanics is similar to that of other occupations that do not involve occupational exposure to asbestos, such as teachers, librarians, and accountants (Teschke *et al.*, 1997). Based on these findings, the available epidemiological data show that employment as a motor vehicle mechanic or, more specifically, a brake repair worker does not result in an increased risk of developing mesothelioma (Paustenbach *et al.*, 2004). Taking the epidemiologic and industrial hygiene findings together, we can conclude that auto mechanics who repair asbestos-containing brakes as a career are exposed on average to 0.04 f/cc (range <0.002–0.68 f/cc) of asbestos, and are therefore not at an increased risk of asbestos-related disease, including mesothelioma (Paustenbach *et al.*, 2003). The range of lifetime cumulative doses of chrysotile have been characterized by Finley *et al.* (2007), and were reported to range from 0.16 to 0.41 f/cc year^{-1} for facilities with no dust–control procedures (1970s) and from 0.010 to 0.012 f/cc year^{-1} for those employing engineering controls (1980s). Upper bound (95%) estimates for the 1970s and 1980s were 1.96–2.79 and 0.07–0.10 f/cc year^{-1}, respectively (Finley *et al.*, 2007). These data also suggest that mechanics conducting brake work on heavy construction equipment similar to that described in this simulation study are comparable to exposures of automobile mechanics (Fig. 7), and, as a result, would also not be expected to be at an increased risk of asbestos-related disease.

In summary, the short-term airborne asbestos concentrations measured for both a worker removing asbestos-containing brakes from heavy construction equipment as well as for a bystander working in the vicinity of such activity were below both the current OSHA excursion limit for asbestos and all the previous US occupational asbestos standards. Similarly, the plausible 8-h TWA exposures of heavy equipment mechanics would be expected to be less than current and past occupational exposure limits. Based on



*8-hour TWA was estimated using short term (30min) samples and assuming 3 brake removals per day. Estimate for Boelter et al. (2007) did not include cutting brake band with an abrasive disc because it is not considered a usual activity in brake replacement.

Fig. 7. Comparison of airborne asbestos exposures for automobile mechanics to those measured by mechanics handling asbestos-containing brakes on heavy construction equipment.

a collection of 44 samples, this study found that short-term exposures (30 min) of a mechanic to airborne asbestos during the removal and disassembly of asbestos-containing brakes from heavy construction equipment average 0.024 f/cc (range: 0.001–0.1 f/cc), whereas 8-h TWA exposures average 0.009 f/cc (range: 0.005–0.23 f/cc), based on the assumption that three brake assemblies could be removed within a workday. The industrial hygiene data presented here should therefore prove useful for retrospective and current exposure assessments of individuals and hazard assessments of work activities that involve repairing and replacing asbestos-containing brakes contained in heavy construction equipment.

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