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ORIGINAL ARTICLE

Airborne asbestos take-home exposures during handling of chrysotile-contaminated clothing following simulated full shift workplace exposures

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The potential for para-occupational, domestic, or take-home exposures from asbestos-contaminated work clothing has been acknowledged for decades, but historically has not been quantitatively well characterized. A simulation study was performed to measure airborne chrysotile concentrations associated with laundering of contaminated clothing worn during a full shift work day. Work clothing fitted onto mannequins was exposed for 6.5 h to an airborne concentration of 11.4 f/cc (PCME) of chrysotile asbestos, and was subsequently handled and shaken. Mean 5-min and 15-min concentrations during active clothes handling and shake-out were 3.2 f/cc and 2.9 f/cc, respectively (PCME). Mean airborne PCME concentrations decreased by 55% 15 min after clothes handling ceased, and by 85% after 30 min. PCM concentrations during clothes handling were 11–47% greater than PCME concentrations. Consistent with previously published data, daily mean 8-h TWA airborne concentrations for clothes-handling activity were approximately 1.0% of workplace concentrations. Similarly, weekly 40-h TWAs for clothes handling were approximately 0.20% of workplace concentrations. Estimated take-home cumulative exposure estimates for weekly clothes handling over 25-year working durations were below 1 f/cc-year for handling work clothes contaminated in an occupational environment with full shift airborne chrysotile concentrations of up to 9 f/cc (8-h TWA).

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INTRODUCTION

Previously published studies and reviews related to asbestos and take-home exposures have primarily explored the association between disease incidence and the reported potential for household or non-occupational exposure.^{1–9} Beginning in 1976, a number of epidemiological studies reported on the risk for developing pleural mesothelioma in the household contacts of asbestos workers.^{1,4,9–13} Some studies have also noted that cases of disease in the household contacts of asbestos workers occurred more commonly in certain professions, such as insulation workers and miners, as well as some asbestos product manufacturing and shipyard workers.^{2,3,5,8–10}

When studies have reported the asbestos mineral fiber type associated with disease in household contacts, authors have specifically cited exposure of the workers to amosite,^{4,13} crocidolite,⁶ or general/mixed amphibole and chrysotile exposure.^{8,9} It is notable that there is a large body of evidence in the published literature supporting substantial differences in fiber potency according to asbestos mineral type, with chrysotile being the least potent of the common industrial mineral types for lung cancer and mesothelioma, and the amphiboles (including both amosite and crocidolite) being far more potent.^{14–18} The accumulated evidence to date points to the potential for increased risk of disease in

household populations with take-home exposure above some cumulative lifetime exposures to amphiboles or mixed asbestos fiber types.^{8,9,13}

World asbestos production data have shown that the use of amphibole asbestos began to decline in the 1970s and ceased in the 1990s, whereas chrysotile production did not begin to decrease until the 1990s.^{19,20} Owing to the marked differences in potency, epidemiological study results of take-home exposures to amphiboles or mixed fibers are not relevant to populations exposed to predominantly or only chrysotile.^{15,21} Additionally, the epidemiology studies on take-home exposure generally involved persons who historically worked in industries with asbestos exposure beginning in the 1930s and 1940s through the 1970s or 1980s.^{9,13,22,23}

Few studies have addressed the magnitude of airborne asbestos concentrations in the home environment associated with take-home contamination potential from the workplace. The National Institute for Occupational Safety and Health (NIOSH) and others have examined available indirect evidence of the asbestos take-home exposures of household members using such methods as questionnaire responses, evidence from medical evaluations, and reports of possible sources of asbestos exposure in the home.^{7,10,24} NIOSH highlighted laundering of the asbestos-contaminated

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clothing of workers as a primary exposure route for asbestos brought home by workers. Correspondingly, the current investigation focused on characterizing airborne concentrations during the handling of asbestos-contaminated clothing consistent with laundering activities.

A handful of studies from the 1970s and 1980s reported airborne fiber concentrations associated with the presence or handling of asbestos-contaminated clothing.^{25–27} Of these, Sawyer and Mangold reported sampling results using the phase contrast microscopy (PCM) analytical method, which, because of its low cost and ease of use in the field, was the analytical method commonly used for regulatory purposes to estimate airborne asbestos concentrations. However, the PCM sampling and analytical method is not specific to asbestos fibers, and therefore will not necessarily be an accurate metric for asbestos exposure potential when non-asbestos fibers are present (e.g., fibers from work clothing).²⁸ A third study, carried out by Nicholson et al.,²⁶ reported air sampling results based on gravimetric analysis in nanograms of asbestos per cubic meter of air (ng/m³), a method that does not allow for a direct comparison with fiber counts per volume of air without a conversion factor (which is likely to vary with each workplace). Owing to the sampling and analytical methods used in these three historic studies, none of their results can be used to provide an accurate range of the airborne asbestos fiber concentrations associated with handling of contaminated work clothing.

Several more recent exposure studies have been published that evaluated the simulated handling of contaminated work clothing following automotive work activities using both PCM and transmission electron microscopy (TEM), which is a specific analytical method for determining asbestos mineral fiber types.^{29–32} In these studies, the reported airborne concentrations of asbestos during work activities associated with friction products were very low or non-detectable (ND), and the airborne asbestos concentrations during clothes handling, when detectable, were even lower.^{29–32} Although these data are informative for the specific tasks evaluated, they have unknown relevance to the handling of clothing that is more heavily contaminated with asbestos fibers or for activities in which the worker exposures were to friable asbestos products or raw asbestos fibers. Further, these studies do not present a basis to quantitatively characterize the relationship between workplace exposures and the exposure potential associated with handling contaminated work clothing in the home.

To address the identified gaps in the available data, an initial study was designed and conducted to compare asbestos exposures at selected simulated workplace concentrations with the corresponding concentrations generated during contaminated clothes handling and shake-out (SO).²⁸ Chrysotile asbestos (grade 7T) was used in that study because of its use in many industrial and consumer products (e.g., brakes, roofing materials, floor tiles, gaskets, packing) and because data indicated that chrysotile asbestos continued to be used in these products after amphibole asbestos use declined substantially.^{19,20} As a result, the potential for take-home exposure to chrysotile was likely to have occurred more frequently and more recently compared with take-home exposures to amphiboles. In the initial study described in Sahmel et al.,²⁸ clothing was fitted on mannequins in a sealed chamber and exposed to target airborne chrysotile concentrations over periods of 30–45 min to concentrations of up to 3.3 f/cc, or 0.55 f/cc as an 8-h time-weighted average (TWA). In six subsequent individual clothes-handling events, the clothing was then handled and shaken out for 15 min to simulate laundry activities in the home.

For direct comparison with the simulated workplace concentrations in the initial study, 8-h TWA clothes-handling concentrations (consistent with daily clothes handling and shaking out) for 15-min active daily clothes handling were calculated and found to

average 1.2% of the 8-h TWA simulated work environment concentrations. When converted to 40-h TWAs, consistent with once weekly laundering of a week's worth of work clothing, chrysotile concentrations during 15-min active clothes handling were found to average 0.25% of the weekly airborne concentrations to which workers were exposed.²⁸

The purpose of this follow-up study was to further evaluate the relationship between the handling of work clothing during laundry activities (take-home exposure potential) and the occupational airborne exposure of the worker. Like the initial study, this study evaluated scenarios in which the clothing was handled and shaken indoors. Historically, workers may have blown or brushed off clothing in the workplace or shaken it outdoors before bringing it into the home; thus, actual exposures of clothes handlers may have been lower than what was measured in our study in certain scenarios. This study also investigated in more detail some of the potentially important exposure factors that could affect indoor airborne chrysotile concentrations during clothes handling. Specifically, the current study (i) simulated a concentration of chrysotile that was many fold higher than what was measured in the initial study and involved work clothing exposed over a full simulated work day; (ii) utilized a lower indoor dilution ventilation rate to more closely approximate the natural room-to-room ventilation rate within a typical residence; and (iii) evaluated the potential influence of work clothing made from different types of fabric (i.e., cotton or polyester/cotton blend), as well as both used and new clothing. And finally, estimated cumulative exposures of the clothes handler were compared with the estimated cumulative worker exposures. For retrospective exposure assessment purposes, often the only available information for estimating clothes handler exposure potential for a specific scenario is the corresponding worker exposure (both in terms of 8-h TWAs and overall cumulative exposure), and so, it is informative to compare daily, weekly, and total cumulative exposures for the simulated worker to the corresponding exposures of the clothes handler. The data generated should help to further inform the scientific understanding of asbestos exposure potential during the handling of contaminated work clothing for the conditions evaluated.

METHODS

Study Preparation and Study Setting

An institutional review board (IRB) reviewed and approved the study design prior to commencement (Copernicus Group; Study ID #CRI1-11-208; Durham, NC, USA). The study was conducted in a negative pressure chamber (volume of 58 m³) at RJ Lee Group in Monroeville, PA, USA that was equipped with an airlock for entering and exiting the chamber after following proper decontamination procedures. The chamber was constructed of non-conductive painted plywood to minimize interaction with airborne fibers or particulates. Safety and clearance sampling procedures, as well as isolation, decontamination, and personnel safety procedures have been described previously.²⁸ During all study events, a high efficiency particulate air (HEPA) ventilation air filtration device (AFD) was operated at a rate of 3.5 air changes per hour (ACH). This rate is consistent with the average U.S. EPA reported rate of the naturally driven (minimum) room to room airflow within residential buildings, as presented in the U.S. EPA's indoor air quality monitoring program RISK, Version 1.5, which is designed to estimate individual exposure to indoor air pollutants.³³

Between study events, a separate AFD was run at a rate of approximately 24 ACH to decontaminate the chamber and decrease the time to background concentrations. During the 5 days of testing, which occurred from April 9 to 13, 2012, ambient outdoor temperatures ranged from 16.7 °C (62.1 °F) to 24.3 °C (75.7 °F), while temperatures within the study chamber ranged from 18.5 °C (65.3 °F) to 23.6 °C (74.5 °F) during testing. Ambient humidity levels outside the chamber ranged from 21.3% to 43.1%, while levels inside the study chamber were found to be 25.4% to 53.6%.

Details about the grade 7T chrysotile fibers used have been previously described.²⁸ Three types of clothing were utilized: new 100% cotton, new

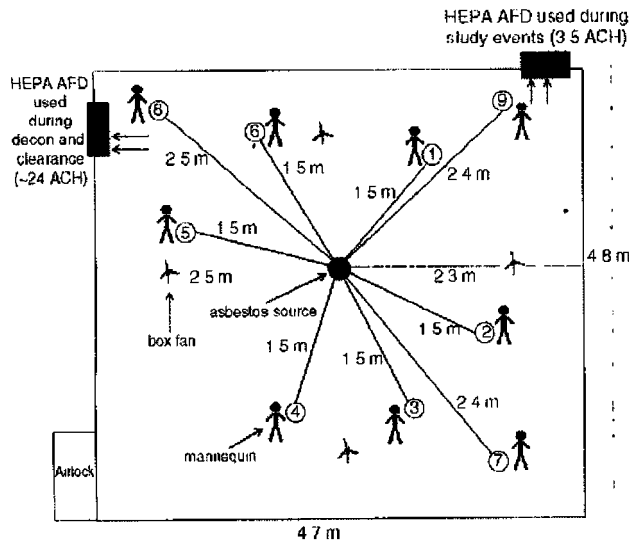


Figure 1. Chamber design for clothes loading events (simulated workplace environment for clothing contamination).

cotton/poly blend of 35% cotton/65% polyester, and used 100% cotton. For consistency, the new uniforms were purchased from the same vendor as the initial study (Banner Uniform Center, San Francisco, CA, USA).²⁸ Both new and used cotton work clothing were of a similar work uniform style. The used clothing was obtained from a variety of sources and was selected to match the style of the new clothing as closely as possible. Human hair wigs were also placed on the mannequins during loading events to characterize the additional exposure potential from contaminated hair after working in an environment with airborne asbestos.

Loading Events (Simulated Workplace Environment)

For the two replicate loading events, an airborne chrysotile concentration of 10 f/cc was targeted. The chrysotile was aerosolized in the chamber using a dust generation system as previously described, with fans running to assist in airborne mixing.²⁸ For each clothes loading event in the chamber, nine dressed mannequins (three mannequins for each of the three clothing types) were placed in a circular pattern at a distance of 1.5–2.5 meters from the dust generator at the center of the chamber. A fresh set of clothing was placed on each mannequin prior to each loading event. Figure 1 illustrates the layout of the study chamber during the loading events.

Exposures to the simulated workers (i.e. dressed mannequins) were estimated by placing sampling cassettes on the right and left lapels of each mannequin at breathing zone height (1.5 meters) during the loading events. To avoid overloading the sample cassette filters during the generation of a high concentration of airborne fibers, consecutive samples were collected for 75 min or less over a total of 6.5 h (to simulate the typical exposure duration in an 8-h workday). No study participants entered the chamber during loading events, and the sampling pumps were turned on and off remotely. Following each loading event, clothing was carefully removed from the mannequins in order to avoid disrupting settled fibers, placed in three non-conductive storage boxes (one box for each of the three clothing types), and stored for later use in the clothes-handling and SO events.

Clothes-Handling and SO Events (Simulated Household Environment)

Six clothes-handling and SO events were performed using the work clothing contaminated during the two simulated workplace loading events. Two separate clothes-handling and SO events were conducted for each of the three clothing types. Three shirt/pants sets of work clothing of the same fabric type were handled in two separate clothes-handling events matched to the corresponding loading event. This design allowed for the direct comparison of the corresponding workplace vs clothes-handling concentrations by event. During each handling and SO event, personal samples were collected on the right and left lapels of the clothes

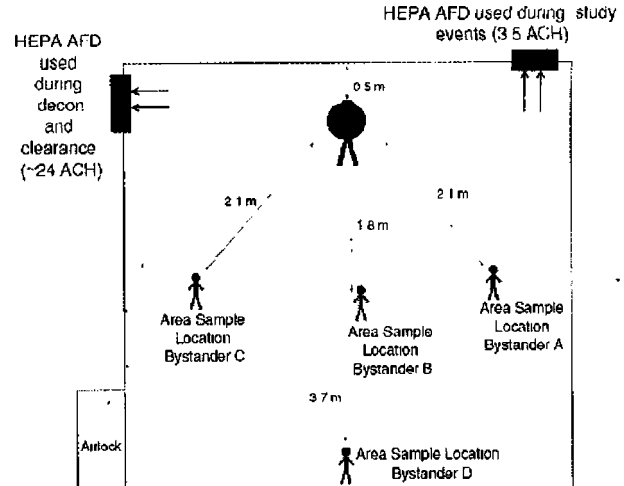


Figure 2. Chamber design for clothes-handling and SO events (simulated household environment).

handler and area samples representing bystanders (BYST) were collected at distances of 1.8–3.7 meters from the handling activities. A diagram of the clothes-handling and SO event layout is shown in Figure 2.

Each handling and SO event consisted of 15 min of active clothes handling followed by a period of no activity for an additional 30 min (for a total of 45 min per event). The additional sampling time following clothes-handling activities allowed for the measurement of potential residual exposure to the clothes handler if he or she stayed in the room following the handling of clothing for an extended period of time performing other activities, such as to iron or fold clean laundry. A total of six personal samples were collected on the clothes handler during each handling and SO event.

Specifically, one 5-min lapel personal sample and a pair of 15-min right and left lapel personal samples were collected during the active clothes-handling period. During the subsequent 30-min period of no activity, one 5-min sample was collected for the 15–20 min time period, one 15-min sample was collected for the 15–30 min period, and a final sample was collected during the 30–45 min period during each of the six clothes-handling events. Four area samples that were intended to represent bystander exposure were also collected over the entire 45-min period. See Figure 3 for a graphical depiction of the sampling timeline for each clothes-handling and SO event.

At the beginning of each clothes-handling event, the handler removed the contaminated clothing from the non-conductive storage box and then handled and periodically shook out the contaminated work clothing consistent with typical laundering activities. The accompanying contaminated human hair wigs associated with the exposed mannequins' work clothing were also shaken out during each clothes-handling event. During the 30-min period of inactivity following active clothes handling, clothes handlers did not physically contact the clothing, but remained in the chamber so that the residual exposure potential associated with the laundry area after clothes handling could be evaluated.

Sampling and Analytical Methods

Air samples were collected and analyzed in accordance with NIOSH 7400 (PCM) and NIOSH 7402 (TEM). PCME concentrations (i.e., asbestos fibers $\geq 5 \mu\text{m}$ in length and $\geq 0.25 \mu\text{m}$ in width with a 3:1 aspect ratio) were calculated by multiplying the ratio of asbestos fibers to non-asbestos fibers (as measured by TEM) by the measured PCM concentration for each sample, as described in NIOSH method 7402. Area and simulated personal breathing zone air samples (including on mannequin lapels during the loading events, BYST samples during clothes-handling events, ambient and background samples, and AFD exhaust samples) were collected with stationary high-volume sampling pumps (Dawson/Emerson; Pennsylvania, USA) at a rate of 5.5–20 liters per minute (l/min). Personal samples of the clothes handlers, study participants working outside the chamber, and

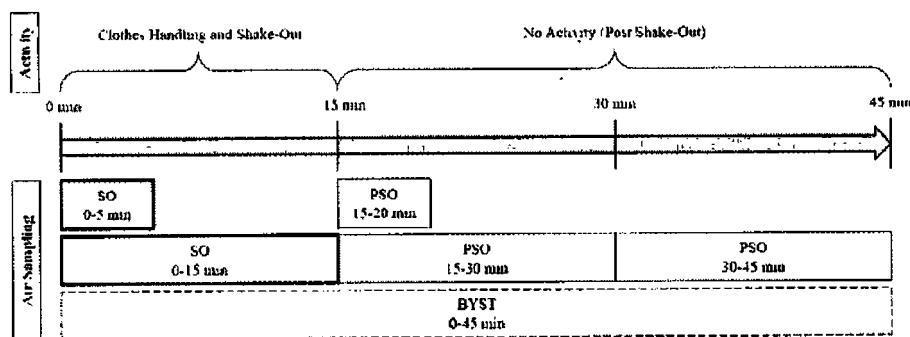


Figure 3. Study sample timeline and nomenclature during clothes-handling and shake-out events. This figure shows the relative time duration and nomenclature of (1) personal samples taken during clothes handling and shake-out (SO), (2) personal samples taken post shake-out (PSO), and (3) samples collected at bystander (BYST) locations.

samples of study personnel during decontamination activities were collected using personal high-volume sampling pumps (SKC; Pennsylvania, USA) at a rate of 1–2 l/min. A minimum of two field blanks was collected during each study event. All samples were analyzed by the RJ Lee Group in Monroeville (accredited by the American Industrial Hygiene Association Laboratory Accreditation Program, #100364).

Data and Statistical Analysis

Descriptive statistics were performed on the PCM, TEM, and calculated PCME results of airborne fiber concentrations collected during the loading and SO events. Arithmetic means and standard deviations (SD) were calculated for each type of sample and analytical method, along with standard error of the mean (SE) when appropriate; Systat 11 (Systat Software, San Jose, CA, USA) was used to perform all statistical tests. Two-factor analysis of variance (ANOVA) was used to evaluate the effects of differences in sampling period and measurement method. Likewise, two-factor ANOVA was used to evaluate the effects of differences in sampling period and fabric type. To perform pair-wise comparisons between different sampling periods or sampling conditions, *t*-tests were used with the Bonferroni adjustment to account for multiple comparisons. For the left and right lapel samples collected during each 15 min clothes-handling period, the paired results were averaged together and treated as a single sample for further calculations and analyses. The sampling results have been presented primarily in PCME; however, PCM data are also presented for comparison to the PCME values in order to explore the differences between total airborne fibers and airborne chrysotile fibers.

Calculation of Cumulative Take-Home Exposure Estimates Associated with Specific Workplace Concentrations

In the workplace, cumulative (lifetime) exposure to asbestos is often expressed as the average 8-h TWA airborne concentration in units of f/cc multiplied by the number of occupational years of exposure (f/cc-years) or by the number of hours of exposure (f/cc-hours). For example, the cumulative asbestos exposure of a worker with an 8-h TWA workplace concentration equal to the current asbestos OSHA PEL of 0.1 fiber/cc for 40–45 years is between 4.0 and 4.5 f/cc-years, or between 8000 and 9,000 f/cc-h (assuming 2000 h worked per year). Cumulative exposure or dose can be defined in terms of different metrics, including cumulative workplace exposure and cumulative environmental exposure (e.g., non-occupational or ambient air exposures). Cumulative occupational exposures are often used when attempting to characterize the plausible lifetime cancer risk for asbestos, because this metric can be most readily compared with dose-response information developed from epidemiology studies of workers who encountered asbestos.^{18,34–36}

When estimating the incremental cancer risk associated with a lifetime of exposure to a carcinogenic agent, an occupational year is defined differently than an environmental or non-occupational year. As stated above, an occupational year is typically defined as 250 days/year or 8 h/day, or 2000 h/year. In contrast, an environmental ambient year, or calendar year, is often defined as 24 h/day for 365 days/year, or 8760 h/year. As the asbestos epidemiology literature is typically presented in terms of f/cc-year of exposure based on a 40 h work week, one must convert the environ-

mental cumulative exposure to an equivalent workplace cumulative exposure in order to be able to estimate the lifetime risk using available epidemiological data. Using units of f/cc-h rather than f/cc-years allows for a direct comparison of cumulative exposure between the workplace, ambient exposure, and the exposure scenario of interest, if long-term average inhalation rates are taken to be relatively similar between scenarios. An analysis of the association between the simulated workplace exposures and clothes-handling exposures measured in this study and the initial study was used to estimate cumulative exposure potential over the range of specific workplace concentrations evaluated.²⁸

RESULTS

A total of eight separate exposure events were conducted (two loading events and six clothes-handling and SO events). For all study events, samples resulted in measureable concentrations (i.e., there were no samples that were ND for asbestos). Personal sampling was also conducted outside the study chamber to monitor participant safety during the study. Sample results demonstrated that personal airborne fiber concentrations for study participants outside the study chamber were ≤ 0.002 f/cc (PCM). Inside the chamber during decontamination activities, personal exposures (collected on the outside of PPE and without regard to respiratory protection) were ≤ 0.03 f/cc (PCME). Outdoor background concentrations were ≤ 0.003 f/cc (PCM) for the duration of the study. Chamber clearance samples prior to clothes-handling events and samples collected at the AFD exhaust points were ≤ 0.003 f/cc (PCM).

Airborne Fiber Concentration Measurements During the Loading Events (Simulated Workplace Environment)

Each loading event lasted approximately 6.5 h (386 and 388 min). Figure 4 shows the overall distribution of the PCM and PCME air concentration results for both events (arithmetic mean, quartiles, fifth and ninety-fifth percentiles). The mean of the PCME airborne concentrations for chrysotile was 11.4 f/cc (11.1 f/cc and 11.7 f/cc for Loading Events #1 and #2, respectively). The mean PCM airborne concentration was 11.6 f/cc (11.4 f/cc and 11.8 f/cc, respectively). Supplementary Table A provides the sample numbers ($n = 15$ –18), sample durations (57–73 min each), arithmetic means, and SDs for PCM, TEM, and PCME results for each loading event.

Airborne Fiber Concentrations During and After Indoor Clothes Handling and SO (Simulated Household Environment)

Figure 5 visually depicts an exemplar clothes-handling and SO event. PCM and PCME airborne fiber concentrations were measured during each active clothes-handling and SO sampling

period (SO 0–5 min and SO 0–15 min), during each post-shake out (PSO) sampling period (PSO 15–20 min, PSO 15–30 min, and PSO 30–45 min), and at area BYST locations during the combined SO and PSO periods (BYST 0–45 min) (Figure 6). Mean PCME airborne fiber concentrations were 3.2 f/cc for SO 0–5 min and 2.9 f/cc for SO 0–15 min. As noted above, the right and left lapel SO 0–15-min samples for each of the six clothes-handling events were averaged together and treated as a single sample, consistent with standard industrial hygiene sample analysis.

Paired *t*-tests for the PCM, TEM, and PCME results indicated that concentration differences between the right and left SO 0–15 min samples were not statistically significant ($\alpha > 0.05$). Airborne concentrations decreased during the post clothes handling and SO period (PSO) compared with the active clothes-handling and SO period; similar decreases in fiber concentrations were observed for both the PCM and PCME measurements, with approximately a 50% decrease in fiber concentrations during the first 15 min PSO to 1.31 f/cc, PCME (a decrease of 49% for PCM and 55% for PCME). A total decrease of over 80% was observed from active SO to the second 15 min PSO, with a reduction in the airborne concentration to 0.45 f/cc, PCME (decrease of 82% for PCM and 85% for PCME)

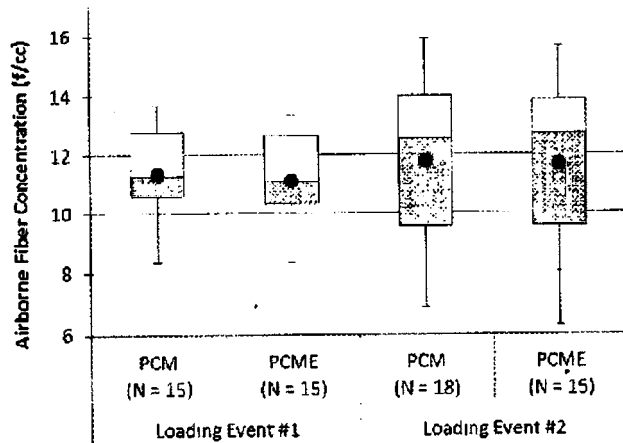


Figure 4. Distribution of the PCM and PCME airborne concentrations for the loading (simulated workplace) events. This figure shows the comparative median, quartiles, fifth percentile, and ninety-fifth percentile values (box plots), and means (black circles) for the loading events #1 and #2. All samples were detected above the limit of detection (LOD). In cases where $N < 18$, the remaining samples were overloaded and not analyzed.

during the PSO (30–45 min) period. The mean PCM and PCME concentrations during the second half of the PSO sampling period (PSO 30–45 min) were statistically significantly lower than during the active clothes-handling period (SO 0–15 min) (*t*-test, Bonferroni-adjusted $\alpha = 0.05$).

Within each of the clothes-handling sampling periods, the mean PCM concentration was higher than the mean PCME concentration. A two-factor ANOVA conducted to evaluate the effect of sampling period and measurement method (i.e., PCM vs PCME) on the measured fiber concentrations indicated that the order of the sampling periods significantly impacted the measured concentrations, as did the analytical method (i.e., PCM vs PCME) ($\alpha = 0.05$). Depending on the sampling period, the PCME results were 10% to 32% lower than the PCM results, with the smallest difference seen for the BYST samples. These results indicated that a statistically significant fraction of the airborne fibers meeting the PCM counting criteria were likely fabric fibers. Additionally, both the PCM and PCME concentrations measured during the first 5 min of clothes handling and SO were virtually the same as concentrations measured during the entire 15 min of clothes handling and SO. This finding suggested that airborne fiber concentrations remained relatively steady between the 5 to 15-min active clothes-handling period. Supplementary Table B reports the sample numbers, arithmetic means, and SDs for the PCM, TEM, and PCME measurements taken during each of the clothes-handling events for all sampling time periods during and after clothes handling/SO.

Personal vs BYST Exposures During and After Indoor Clothes Handling and SO (Simulated Household Environment)

To evaluate the potential for exposure to bystanders during the clothes-handling events, area samples were collected at 1.8 meters ($n = 1$ per event), 2.1 meters ($n = 2$ per event), and 3.7 meters ($n = 1$ per event) from the clothes handler. BYST samples were collected throughout each 45-min clothes-handling and SO event period, which did not allow for a direct comparison with the active personal clothes handler measurements. Therefore, to compare the personal and BYST samples, the clothes handler exposure during the full 45-min period was calculated by averaging the PCME results for the three 15-min time periods (SO 0–15 min, PSO 15–30 min, and PSO 30–45 min), with equal weighting for each 15-min time period. The arithmetic mean calculated personal PCME concentration for the clothes handler during this 45-min period was 1.57 f/cc, whereas the mean measured PCME concentration at the BYST locations was 0.63 f/cc (range 0.61–0.65 f/cc) (Figure 7). No trend was observed among the BYST concentrations with increasing distance from the clothes handler up to a distance of 3.7 m. However, analysis of this



Figure 5. Photos depicting clothes handling and shake out.

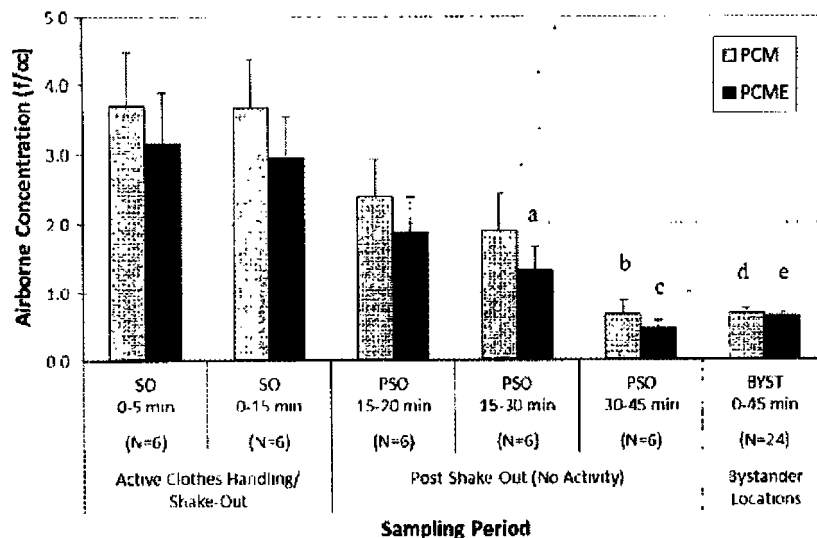


Figure 6. PCM and PCME mean airborne fiber concentrations measured during clothes handling and SO, post shake-out (PSO), and at BYST locations. This figure presents the PCM (grey) and PCME (black) average airborne fiber concentrations measured during clothes-handling and SO events. Letters and notations below the figure indicate the sampling periods for which the mean concentration was statistically significantly lower (signified by the symbol "a") compared with other sampling periods (t-test, Bonferroni-adjusted $\alpha = 0.05$). All samples were detected above the LOD. Error bars indicate SE. ^aPCME: PSO 15–30 min < SO 0–5 min; ^bPCM: PSO 30–45 min < SO 0–5 min and SO 0–15 min; ^cPCME: PSO 30–45 min < SO 0–5 min and SO 0–15 min; ^dPCM: BYST 0–45 min < SO 0–5 min, SO 0–15 min, and PSO 15–20 min; ^ePCME: BYST 0–45 min < SO 0–5 min and SO 0–15 min.

comparison was limited because of the continuous sampling at all BYST locations across both the active and inactive clothes-handling periods that did not allow for a direct ratio of concentrations at distance by activity. For the exposure conditions used in this study (chamber volume of 58 m³, ventilation rate of 3.5 ACH), chrysotile concentrations at the BYST locations (1.8–3.7 m from the source) were just below 50% of the concentrations measured in the personal breathing zone of the clothes handler.

Effect of Fabric Type on Exposure Potential During Clothes Handling and SO

For the six clothes-handling events, two events utilized new cotton fabric clothing, two utilized new polyester fabric clothing, and two utilized used cotton fabric clothing. Figure 8 shows the PCM and PCME concentrations by clothing type associated with the active clothes-handling periods for all events (SO 0–5 min and SO 0–15 min). There were no statistically significant differences observed in PCM or PCME concentrations for the three different fabric types (ANOVA, $\alpha = 0.05$). Additionally, no trends were observed between results during the first 5 min of SO as compared with the entire 15 min SO period for any of the fabric types. Supplementary Table C provides the sample numbers, arithmetic means, and standard deviations for the PCM, TEM, and PCME measurements taken during active clothes handling/SO for each fabric type.

Comparison Between Loading Events (Simulated Workplace Environment) and Clothes-Handling/SO Events (Simulated Household Environment)

To facilitate a comparison between the loading (simulated workplace environment) and clothes-handling (simulated household environment) PCME concentrations, TWA airborne concentrations were calculated for each simulated workplace event and clothes-handling event to evaluate the relative household exposures associated with specific workplace exposures. For direct comparison with the 8-h workplace TWA measurements,

8-h clothes-handling TWA concentrations were calculated, representing the measured exposure potential associated with daily washing of three sets of contaminated work clothing compared with the daily 8-h TWA in the workplace. Forty-hour TWA clothes-handling concentrations were also calculated to account for the fact that, for household washing contaminated clothing for a single worker, multiple sets of contaminated work clothes would more likely be laundered together approximately once per week. For both the simulated workplace and simulated clothes-handling events, the TWA values were calculated assuming that clothes-handling-related asbestos exposure did not occur for the remaining period of time outside of the 45-min duration of the active clothes handling and staying in the laundry room after clothes handling (and for which no data were obtained in this study).

The arithmetic mean of the calculated PCME 8-h TWA values was 9.2 f/cc for the simulated workplace exposure events (loading); and the 40-h TWA was also 9.2 f/cc (PCME), assuming the same consistent concentration in the workplace over the 5-day work week. The mean clothes-handling PCME 8-h TWA concentrations were 0.033 f/cc (5 min) and 0.092 f/cc (15 min) for active clothing SO. The mean calculated PCME 8-h TWA values associated with 15 min of daily active clothes handling (SO 0–15 min) were therefore 1.0% of the simulated workplace 8-h TWA. This compared with a value of 1.2% for the initial study, which involved lower loading concentrations of up to 0.55 f/cc as an 8 h TWA (TEM) (Table 1).²⁸ For BYST exposure potential, the mean calculated BYST PCME 8-h TWA during the 15 min of daily clothes handling and subsequent 30 min of inactivity was an average of 0.6% (range 0.3–1.3%) of the PCME 8-h TWA for the simulated workplace.

Additionally, 40-h TWA or weekly percentage ratios for clothes handling were calculated by dividing the 40-h clothes-handling TWA concentrations by the 40-h workplace TWA concentration (Table 2). The 40-h workplace TWA concentration is the same as the 8-h workplace TWA concentration, as it was assumed that workplace exposures were consistent from day to day. For the 40-h clothes-handling TWAs, it was assumed that either one or

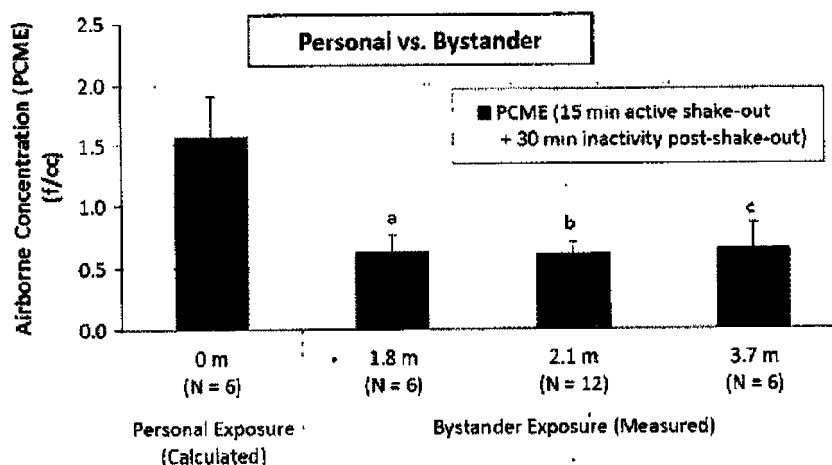


Figure 7. Comparison of mean PCME concentrations associated with personal vs BYST exposures during clothes-handling events. Area samples to estimate BYST exposure potential were collected during each 45-min clothes-handling event sampling period. As no single personal sample spanned the entire 45 min, personal concentrations for each event were calculated from the 15 min sampling periods as follows: $[(1/3)(SO\ 0-15\ min) + (1/3)(PSO\ 15-30\ min) + (1/3)(PSO\ 30-45\ min)]$. The mean 45-min calculated personal clothes-handling exposure was 1.57 f/cc (PCME). Error bars indicate SE. Letters and notations below the figure indicate the datasets for which the arithmetic mean was statistically significantly lower (signified by the symbol “<”) compared with the mean personal exposure (t-test, Bonferroni-adjusted $\alpha = 0.05$). ^aArithmetic mean for BYST 1.8 m away (0.62 f/cc, PCME) < calculated personal concentration (1.57 f/cc, PCME). ^bArithmetic mean for BYST 2.1 m away (0.61 f/cc, PCME) < calculated personal concentration (1.57 f/cc, PCME). ^cArithmetic mean for BYST 3.7 m away (0.65 f/cc, PCME) < calculated personal concentration (1.57 f/cc, PCME).

two loads of work laundry would be handled in a typical household per week (three or six sets of work clothing total). Two different numbers of clothing sets were evaluated in order to assess the potential effect of the number of sets handled on the airborne concentrations and for comparison with the initial study.²⁸ For active clothes handling, the mean clothes-handling PCME 40-h TWA values ranged from 0.007 (5 min) to 0.018 f/cc (15 min). The 40-h TWA percentage ratio of clothes handling to simulated workplace concentrations for handling clothing for 15 min once per week averaged 0.20% in the current study compared with 0.25% in the initial study (Table 2). The mean calculated PCME 40-h TWA for BYSTs over the 15 min of clothes handling and subsequent 30 min of inactivity was 0.13% of the simulated workplace concentration (0.012 f/cc for BYSTs vs 9.18 f/cc for the simulated workplace). Results indicated that the TWA ratios remained relatively consistent despite differences in average simulated workplace concentrations across the two studies of approximately 30-fold (0.3–9 f/cc). Clothes-handling duration appeared to be a better predictor of exposure potential than the number of sets of clothing handled, based on the combined results of the two studies.

Measured R_{TH} Values for Determining Cumulative Exposure Estimates

On the basis of the very consistent results obtained for the take-home-to-workplace concentration ratios over a substantial range of airborne asbestos concentrations, it was determined that cumulative exposures associated with clothes-handling activities could be estimated for take-home exposure over a range of airborne concentrations. The ratio of the take-home to occupational airborne concentrations measured over the range of simulated concentrations tested in the two studies was therefore used to develop an approach for conducting cumulative exposure calculations. This ratio is referred to as R_{TH} , and is defined as the take-home task-based concentration ($C_{TH,task}$) divided by the 8-h TWA occupational or workplace concentration ($C_{OCC, 8hr}$), that is, $R_{TH} = \frac{C_{TH,task}}{C_{OCC, 8hr}}$ (for clothes-handling exposure times ranging from 0.08 to 0.75 h). R_{TH} values for the scenarios examined in the

current study are presented in Table 3. These values were very consistent over the breadth of simulated workplace concentrations evaluated in the two studies (average was 0.35 ± 0.04) for active clothes-handling activities. Using the information presented in Table 3 and the calculated R_{TH} values, the estimated take-home airborne concentration for a specific task of interest ($C_{TH,task}$) can be determined when the 8-h TWA workplace exposure concentration ($C_{OCC, 8hr}$) for the worker bringing home contaminated clothing is known or can be reliably estimated ($C_{TH,task} = C_{OCC, 8hr} \times R_{TH}$).

It should be noted that the corresponding airborne concentrations for clothes-handling times shorter than 5 min were not measured, and therefore estimates for clothes-handling exposures less than 5 min may not be accurate using the R_{TH} values from this study. However, according to the airborne clothes-handling concentrations presented in Tables 1 and 2, it does appear that the clothes-handling exposure potential was consistent between 5 and 15 min, allowing for the consideration of exposure estimates for different time durations within this range.

DISCUSSION

This study quantitatively compared the concentrations of asbestos in a simulated work environment with the corresponding airborne concentrations generated during the subsequent handling of contaminated work clothing for laundering in a household environment. The TWA concentrations of airborne chrysotile obtained for the simulated workplace conditions evaluated in this study (clothes loading events) averaged 9.2 f/cc as determined by PCME. This concentration was consistent with historical airborne fiber concentrations that were observed in many industrial environments in the 1940s–1960s.^{37,38} The corresponding mean of the airborne concentrations associated with active handling of contaminated work clothes in the home between 5 and 15 min was 3.1 f/cc (PCME).

Airborne chrysotile concentrations declined substantially during the period following the 15 min of active clothes handling, from 2.9 to 1.3 f/cc (PCME) during the first 15 min of inactivity and then to 0.45 f/cc (PCME) during the second 15-min period of inactivity.

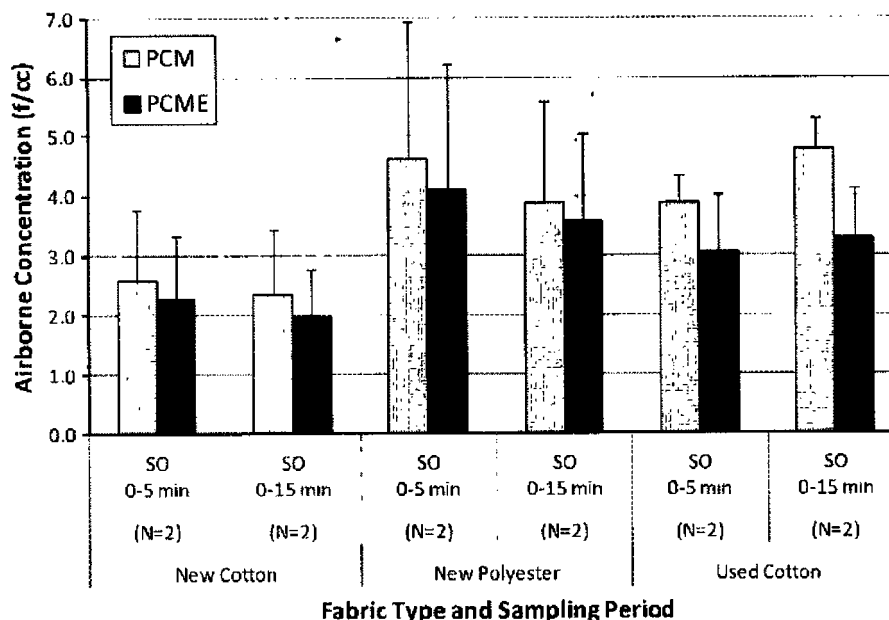


Figure 8. Comparison of airborne PCM and PCME fiber concentrations measured during handling of different clothing fabric types. Clothes used in the study were made of new cotton, new polyester, and used cotton. PCM (grey) and PCME (black) results are shown for the SO 0-5 min and SO 0-15 min sampling periods. Error bars indicate SE. There were no statistically significant differences in PCM or PCME concentrations by clothing fabric type.

The 15-min active clothes-handling value could be considered a maximum plausible concentration associated with clothes handling at the workplace concentrations evaluated, as it is unlikely that the duration of handling and SO of contaminated clothes would have typically exceeded 5 min. Additionally, heavily contaminated, dust-laden work clothing may have been brushed off before leaving the workplace or shaken out before bringing it into the household environment, rather than the assumed indoor clothes-handling scenario used in this study. Such activities could result in lower exposure potential to the household member.

On a TWA basis, 15-min clothes-handling concentrations equated to either 1% on a daily basis (8-h TWA) or 0.20% on a once per week basis (40-h TWA) of the measured exposures for the simulated worker. The corresponding percentage ratio values from the initial study were 1.2% (8-h TWA) and 0.25% (40-h TWA).²⁸ Taken together, the ratios between clothes-handling concentrations and workplace concentrations were extremely consistent between the two studies and showed a trend of increasing airborne chrysotile concentrations during clothes handling with increasing workplace airborne concentrations.²⁸ The combined results of this study and the prior published study demonstrated that either daily or weekly exposures based on an 8-h or 40-h TWA airborne concentration for clothes handling were likely to be a small fraction (1% or below) of the corresponding workplace airborne loading concentrations despite a 30-fold range in the simulated average workplace airborne chrysotile concentrations that were evaluated (see Table 2) (0.3 f/cc to over 9 f/cc, PCME, 8-h simulated workplace TWA).

On the basis of the consistency of the measured ratios between workplace and household exposures, the results of the study were also used to estimate cumulative exposure potential for take-home scenarios using the R_{TH} ratio values as presented in Table 3. Examples of the use of R_{TH} to estimate cumulative take-home exposure for clothes loading in work environments with hypothetical 8-h occupational TWAs of 0.1, 1 and 9 f/cc are shown in Table 4. For the purposes of these examples, a clothes-handling frequency of 50 weeks/year and a duration of 25 years were

assumed.³⁹ The units of f/cc-hour allowed for a direct comparison of the ambient, occupational, and take-home cumulative exposures. Corresponding cumulative exposures in f/cc-year were also presented on both an occupational basis and environmental basis for comparison. Table 4 shows that similar estimates of cumulative exposure were derived from the current study and the initial study for various exposure scenarios, despite appreciable differences in the loading concentrations between the two studies. This result indicated that cumulative exposure potential appeared to be linearly proportionate to workplace loading concentration (expressed as an 8-h TWA). Table 4 also illustrates the use of our data to reconstruct cumulative exposures for different combinations of occupational loading and take-home scenarios. For example, 15 min per week of handling clothing that was exposed to a high occupational loading environment of 9 f/cc (as an 8-h TWA) corresponded to a take-home cumulative exposure of 0.45 f/cc-year on an occupational year basis. The data also indicated that remaining in the room after SO for 15-min would contribute an additional 0.20 f/cc-year to lifetime cumulative exposure.

For comparison, these cumulative exposure values for the clothes handler are within the range of allowable cumulative lifetime equivalent exposures for workers at the current Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) and American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) of 0.1 f/cc as an 8-h TWA. Over a working lifetime of 45 years, daily workplace exposures of 0.1 f/cc would translate to a theoretical tolerable lifetime equivalent cumulative exposure of 4.5 f/cc-year.⁴⁰ Toxicologically and epidemiologically, there is as much (or more) than a 500-fold difference in the potency of the various asbestos fiber types with respect to mesothelioma (if chrysotile is potent at all).^{15,21,41,42} Therefore, when estimating risk, this difference must also be considered as it is currently not addressed in the PEL or TLV for asbestos.

With respect to residual exposure in a small room with a residential ventilation rate, the study results showed that chrysotile fibers, in the size range of interest for the regulatory

Table 1. Mean calculated 8-h time-weighted average (TWA) PCME concentrations.

Activity ^a	Samples used for calculation ^b	Assumptions used for 8-h TWA calculation					Percent of loading 8-h TWA (range) (%)
		Loads of laundry done per day	Sets of work clothes washed per load of laundry	Total duration of clothes handling/shake-out (min)	Total time spent in room after clothes handling/shake-out (min)	Number of events	
Current study	Loading	1	3	5	0	2	9.184 (8.942–9.425)
	During shake-out	1	3	15	0	6	0.33 (0.013–0.065)
	During shake-out	1	3	0	0	6	0.92 (0.037–0.158)
	Post shake-out	1	3	0	5	6	0.019 (0.006–0.038)
	PSO 15 20 min	1	3	0	15	6	0.041 (0.005–0.068)
	PSO 15 30 min	1	3	0	15	6	0.014 (0.005–0.026)
	PSO 30 45 min	1	3	15	15	6	0.133 (0.043–0.226)
	SO 0 15 min+PSO 15 30 min	1	3	15	30	6	0.147 (0.048–0.251)
	SO 0 15 min+PSO 15 30 min+PSO 30 45 min	1	3	15	30	6	0.058 (0.029–0.119)
	BYST 0 45 min	1	3	15	30	6	0.2964 (0.0976–0.5491)
Initial study ^c	Loading	1	6	15	0	4	0.0026 (0.0021–0.0030)
	During shake-out	1	6	15	15	3	0.0022 (0.0004–0.0040)
	During and post shake-out	1	6	15	15	4	0.0004 (0.0002–0.0007)
	Bystander during and post shake-out	1	6	15	15	4	0.2 (0.1–0.5)

Measured 8-h TWA airborne chrysotile concentrations are presented assuming only clothes handling and shake-out compared with the measured 8-h simulated workplace airborne chrysotile TWA concentrations. The results are also compared with our initial study of lower airborne chrysotile loading concentrations. ^a“Shake-out” refers to clothes-handling and shake out activities performed to simulate laundry handling. ^bInitial study. ^cCalculated from 30-min samples collected during 15 min of active clothes-handling followed by 15 min of inactivity. TEM as opposed to PCME was used for the calculations in the initial study owing to the large number of PCM and TEM non-detects, so as not to underestimate concentrations.

control of airborne asbestos fibers ($\geq 5 \mu\text{m}$ in length, $\geq 0.25 \mu\text{m}$ in width, and an aspect ratio of 3:1), settled out of the air fairly rapidly (with fiber concentrations decreasing by 55% after 15 min and 85% after 30 min). These data are useful for understanding and characterizing chrysotile exposure potential in a home environment with a typical air exchange rate (3.5 ACH) after active fiber disturbance has ended. This drop in airborne concentrations was more rapid than expected based on either gravitational settling calculations of asbestos exposure potential or dilution ventilation models in the published literature.^{43–46} The decline in fiber concentrations was more likely due to the effects of diffusion, electrification, impaction on other bodies, centrifugation, and agglomeration, as described in particulate research and textbooks.^{47–50}

It was notable in this study that the workplace-to-clothes handling TWA air concentration ratios between the current study and the initial study remained consistent despite differences in certain study conditions and exposure factors. The first of these different exposure factors was the use of a longer duration of time for simulated workplace exposures, consistent with contamination of the clothing over a full work shift (6.5 h in this study vs 30–45 min in the previous study).

A second important difference between the two studies was the ventilation rate in the chamber. In the prior study, an air exchange rate of 13–19 ACH was used during all study events, whereas in the current study, a room air exchange rate of 3.5 ACH was used to more closely approximate the natural (non-mechanical) residential ventilation rate between rooms in a house.³³ This notable difference in ventilation rates did not appear to affect the personal sample results. This consistency was not surprising because of the proximity of the clothes handler's breathing zone to the airborne fibers generated. However, the lower ventilation rate may have had some effect on BYST airborne concentrations, which were 0.6% of the simulated workplace concentrations (range 0.3–1.3%) on an 8-h time weighted basis in the current study vs 0.2% (range 0.1–0.5%) in the initial study.

A third exposure factor evaluated was the potential for differences to occur in airborne chrysotile concentrations during clothes handling owing to differences in work clothing fabric type. Interestingly, neither fabric type nor the age of the clothing appeared to have a significant effect on the overall airborne chrysotile concentrations generated during clothes handling. This result was somewhat unexpected, as it was hypothesized that new vs old fabrics or fabrics of different types could lead to differences in electrical charge or adherence properties of chrysotile fibers to fabrics.^{51,52}

Another notable finding of this study was that, during both the 15 min of active clothes handling and the subsequent 30 min of inactivity, the mean PCME concentrations were approximately 10–32% lower than the mean PCM concentrations, and were statistically significantly different. It appeared that a substantial number of clothing fibers in the counting range for the PCM analytical method were released from the work clothing during handling. This result demonstrated that the use of PCM analysis alone to estimate clothes-handling exposures is likely to overestimate total asbestos exposure, as clothing fibers can influence the results. In the prior study, which was conducted at lower chrysotile loading concentrations, the relative PCME concentrations during clothes handling compared with PCM were even lower (55–85% lower than the mean PCM concentrations). This suggests that it is important, and in some cases critical, to differentiate between asbestos and non-asbestos fibers when evaluating exposures associated with the handling of asbestos-contaminated clothing.

There are very few other datasets against which the results of this study can be compared. The results of early studies conducted in the 1970s and 1980s suggest consistency with the findings of this study, despite the use of PCM rather than TEM or PCME for fiber measurement in these early studies. In 1977, Sawyer²⁵

Table 2. Mean calculated 40-h time-weighted average (TWA) PCME concentrations.

Assumptions used for 40-h TWA calculation								
Activity ^a	Samples used for calculation	Loads of laundry done per week	Sets of work clothes washed per load of laundry	Total duration of clothes handling/shake-out (min)	Total time spent in room after clothes handling/shake-out (min)	Number of events	Mean calculated 40-h TWA (range) (f/cc)	Percent of loading 40-h TWA (range) (%)
Current study								
Loading	Loading	—	—	—	—	2	9.184 (8.942–9.425)	100
During shake-out	SO 0–5 min	1	3	5	0	6	0.007 (0.003–0.013)	0.07 (0.03–0.14)
During shake-out	SO 0–15 min	1	3	15	0	6	0.018 (0.007–0.032)	0.20 (0.08–0.34)
Post shake-out	PSO 15–20 min	1	3	0	5	6	0.004 (0.001–0.008)	0.04 (0.01–0.08)
Post shake-out	PSO 15–30 min	1	3	0	15	6	0.008 (0.001–0.014)	0.09 (0.01–0.15)
Post shake-out	PSO 30–45 min	1	3	0	15	6	0.003 (0.001–0.005)	0.03 (0.01–0.06)
During and post shake-out	SO 0–15 min+PSO 15–30 min	1	3	15	15	6	0.027 (0.009–0.045)	0.29 (0.09–0.49)
During and post shake-out	SO 0–15 min+PSO 15–30 min+PSO 30–45 min	1	3	15	30	6	0.029 (0.010–0.050)	0.32 (0.10–0.55)
Bystander during and post shake-out	BYST 0–45 min	1	3	15	30	6	0.012 (0.006–0.024)	0.13 (0.06–0.26)
During shake-out	SO 0–15 min	2	3	30	0	6	0.037 (0.015–0.063)	0.40 (0.16–0.69)
During and post shake-out	SO 0–15 min+PSO 15–30 min	2	3	30	30	6	0.053 (0.017–0.090)	0.58 (0.19–0.98)
Initial study ^b								
Loading	Initial study	—	—	—	—	4	0.2964 (0.0976–0.5491)	100
During shake-out	Initial study ^c	1	6	15	0	3	0.00052 (0.00043–0.00061)	0.25 (0.10–0.44)
During and post shake-out	Initial study ^c	1	6	15	15	4	0.00045 (0.00008–0.00081)	0.17 (0.03–0.27)
Bystander during and post shake-out	Initial study ^c	1	6	15	15	4	0.00009 (0.00004–0.00015)	0.04 (0.01–0.10)

Measured 40-h TWA airborne chrysotile concentrations are presented assuming weekly clothes handling and shake-out. For comparison, concentrations for both one and two loads of laundry per week were calculated, for a total of either three or six sets of work clothing. The concentrations were then compared with the measured 40-h simulated workplace airborne chrysotile TWA concentrations to determine the percent of the loading concentration. The results are also compared with our initial study of lower airborne chrysotile loading concentrations. ^a"Shake-Out" refers to clothes-handling and shake out activities performed to simulate laundry handling. ^bInitial study.³⁸ ^cCalculated from 30-min samples collected during 15 min of active clothes-handling followed by 15 min of inactivity. TEM as opposed to PCME was used for the calculations in the initial study owing to the large number of PCM and TEM non-detects, so as not to underestimate concentrations.

Table 3. Take-home to occupational exposure concentration ratio values (R_{TH}) for cumulative exposure calculations^a of clothes handling over time.

Activity ^b	Samples used for calculation	Sets of work clothes washed per load of laundry	Total duration of clothes handling/shake-out	Total time spent in room after clothes handling/shake-out	Average task concentration during simulated clothes handling, C_{TH} (range)	Average calculated 8-h TWA for simulated workplace, $C_{OCC,8h}$ (range)	Take-home to occupational exposure concentration ratio, R_{TH} (range) ($R_{TH} = C_{TH}/C_{OCC,8h}$)
Units	Sample name	Number of clothing sets handled	min	min	f/cc as task concentration	f/cc as 8-h TWA	(f/cc as task concentration) = (f/cc as 8-h TWA)
Current study^c							
During shake-out	SO 0–5 min	3	5	0	3.15 (1.24–6.24)	9.184 (8.942–9.425)	0.343 (0.135–0.679)
During shake-out	SO 0–15 min	3	15	0	2.94 (1.17–5.05)	9.184 (8.942–9.425)	0.321 (0.127–0.550)
Post shake-out	PSO 15–20 min	3	0	5	1.87 (0.53–3.64)	9.184 (8.942–9.425)	0.203 (0.058–0.396)
Post shake-out	PSO 15–30 min	3	0	15	1.31 (0.21–2.17)	9.184 (8.942–9.425)	0.143 (0.023–0.237)
Post shake-out	PSO 30–45 min	3	0	15	0.45 (0.15–0.83)	9.184 (8.942–9.425)	0.049 (0.016–0.090)
During and post shake-out	SO 0–15 min+PSO 15–30 min	3	15	15	2.13 (0.69–3.61) ^d	9.184 (8.942–9.425)	0.232 (0.075–0.393)
During and post shake-out	SO 0–15 min+PSO 15–30 min+PSO 30–45 min	3	15	30	1.57 (0.51–2.68) ^d	9.184 (8.942–9.425)	0.171 (0.055–0.292)
Bystander during and post shake-out	BYST 0–45 min	3	15	30	0.62 (0.31–1.27)	9.184 (8.942–9.425)	0.068 (0.034–0.138)
Initial study^d							
During shake-out	Initial study ^e	6	15	0	0.083 (0.068–0.097)	0.311 (0.098–0.549)	0.397 (0.155–0.697)
Post shake-out	Initial study ^e	6	0	15	0.011 (0.009–0.014)	0.311 (0.098–0.549)	0.054 (0.020–0.092)
During and post shake-out	Initial study ^f	6	15	15	0.035 (0.006–0.063)	0.296 (0.098–0.549)	0.132 (0.024–0.215)
Bystander during and post shake-out	Initial study ^f	6	15	15	0.007 (0.003–0.011)	0.296 (0.098–0.549)	0.034 (0.012–0.082)

^aThe cumulative exposure potential from take-home activities can be estimated using the R_{TH} values in this table and the following equation: $CE_{TH} = C_{OCC,8h} \times R_{TH} \times E_T \times E_F \times E_D \times C_F$ where CE_{TH} is the cumulative lifetime exposure from handling contaminated clothing in f/cc-years; $C_{OCC,8h}$ is the exposure concentration for the worker in f/cc as an 8-h TWA; R_{TH} is the take-home to occupational concentration ratio for the specific clothes-handling scenario of interest, units of (f/cc as a task concentration) = (f/cc as an 8-h TWA); E_T is the clothes-handling exposure time in hours per week; E_F is the clothes-handling exposure frequency in weeks per year; E_D is the duration of clothes-handling exposure in years, and C_F is the conversion factor for a cumulative occupational or cumulative environmental year, $\frac{\text{year}}{2000 \text{ hours}}$ or $\frac{\text{year}}{8760 \text{ hours}}$. The R_{TH} value used in this calculation should be selected based on known information about the clothes-handling scenario of interest. For example, a different R_{TH} value would be selected if clothing is handled for 5 min (0.08 h) or 15 min (0.25 h) per clothes-handling event, and whether or not the household individual remains in the room following clothes handling. $C_{OCC,8h}$ can be measured or estimated for various tasks or job titles from the published literature. This study and the prior study involved simulated occupational exposures within a range of 0.1 to 9 f/cc as an 8-h TWA; thus, the results presented here are best suited to address take-home cumulative exposures for workers who were exposed to airborne concentrations between these values. ^b"Shake-out" refers to clothes-handling and shake-out activities performed to simulate laundry handling. ^cOn the basis of the average values from each of the six clothes-handling and shake-out events in our study. ^dTEM as opposed to PCME was used for the calculations in the initial study owing to the large number of PCM and TEM non-detects, so as not to underestimate concentration. ^eOn the basis of the average values from three clothes-handling and shake-out events in our initial study. ^fOn the basis of average values from four clothes-handling and shake-out events in our initial study. Calculated from 30 min samples collected during 15 min of active clothes-handling followed by 15 min of inactivity. ^gCalculated by averaging the appropriate 15 min measured values.

Table 4. Example cumulative exposure estimates based on the mean take-home to occupational exposure concentration ratio (R_{TH}).

Scenario ^a	Mean take-home to occupational exposure concentration ratio, R_{TH}	Total exposure time (min/week)	Low occupational loading, C_{occ} (0.1 f/cc as 8-h TWA)			Moderate occupational loading, C_{occ} (1 f/cc as 8-h TWA)			High occupational loading, C_{occ} (9 f/cc as 8-h TWA)		
			Take-home cumulative exposure			Take-home cumulative exposure			Take-home cumulative exposure		
			Take-home task exposure concentration, C_{task} (f/cc) ^b	(f/cc-h) ^c	(f/cc-occup. year) ^d	Take-home task exposure concentration, C_{task} (f/cc) ^b	(f/cc-h) ^c	(f/cc-occup. year) ^d	Take-home task exposure concentration, C_{task} (f/cc) ^b	(f/cc-h) ^c	(f/cc-occup. year) ^d
<i>Current study^e</i>											
During shake-out (SO 0-5 min)	0.343	5	0.034	3.6	0.0018	0.00041	0.34	36	0.018	0.0041	3.1
During shake-out (SO 0-15 min)	0.321	15	0.032	10	0.0050	0.0011	0.32	100	0.050	0.011	2.9
Post shake-out (PSO 15-30 min)	0.203	5	0.020	2.1	0.0011	0.00024	0.20	21	0.011	0.0024	1.8
Post shake-out (PSO 15-30 min)	0.143	15	0.014	4.5	0.0022	0.00051	0.14	45	0.022	0.0051	1.3
Post shake-out (PSO 30-45 min)	0.049	15	0.0049	1.5	0.00077	0.00017	0.049	15	0.0077	0.00017	0.44
During and post shake-out (SO 0-15 min+PSO 15-30 min)	0.232	30	0.023	15	0.0073	0.0017	0.23	150	0.073	0.017	2.1
During and post shake-out (SO 0-15 min+PSO 15-30 min)	0.171	45	0.017	16	0.0030	0.0018	0.17	160	0.080	0.018	1.5
During and post shake-out (SO 0-15 min+PSO 15-30 min+PSO 30-45 min)	0.068	45	0.0068	6.4	0.0032	0.00072	0.068	64	0.032	0.0073	0.61
Bystander during and post shake-out (BYST 0-45 min)											
<i>Initial study^f</i>											
During shake-out	0.397	15	0.040	12	0.0062	0.0014	0.40	120	0.062	0.014	3.6
Post-shake-out	0.054	15	0.0054	1.7	0.00084	0.00019	0.05	17	0.0084	0.0019	0.5
During and post shake-out	0.132	30	0.013	8.2	0.0041	0.00094	0.13	83	0.041	0.0094	1.2
Bystander during and post shake-out	0.034	30	0.0034	2.1	0.0011	0.00024	0.034	21	0.011	0.0024	0.31

Cumulative exposure presented assuming weekly clothes-handling and laundry room activities lasting 5-45 min per week. An exposure frequency of 25 years was selected based on the estimated upper bound for the amount of time that a worker will remain in a single job.³⁹ Event exposure times were set equal to the sampling times. A standard occupational exposure frequency of 50 weeks/year was assumed. The results are compared with our initial study of lower airborne chrysotile-loading concentrations. ^aShake-out refers to simulated clothes-handling and shake-out activities performed prior to laundering. ^b $C_{task} = R_{TH} \times C_{occ}$. ^c $CE_{f/cc-h} = C_{task} \times (\text{min/wk}) \times (1 \text{ h}/60 \text{ min}) \times (50 \text{ wk/year}) \times (25 \text{ year})$. ^d $CE_{f/cc-occup. year} = CE_{f/cc-h} / (2000 \text{ h/year})$. ^e $CE_{f/cc-occup. year} = CE_{f/cc-h} / (8760 \text{ h/year})$. The samples included in the current study scenarios are indicated in parentheses. ^fInitial study.²⁸

measured the handling of clothing worn during the removal of asbestos-containing building materials. The author presented airborne concentrations collected at a distance of 1.5 meters from contaminated clothes handling, and reported that the concentrations ranged from ND to 0.4 f/cc over variable time durations using PCM. The PCM concentrations measured during clothing SO in this study were consistent with the PCM concentrations reported by Sawyer.²⁵ Additionally, in 1982, Mangold²⁷ compared the mean airborne fiber concentrations for individuals wearing light, medium, or heavily asbestos-contaminated clothing and found a correlation between the airborne fiber concentrations and the different levels of clothing contamination. The current study results are consistent with the reported findings by Mangold, in that airborne fiber concentrations were correlated with the magnitude of clothing contamination.²⁷ However, as previously mentioned, neither Sawyer nor Mangold measured the asbestos-specific proportion of measured airborne fibers (by TEM) and thus additional direct comparisons with these studies are not possible. On the basis of the statistically significant ($\alpha = 0.05$) lower PCME concentrations as compared with the PCM concentrations observed in both this study and the prior study, it appears likely that an appreciable fraction of measured fibers was due to the clothing, particularly with decreasing asbestos workplace concentrations.

More recent simulation studies (2008–2009) evaluating the handling of clothing worn during work activities with asbestos-containing friction products have generally shown that airborne asbestos exposures from simulated laundering activities of asbestos-contaminated work clothing were undetectable, or were a fraction of the exposures experienced in the simulated occupational environment.^{30–32} A study evaluating exposures during the unpacking and repacking of clutch parts reported mean worker exposures ranging from 0.002 to 0.231 f/cc (PCME) over a 15-min time period, and a corresponding mean chrysotile concentration during the handling of clothing worn during these activities of 0.003 f/cc (range 0–0.005 f/cc by PCME).³⁰ In a similar study involving unpacking and repacking of automobile brake pads and shoes, mean worker exposures ranging from 0.004 to 0.541 f/cc (PCME, 15 min) resulted in corresponding clothes-handling exposures of 0.011 f/cc (range 0.007–0.015 f/cc by PCME for detectable samples).³¹ In a simulation study to characterize exposures during the removal of asbestos-containing heavy equipment brakes, mechanics were exposed to mean airborne chrysotile concentrations ranging from 0.003 to 0.044 f/cc by PCME, with subsequent mean clothes-handling exposures of 0.036 f/cc by PCME for the samples in which asbestos was detected.³² A fourth study evaluated airborne concentrations associated with clothes handling in a small chamber of 150 l (0.15 m³) in volume, making the results difficult to compare with concentrations measured in larger study chambers or rooms (such as this study).²⁹ Additionally, for all four of these studies, the exposure conditions were different from the current study in that the impact of work with specific products was evaluated, rather than the effect of a specific target occupational concentration on clothes-handling exposures.

As with any study, despite the careful design and data collection process, there are several factors that should be considered when evaluating the results presented here. The use of stationary mannequins as a surrogate for active workers to load the work clothing with chrysotile may have affected the potential for fibers to deposit and remain adhered to the clothing. It is plausible that movement by workers could lessen, although perhaps to a negligible extent, the concentration of fibers deposited on or adhered to the clothing at the end of the work day. Additionally, this study did not consider the effects of commuting or blowing/brushing off of work clothing before entering the home. It is likely that these activities, if they occurred, would have removed some of the fibers adhered to work clothing before they could be

brought into the home environment. In contrast, this study was designed to maximize the number of fibers that remained adhered to the clothing between the workplace loading and clothes-handling events.

This study did not specifically assess the in-home fiber resuspension exposure potential from other surfaces or materials other than resuspension from active clothes handling. However, based on previously published data on fiber adherence and re-entrainment from other surfaces, it appears unlikely that substantial airborne asbestos concentrations could be generated simply by moving around in rooms where asbestos fibers have settled out of the air or where contaminated clothing has previously been shaken out and handled.^{49,53,54} Esmen performed experimental measurements which supported the conclusion that fibers which are adhered to a surface will require air speeds of at least 10 m/s to become resuspended into the air.⁴⁹ This air speed is much higher than would be encountered in an indoor environment without mechanical disturbance, and therefore normal air currents in an indoor space would likely be insufficient to resuspend settled asbestos fibers. Similarly, in a U.S. EPA report on the resuspension of fibers from indoor surfaces due to human activity, the authors remarked that, “no measureable dusts were observed from [particulate deposits] on bare flooring. It could be conjectured that resuspending dust from bare floors requires substantial turbulence from either stomping or very fast walking to provide the energy to both release particles from the surface and elevate them into the air sufficiently to add to the air concentration. Low pile, indoor-outdoor carpeting also provided essentially immeasurable air concentration levels.”⁵⁵ Testing data using asbestos surrogate (Wollastonite) fibers in medium pile carpets showed some fiber release under certain conditions, but the results were difficult to interpret because airborne fiber concentration measurements were not reported using relevant dimension criteria such as PCM.⁵⁵ If household cleaning or laundering activities involving mechanical disturbance did yield the resuspension of fibers brought into the home on workers’ clothing, it is likely that fibers in the PCME size range would settle out of the air at a similar rate as was observed following clothes handling in this study. As seen in Figure 6, both PCM and PCME fiber concentrations decreased significantly within approximately 30 min after clothes handling ended.

It should also be noted that this study evaluated clothes-handling activities between 5 and 15 min in duration, which is likely to be at the upper end of plausible clothes handling duration prior to laundering. In this study, 5-min and 15-min clothes-handling airborne concentrations were not statistically significantly different, but the weekly TWA concentrations for 5-min clothes handling were approximately one-third of the TWAs for 15-min clothes handling (0.003–0.013 f/cc as a 40-h TWA for 5-min clothes handling vs 0.007–0.032 as a 40-h TWA for 15-min clothes handling). This finding suggested that exposure duration is an important factor for evaluating the exposure potential associated with clothes-handling activities.

And finally, this study focused on chrysotile asbestos. Physical differences have been noted between the amphibole and chrysotile minerals that could affect take-home exposure potential, including surface electrical charge, differences in fiber shape, and possible differences in affinity for surfaces and agglomeration.^{51,52} However, it is possible these physical differences may have little effect on the surface adherence and release behavior of the different asbestos fiber types.

CONCLUSIONS

The results of the current study indicated that for loading over a full work shift at 8-h TWA airborne concentrations of approximately 9 f/cc, the household concentrations related to the handling of contaminated work clothing were consistently a small

proportion of the simulated workplace airborne exposures. When the results of this study were considered together with the prior study, a clear trend was seen of increasing TWA airborne concentrations of asbestos during clothes handling with increasing TWA workplace concentrations in ratios of approximately 1% or less for clothes handling to workplace concentrations. These ratios remained consistent even with the use of a substantially lower ventilation rate of 3.5 ACH in the current study compared with 13–19 ACH in the initial study.²⁸ The results confirm that dilution ventilation rates did not have a significant impact on personal exposures resulting from airborne fiber concentrations generated in an individual's breathing zone; this was not altogether surprising as dilution ventilation has little impact on personal breathing zone airborne concentrations for the primary worker.⁵⁶ On the basis of measurements collected for passive exposure potential over 30 min following active clothes handling, the data indicated that the rate of settling of PCME fibers is faster than has been previously suggested by either ventilation models or gravitational settling calculations. The results also demonstrated that the use of the PCM vs PCME analytical method overestimated chrysotile exposure potential by 11–47% in the current study and 2 to 7-fold in the initial study owing to the presence of clothing fibers. Despite differences in simulated workplace airborne concentrations of more than an order of magnitude between the two studies, the corresponding estimated weekly household clothes-handling TWA concentrations remained at approximately 0.25% of the workplace concentrations on a time-weighted basis. Take-home cumulative exposure estimates, based on a greater than 25-year period of weekly laundry activities by a single household contact, were below 1 f/cc-year for handling contaminated work clothes worn in an occupational environment with an airborne chrysotile concentration of up to 9 f/cc (8-h TWA).

CONFLICT OF INTEREST

At the time of the study, 8 of the 13 authors were employed by Cardno ChemRisk, a consulting firm that performs scientific research and support for the government, corporations, law firms, and various scientific/professional organizations. The other five authors were employed by RJ Lee Group, an analytical laboratory and consulting firm. A portion of the funding for the preparation of this article and the underlying research was provided by John Crane Inc., a manufacturer of sealing devices that historically manufactured or supplied asbestos containing gaskets and packing. Funding was also provided by Cardno ChemRisk and the RJ Lee Group. Cardno ChemRisk has been engaged by John Crane Inc., to provide general consulting, expert advice, and litigation support on scientific matters involving asbestos. This paper was prepared and written exclusively by the authors without any review or input by John Crane Inc. employees or legal counsel. Seven of the authors (DJP, JLH, DG, JS, AKM, RJL, and DVO) have served as expert witnesses regarding historical exposures of various tradesmen to asbestos. AKM, JLH, and DG have testified on matters related to the historical use of asbestos-containing gasket and packing materials on behalf of John Crane Inc.

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