Measured removal rates of chrysotile asbestos fibers from air and comparison with theoretical estimates based on gravitational settling and dilution ventilation

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Abstract

Context: Industrial hygiene assessments often focus on activity-based airborne asbestos concentration measurements, but few empirical data exist regarding the fiber removal rate from air after activities cease.

Objective: Grade 7T chrysotile indoor fiber settling (FS) rates were characterized using air sampling (NIOSH Method 7402).

Materials and methods: Six replicate events were conducted in a 58 m³ study chamber (ventilation 3.5 ACH), in which chrysotile-contaminated work clothing was manipulated for 15 min followed by 30 min of no activity. The fiber concentration decay constant and removal rate were characterized using an exponential decay model based on the measurements.

Results: Breathing zone airborne chrysotile concentrations decreased by 86% within 15–30 min after fiber disturbance, compared to concentrations during active disturbance ($p < 0.05$). Estimated mean time required for 99% of the phase contrast microscopy-equivalent (PCME) fibers to be removed from air was approximately 30 min (95% CI: 22–57 min). The observed effective FS velocity was 0.0034 m/s. This settling velocity was between 4.5-fold and 180-fold faster than predicted by two different particulate gravitational settling models. Additionally, PCME concentrations decreased approximately 2.5-fold faster than predicted due to air exchange alone (32 versus 79 min to 99% decrease in concentration).

Discussion: Other measurement studies have reported similar airborne fiber removal rates, supporting the finding that factors other than gravitational settling and dilution ventilation contribute measurably to PCM fiber removal from air (e.g. impaction, agglomeration).

Conclusion: Overall, the scientific weight of evidence indicates that the time necessary for removal of 99% of fibers greater than 5 μm in length (with aspect ratios greater than 3:1) is approximately 20–80 min.

Keywords

Asbestos, concentration decay, exposure modeling, fiber settling, fiber removal, particulate removal

Introduction

The three primary forms of commercial asbestos (chrysotile, amosite, and crocidolite) have had many industrial uses over the past century because of their physical properties, including heat resistance, strength, and flexibility (Virta, 2006). However, these mineral fiber types (as a class) have also been identified as a human carcinogen after sufficient inhalation exposure (IARC (International Agency for Research on Cancer), 2012; NIOSH, 2008). As a result, in some industrial settings, exposure concerns have extended beyond the primary worker to include bystanders and others remote to the immediate working environment (Donovan et al., 2011). It has also been theorized that asbestos fibers could remain aloft for significant periods of time after becoming airborne, and that fiber removal rates from air are primarily dependent on gravitational settling mechanisms. For example, in 1986, the U.S. Environmental Protection Agency (EPA) stated in its Guidance for Preventing Asbestos Disease Among Auto Mechanics that, “Asbestos released into the air lingers around a garage long after a brake job is done and can be breathed in by everyone inside a garage, including customers” (USEPA, 1986, p. 1). Similarly, the Agency for Toxic Substances and Disease Registry stated in their 2001 Toxicological Profile for Asbestos that “Large fibers are removed from air and water by gravitational settling at a rate dependent upon their size, but small fibers may remain suspended for long periods of time” (ATSDR, 2001, p. 149).

Despite concerns about bystanders (Donovan et al., 2011) and residual exposure potential, very few data have been collected to characterize the rate at which asbestos fibers in
the size range of interest to the U.S. Occupational Safety and Health Administration (OSHA) and other regulatory agencies are removed from air (i.e. fibers \( \geq 5 \mu m \) in length and \( \geq 0.25 \mu m \) in width, with an aspect ratio of 3:1 or greater, detectable using the phase contract microscopy or PCM method). This lack of measured data has led to the practice of using of mathematical models to estimate the rate at which asbestos fibers will likely settle out of air or be removed by ventilation. A number of these models have been based on the gravitational settling properties of particles using a small number of particle movement and interaction properties in the air, such as particle density and aerodynamic diameter, and often are not designed to specifically evaluate the rate at which fibrous-shaped particulates, such as asbestos, can be removed from air. Existing particulate exposure estimation models rely heavily on two primary factors to predict removal time from air: (1) the ventilation or air exchange rate and (2) estimation of the gravitational (or terminal) settling rate (Drivas et al., 1996; Keil, 2000; Keil et al., 2009; Timbrell, 1965).

In many ventilation removal models used by industrial hygienists, the air exchange rate in a space is often assumed to be the primary removal mechanism for particulates (of any shape) from the air through either simple mechanisms such as air dilution (Keil, 2000) or more complex air movement mechanisms such as diffusion, turbulent eddy diffusion, or advection (Drivas et al., 1996; Nicas, 2001, 2011). Such models often do not distinguish between physical property differences of the contaminants under evaluation, including whether a substance is in a gas or particulate form, or whether there are other specific particulate characteristics that could affect movement in air and removal from air (such as particulate surface characteristics, dimensions, electrical charge, and shape).

In gravitational settling models, the particle removal rate from air is typically estimated using the diameter and density of particles, as well as the forces of gravity and viscosity of air. When these models are applied, the ventilation rate is sometimes assumed to be very low or zero. Common applications of this modeling approach therefore rely on the relationship between particle density and air viscosity to determine the rate at which particles will be removed from the air. Additionally, because gravitational settling models often assume that all particles are rigid spheres, a correction factor such as the dynamic shape factor is frequently used to estimate an equivalent aerodynamic diameter for non-spherical particles (Hinds, 1999; Reist, 1984). Further, the mathematical correction for non-spherical particle shapes to an equivalent sphere is often a simplistic approximation when compared to the actual particulate shape, and can introduce uncertainty into the resulting estimates for fiber settling (FS).

For example, when estimating the aerodynamic diameter for fiber sizes of interest to human health, the length, width, and aspect ratio of the fibers must be combined into a single factor (Hinds, 1999).

When evaluating airborne asbestos fibers specifically, it is well established in the published literature that fibers of less than 5 \( \mu m \) in length are not considered to be biologically significant by regulatory agencies and a number of published researchers (Berman, 2010; Davis et al., 1978; ERG (Eastern Research Group), 2003a,b; Platek et al., 1985; Stanton, 1973; Stanton et al., 1977; Stettler et al., 2008). Some regulatory agencies specify using the PCM method to collect and count airborne fibers, and this method only counts fibers \( \geq 5 \mu m \) in length (NIOSH, 1994b; OSHA, 1997). The minimum detectable fiber diameter counted by PCM is estimated to be 0.25 \( \mu m \). Since the PCM method cannot distinguish asbestos fibers from non-asbestos fibers, techniques such transmission electron microscopy (TEM) methods (NIOSH, 1994a) can be used to discriminate and estimate the concentration of asbestos fibers only. When used in a method such as NIOSH 7402, PCM and TEM together can estimate airborne asbestos fiber concentrations for fibers meeting the specified PCM dimensions. The resulting airborne asbestos fiber concentrations determined by NIOSH 7402 are often referred to as phase contrast microscopy-equivalent (PCME) concentrations. Other than the minimum PCME length and width, the aspect ratio (i.e. 3:1 or greater) is the primary characteristic which defines a particle as a fiber. The impact of such fiber-specific characteristics can be lost when equivalent spherical diameters are Used in gravitational settling models.

Beginning in the 1970s, the scientific community published several estimates of airborne fiber exposure potential based on models using gravitational settling velocity (Bragg et al., 1974; NRC, 1981; Sawyer & Spooner, 1978). In 1978, the U.S. EPA estimated the speed with which asbestos fibers may settle out of air (Sawyer & Spooner, 1978), and concluded that based on estimates of gravitational settling, fibers of \( 5 \mu m \) in length with a 5:1 aspect ratio would require 4 h to settle out of still air from a height of 9 feet. They also estimated that fibers 2 \( \mu m \) and 1 \( \mu m \) in length would require 20 and 80 h, respectively, to settle out of air. Similarly, the National Research Council’s Committee on Indoor Pollutants estimated that in still air at a height of 3 meters, a fiber with dimensions of \( 5 \mu m \) long by 1 \( \mu m \) in diameter would remain airborne for approximately 4 h, and that a fiber of the same length with a 0.1 \( \mu m \) diameter would remain airborne for close to 20 h (NRC, 1981). Based on their calculations, PCME fibers (i.e. those equal to or longer than 5 \( \mu m \)) were predicted to fall faster than shorter fibers, and fiber diameter was also identified as an important factor, with thinner diameter fibers remaining airborne longer.

However, it has been recognized in the particle dynamics literature over many decades that factors other than ventilation and gravitational settling velocity can have substantial effects on the removal efficiency of particulates from air. These mechanisms of particle removal include van der Waals forces, electrification, impaction on other bodies, centrifugation, agglomeration, diffusion, and cohesion due to water molecules (Corn, 1961a,b; Drinker & Hatch, 1954; Esmen, 1996; Hinds, 1999; Reist, 1984; Zimon & Corn, 1969). Consistent with this particle dynamics research, limited laboratory and field studies have shown that asbestos fibers and other particulates appear to remain airborne for shorter periods of time than would be expected based on either gravitational settling velocity or ventilation-based estimates alone (Corn & Stein, 1966; Moorcroft & Duggan, 1984). Therefore, additional quantitative data on asbestos fiber removal rates are important for accurately characterizing exposure potential, particularly given the interest in the
use of mathematical modeling for estimating exposure potential to airborne particulates (including asbestos) in a variety of scenarios when no sampling data are available. Such data will also help to shed light on the relative impact of the factors that influence the removal of particulates and fibers from the air.

The purpose of this study was to measure the rate of removal from air of chrysotile fibers in the PCME size range and to compare this rate to modeled estimates of the removal of asbestos from air based on simple theoretical calculations relying only on factors such as gravitational settling and/or dilution ventilation. To evaluate removal rates from air, breathing zone airborne chrysotile fiber concentrations were measured over time under known ventilation conditions in a controlled study chamber. The PCME sampling results were then used to develop a fiber concentration decay curve that characterized the observed rate of fiber removal. This curve was used to estimate an overall concentration decay half-life and the time required to reduce the airborne concentration of PCME chrysotile fibers by 99%. The results were directly compared to theoretical estimates of fiber removal rates from ventilation-only and gravitational settling velocity models for fiber sizes of interest to human health risk assessment. The results were also compared to previously published measurements of asbestos fiber removal rates in the literature.

Methods

Study design and sample collection

Prior to commencement of the study, an Institutional Review Board (IRB) reviewed and approved the study protocol (Copernicus Group; Study ID #CR11-11-208; Durham, NC). Six replicate study events were conducted in which airborne PCME chrysotile fiber concentrations were measured both during and after the handling and vigorous shaking of clothing that had been previously contaminated with Grade 7T chrysotile asbestos (Sahmel et al., 2015). The 7T chrysotile was obtained from Thetford Mines (Quebec, Canada). The general characteristics of grade 7 chrysotile have been defined by the Quebec Grading System; this grade 7 chrysotile was also characterized and is summarized in Supplemental Figure A. After the clothes were contaminated with chrysotile, study participants performed a total of six clothes handling and shake-out (SO) replicate events (Sahmel et al., 2015). The study chamber was thoroughly decontaminated between each sampling event in order to minimize or eliminate the potential for any fiber resuspension from one event to another. Multiple 30-min clearance samples were collected prior to each sampling event to ensure that fiber concentrations in the chamber were below the limit of detection for NIOSH 7400 (Sahmel et al., 2015).

For each SO event, the study participant handled and shook out the clothing for 15 min. The 15-min active clothes handling time was followed by a 30-min period of no activity from which the FS rates could be evaluated. The airborne concentrations of chrysotile in the clothes handler’s breathing zone were measured during both periods (Sahmel et al., 2015). Substantial dust generation was visible in the chamber during the handling and shaking out of the contaminated clothing (see Supplemental Figure B). The schematic in Figure 1 depicts the relative time duration and the nomenclature used for samples collected during the active clothes handling and SO period and the FS period. During each event, a total of six personal samples were collected from the breathing zone of the study participant at the following time intervals: 0–5 min (right lapel), 0–15 min × 2 (left and right lapels), 0–15 min, 15–20 min (right lapel) (FS 0–5 min), 15–30 min (left lapel) (FS 0–15 min), and 30–45 min (left lapel) (FS 15–30 min). All air samples for asbestos were collected in accordance with the NIOSH 7402 analytical method to determine airborne PCME asbestos fiber concentrations; details of the sampling procedures have been described previously (Sahmel et al., 2014, 2015).

Air sampling data analysis

For each of the sampling periods shown in Figure 1, the mean, median, 5th, 25th, 75th, and 95th airborne PCME chrysotile fiber concentration percentiles were calculated. Pairwise comparisons were performed between different sampling periods using t-tests with the Bonferroni adjustment to account for multiple comparisons. Since there were two SO 0–15 min samples per event (left and right lapels), the average of the two values was used in these analyses. To estimate the percent decrease in TWA concentrations during FS sampling periods as compared to the clothes handling period, an overall estimate of the concentration during fiber generation was calculated by averaging together the SO 0–5 min, SO 0–15 min (left lapel), and SO 0–15 min (right lapel) samples (see Supplemental Materials for further details). In addition, the rate of fiber removal was characterized by fitting an exponential decay curve to the measured data, as described in detail below.
Using an exponential decay equation to compare measured and modeled rates of fiber removal from air: prediction of fiber half-life and time needed for 99% of fibers to settle

For industrial hygiene and exposure assessment applications, decreases in airborne concentrations over time are commonly characterized using a simple exponential decay equation consistent with Equation (1) (Keil et al., 2009):

\[ C(t) = C_0 \exp(-kt) \]  

(1)

where \( t \) is the time (min), \( C(t) \) is the fiber concentration at time \( t \) (f/cc), \( C_0 \) is the initial fiber concentration at \( t = 0 \) (f/cc), and \( k \) is the overall fiber decay constant (1/min). In implementing an exponential decay curve to characterize the FS rate, the simplifying assumption was made that the concentration was uniform throughout the chamber.

The overall decay constant \( k \) can be estimated for a particular exposure scenario by fitting the decay curve (Equation 1) to measured data. Alternatively, in the absence of measured concentration data, the overall decay constant \( k \) for fibers in air can be estimated using Equation (2) based on Drivas et al. (1996). The result can then be substituted for the \( k \) value in Equation (1):

\[ k = a + \left( \frac{A}{V} \right) \]  

(2)

where \( a \) is the measured ventilation rate (1/min), \( w_d \) is the FS rate in (m/min), \( A \) is the area (m²) over which fiber deposition occurs, and \( V \) is the volume (m³) of the room of interest. For this study, the ventilation rate was measured at a fixed rate of 3.5 air changes per hour or 0.058 air changes per min, the area of the room was 24m², and the volume of the room was 58 m³. Equation (2) is useful because it allows \( k \) to be defined in terms of multiple concentration decay factors, including both ventilation-only removal effects and non-ventilation removal effects.

In order to compare the measured data to the decay rates expected from ventilation alone and calculated gravitational settling, fiber decay curves were generated based on three approaches, as described in the sections ‘‘(1) Measurement approach: estimation of fiber concentration decay using measured air sampling data’, ‘‘(2) Distinguishing ventilation vs. non-ventilation effects: estimation of fiber concentration decay using measured dilution ventilation’, and ‘‘(3) Modeling approach: estimation of fiber concentration decay using calculated gravitational settling velocities’. Then, the half-lives and times to 99% reduction in concentration were examined for all three approaches. The fiber decay half-life and the time at which the concentration decreased by 99% from the initial concentration were estimated from the fiber decay constant \( k \) using Equations (3a) and (3b):

\[ T_{1/2} = \frac{\ln(2)}{k}; \quad T_{99\%} = \frac{\ln(100)}{k} \]  

(3a and 3b)

where \( T_{1/2} \) is the overall fiber decay half-life (min) and \( T_{99\%} \) is the time (min) at which the concentration decreases by 99%.

(1) Measurement approach: estimating the fiber decay constant \( k \) using measured air sampling data

In order to characterize the observed rate of fiber removal from air, Equation (1) was fit to the measured concentration data, yielding an estimate for \( k \) and \( C_0 \). The decay constant that was fit from the measured data is referred to as \( k_{fit} \). Although \( C_0 \) is a measured value, letting the model fit this parameter yielded a better fit of the curve to the data as compared to forcing \( C_0 \) to equal the measured value. To fit the decay curve to the measured data, it was necessary to estimate the airborne chrysotile concentration at the beginning of the FS period. To characterize the initial airborne fiber concentration for each event, the three time-weighted average (TWA) PCME concentrations from samples collected for each event during active clothes handling and SO were averaged together (i.e. SO 0–5 min, SO 0–15 min [left lapel], and SO 0–15 min [right lapel] depicted in Figure 1) (see Supplemental Materials for further details).

(a) Decay curve fit to each study event separately. Due to variations in the amount of chrysotile released during each event, the starting air concentration in the breathing zone for each study event (SO 0–5 min and SO 0–15 min samples) varied. Therefore, an exponential decay curve was initially fit to the data from each event separately.
(b) Decay curve fit to all study events. To investigate trends across all events, the decay curve was also fit to concentration data that were normalized by dividing each concentration by the estimated initial concentration for that event, such that all normalized initial concentrations were equal to 1. Additional details on the approach used to fit Equation (1) to the measured data have been provided in the Supplemental Materials. Since \( k_{\text{fit}} \) was fit from the measured concentration data, the resulting fiber decay curve did not rely on Equation (2).

(2) Distinguishing ventilation versus non-ventilation fiber removal effects: estimating the fiber decay constant \( k \) using measured dilution ventilation

(a) Ventilation effects. Rather than relying on measured data, the decay constant \( k \) in Equation (1) may also instead be calculated from the ventilation rate and/or an assumed FS rate as shown in Equation (2). It is of interest to consider the relative contribution to overall fiber removal from different removal mechanisms. Ventilation was expected to be the largest contributor to airborne fiber removal in the current study. To estimate the contribution that ventilation had upon the observed fiber removal rate, a fiber decay curve was created in which ventilation was assumed to be the only fiber removal mechanism. This was achieved by solving for the decay constant \( k \) in Equation (2) equal to the measured ventilation rate \( a \) as shown in Equation (4):

\[
k = a
\]

(b) Observed non-ventilation effects. It was also of interest to determine the contribution of non-ventilation effects to the observed fiber removal rate. These non-ventilation effects can include gravitational settling, but also such effects as electrification, impaction, and agglomeration and their combined effect on fiber removal from air based on the measured data. To estimate the rate of concentration decay attributable to non-ventilation fiber removal effects alone, a decay curve was created in which the decay constant was calculated as shown in Equation (5):

\[
k = k_{\text{fit}},1–6 – a
\]

where \( k_{\text{fit}},1–6 \) is the decay constant fit to the combined measurement data across all six events, and \( a \) is the measured ventilation rate.

An estimate of the observed effective FS velocity can be determined by rearranging Equation (2) to solve for \( w_d \) as shown in Equation (6):

\[
w_{d, \text{obs}} = \left( k_{\text{fit}},1–6 – a \right) \left( \frac{V}{A} \right)
\]

As discussed, this effective observed FS velocity \( w_{d, \text{obs}} \) will encompass all non-ventilation removal mechanisms that may have occurred during this study, and thus is distinct from the settling rates estimated using gravitational settling models alone.

(3) Modeling approach: estimating the fiber decay constant \( k \) using calculated gravitational settling velocities

To evaluate the utility of gravitational settling models alone for estimating the rate of airborne fiber removal, fiber decay curves were also generated that relied on calculated estimates of gravitational settling velocity \( w_d \) based on modeling approaches described in the literature. In the absence of ventilation, the fiber decay curve would rely only on the calculated gravitational settling velocity \( w_d \), the room area \( A \), and the room volume \( V \) as shown in Equation (7):

\[
k = w_{d} \left( \frac{A}{V} \right)
\]

In the presence of ventilation, the fiber decay curve would also rely on the ventilation rate \( a \) as shown in Equation (2).

In this study, two gravitational settling model approaches from the literature were selected to calculate the gravitational settling velocity \( w_{d} \) parameter in Equations (2) and (7) for fibers.

(a) The first gravitational settling model used was from Sawyer and Spooner and is a historical gravitational settling calculation approach for fibers (Sawyer & Spooner, 1978).
(b) The second gravitational settling model came from Hinds, and is a newer gravitational settling model (Hinds, 1999).

The Hinds model incorporated a unitless shape factor to account for the fibrous shape of asbestos particles, whereas the method used by Sawyer and Spooner treated the fibers as ellipsoids (Hinds, 1999; Sawyer & Spooner, 1978). Details on the gravitational settling model calculations have been provided in the Supplemental Materials.

Results

Analysis of the fiber settling air sample results

The distribution of the PCME airborne concentrations across the six replicate events for each of the sampling time periods is presented using box plots in Figure 2. Results for all of the

![Figure 2. Box plots of measured concentration data for fiber removal from air. This figure shows the 50th percentile, 5th, 25th, 75th, and 95th percentiles, and average breathing zone concentrations (black dot) for each sampling period. Letters and notations below the figure indicate the sampling periods for which the mean concentration was statistically significantly lower (signified by the symbol ‘‘<’’) compared to other sampling periods (t-test, Bonferroni-adjusted \( \alpha = 0.05 \)). All samples were detected above the LOD.
](image-url)
asbestos airborne concentration samples collected in the breathing zone were above the limit of detection for the NIOSH 7400 and 7402 methods. The lowest reported limit of quantitation for the samples used in this study was 0.0057 f/cc. Each box plot represents the percentiles of the sampling distribution for the time period of interest. The mean PCME fiber concentration during the last 15 min of FS (FS 15–30 min) was statistically significantly lower than the concentration during the clothes handling period (SO 0–5 min and SO 0–15 min). Additionally, the mean concentration during the first 15 min of FS (FS 0–15) was statistically significantly lower than the mean concentration during the first 5 min of clothes handling (SO 0–5 min). These data confirm that significant decreases in fiber concentration are observed within the first 15–30 min after the generation of fibers ceased. The measured TWA concentrations for the period 15–30 min after fiber generation ceased (FS 15–30 min) were reduced 86% on average (range: 80–92% reduced) compared to concentrations measured during the fiber generation period, indicating that the vast majority of the fibers were removed from the air within 30 min.

Fiber half-life and time needed for 99% of fibers to settle: results of using an exponential decay equation to compare measured and modeled rates of fiber removal from air

(1) Measurement approach: estimation of fiber concentration decay using measured air sampling data

To facilitate an estimate of the instantaneous (as opposed to the TWA) concentration at specific time points, the observed fiber removal rate was characterized by fitting the exponential concentration decay curve described in Equation (1) to the measured TWA chrysotile concentrations.

(a) Decay curve fit to each study event separately. Figure 3 presents the fitted concentration decay curve and apparent chrysotile PCME concentration decay half-life for each sampling event (n = 6). The apparent decay half-lives for each event ranged from 1.1 to 11.4 min.

(b) Decay curve fit to all study events. In order to analyze the trend of all six events together, the airborne concentration data for all events were normalized by dividing each concentration by the initial fiber concentration for that event, such that the normalized initial concentration for each event was 1. Then, a concentration decay curve (again using Equation (1)) was fit to the normalized data for all six events combined. Figure 4 shows the combined decay curve for all six events using the best estimate of the model parameters (k_fit and C_0), as well as the decay curves obtained using the upper and lower 95% confidence limits (UCL and LCL, respectively) of the model parameters. To facilitate a direct comparison of the measured data to the fitted decay curves, the measured TWA concentrations were also added to Figure 4 for comparison, with the FS 0–5 min samples shown at 2.5 min, the FS 0–15 min samples shown at 7.5 min, and the FS 15–30 min samples shown at 22.5 min. Additionally, the TWA concentration values from the best fit, UCL, LCL, and ventilation-only decay curves for the corresponding time periods (FS 0–5 min, FS 0–15 min, and FS 15–30 min) have been provided in Supplemental Table C. Nearly all of the measured breathing zone concentration values fell within the 95% confidence interval of the decay curve.

For each of the six events and for all events combined, Table 1 provides the key fitted parameters and calculated values, including the initial fiber concentration (C_0) (f/cc, PCME), the decay coefficient (k_fit) (1/min), the estimated fiber concentration decay half-life (min), and the estimated time to 99% removal of the fibers from the air (min). As shown in Table 1, the measured initial PCME concentrations during the fiber generation period ranged across the events from 1.2 f/cc to 5.4 f/cc. The R^2 value
Figure 4. Results of fitting the exponential decay equation to the measured airborne chrysotile concentrations for all events combined and comparison to the expected concentration decay associated with ventilation effects alone. A single exponential concentration decay equation (Equation 1) was fit to the airborne chrysotile breathing zone concentration PCME measurements for all events combined and was plotted for comparison with the expected concentration decay attributable to ventilation effects alone (measured ventilation of 3.5 ACH). The data were normalized by dividing each measurement by the measured initial concentration for the same study event. Decay concentration estimates are shown employing both the best estimates for the Equation (1) parameters, as well as using the 95% lower confidence limit (LCL) and 95% upper confidence limit (UCL) estimates of the Equation (1) parameters. The six measured TWA concentrations during the first 5 min after SO are shown at time = 2.5 min. The six measured TWA concentrations during the first 15 min after SO are shown at time = 7.5 min. The six measured TWA concentrations between 15 min and 30 min after shake out are shown at time = 22.5 min.

Table 1. Characterization of the fiber concentration decay curves fit to measured data and comparison to the decay curves expected based on only ventilation effects.

| Events included in the model | Measured initial breathing zone fiber concentration (f/cc, PCME) | Estimated initial breathing zone fiber concentration ($C_0$) (f/cc, PCME) | Decay coefficient ($k$) (1/min) | $R^2$ | Settling velocity (m/s) | Estimated fiber concentration decay half-life (min) | Estimated time to 99% removal (min)$^b$ |
|-----------------------------|--------------------------------------------------|--------------------------------------------------|-------------------------------|-------|-----------------------|---------------------------------|------------------------|
| Event 1                     | 1.19                                             | 1.19                                             | 0.353                         | 99%   | 0.0119                | 2.0                             | 13.0                    |
| Event 2                     | 2.36                                             | 2.28                                             | 0.061                         | 97%   | 0.0001                | 11.4                           | 75.5                    |
| Event 3                     | 2.06                                             | 2.06                                             | 0.615                         | 97%   | 0.0224                | 1.1                             | 7.5                     |
| Event 4                     | 2.91                                             | 2.92                                             | 0.137                         | 100%  | 0.0032                | 5.1                             | 33.6                    |
| Event 5                     | 4.11                                             | 3.85                                             | 0.097                         | 99%   | 0.0016                | 7.1                             | 47.5                    |
| Event 6                     | 5.35                                             | 5.18                                             | 0.127                         | 99%   | 0.0028                | 5.5                             | 36.3                    |
| Average                     | 3.00                                             | 2.91                                             | 0.232                         | NA    | 0.0070                | 5.4                             | 35.6                    |
| Events 1–6 Best fit model   | 1.00                                             | 0.95                                             | 0.143                         | 94%   | 0.0034                | 4.8                             | 32.2                    |
| Events 1–6 LCL model        | 1.00                                             | 0.82                                             | 0.206                         | NA    | 0.0059                | 3.4                             | 22.4                    |
| Events 1–6 UCL model        | 1.00                                             | 1.07                                             | 0.081                         | NA    | 0.0009                | 8.6                             | 56.9                    |
| Ventilation Only Model      | 1.00                                             | 1.00                                             | 0.058                         | NA    | 0.0000                | 11.9                            | 78.9                    |

$^a$When the decay curve was fit to measured data from each event separately, the initial fiber concentration ($t = 0$ min) was estimated considering the duration of each sample during the fiber generation period: [(5/20)*(SO 0–5 min sample) + (15/20)*(SO 0–15 min sample)]. For the curve fits that considered all of the events together, the concentrations were normalized such that the initial concentration was equal to 1.

$^b$The estimated time to 99% removal is the time required for the initial airborne fiber concentration to decrease by 99%.

for the model fit across all events was 94%. For the combined decay curve, estimated mean fiber half-life was 4.8 min (95% CI: 3.4–8.6 min) and the average time to 99% fiber removal from the air was 32 min (95% CI: 22–57 min).

(2) Distinguishing ventilation versus non-ventilation effects: estimation of fiber concentration decay using measured dilution ventilation

(a) Ventilation effects. Since ventilation was expected to be one of the major mechanisms of fiber removal in the current
study, it was of interest to compare the measured breathing zone airborne chrysotile concentrations to the estimated concentrations that would be expected based on ventilation effects alone. The dilution ventilation rate measured in the study chamber was 3.5 ACH. The fiber decay curve that would be expected based on ventilation effects alone is shown in Figure 4 along with the measured TWA concentration data. All but one of the measured TWA breathing zone concentrations were lower than would have been expected if fiber removal had occurred by ventilation alone. The fiber concentration decay half-life based on only ventilation removal effects at this rate of dilution was 12 min, and the time to 99% fiber removal from air due to dilution ventilation mechanisms alone was 79 min (Table 1). These results indicate that removal mechanisms in addition to ventilation were an important factor in the observed FS rate.

(b) Observed non-ventilation effects. Non-ventilation effects that likely contributed to or affected the observed rate of fiber removal from the breathing zone included simple gravitational settling of the fibers, as well as other factors such as adhesion to surfaces and agglomeration of the fibers in air. To characterize the impact that these non-ventilation factors had on fiber removal, a fiber decay curve was generated that accounted for the remainder of the observed fiber removal that was not already attributable to ventilation. An effective observed FS velocity encompassing all non-ventilation effects was calculated and found to be 0.0034 m/s on average (95% CI: 0.0009–0.0059 m/s). The estimated fiber concentration decay half-life was 8 min and the time to 99% fiber removal was 54 min for non-ventilation effects (compared to 79 min for ventilation effects alone) (Table 1). Thus, for the conditions assessed in this study, it appears that the non-ventilation fiber removal effects were slightly larger than the ventilation fiber removal effects.

(3) Modeling approach: estimation of fiber concentration decay using calculated gravitational settling velocities

To evaluate the utility of calculated gravitational settling velocities for estimating airborne fiber removal rates, fiber concentration decay curves were also derived using calculated gravitational settling velocities for fibers of various dimensions. One set of decay curves was derived assuming that the calculated settling velocity was the only removal mechanism (i.e. no ventilation), and a second set of decay curves was derived from the calculated settling velocities in combination with an assumed ventilation rate of 3.5 ACH. The derived decay curves were then used to estimate fiber half-life and time to 99% fiber removal (Table 2). Two different modeling approaches were used to estimate asbestos fiber gravitational settling rates: (a) the historic published gravitational settling model approach (Sawyer and Spooner, 1978) and (b) the more recently published gravitational settling model approach (Hinds, 1999).
Historic published gravitational settling model approach (Sawyer & Spooner, 1978) and more recently published gravitational settling model approach (Hinds, 1999)

For both gravitational settling model approaches (Hinds, 1999; Sawyer & Spooner, 1978), three different ranges of fiber lengths and diameters were considered in the calculations based on the PCME fiber dimension definitions, as well as the results of the bulk dimension analysis for the 7T chrysotile used in the study (Supplemental Figure A). These ranges were organized according to a lower end, a mid-range, and an upper end range of fiber dimensions. The lower end range was derived from the lower bound values of the minimum PCME dimension definitions, which were specified as a length of 5 \( \mu \text{m} \) and diameter of 0.25 \( \mu \text{m} \). The mid-range values were derived from a length of 20 \( \mu \text{m} \) and diameter of 0.5 \( \mu \text{m} \), which were approximately the mean length and width of PCME measured fibers from the bulk analysis, respectively, and the upper end were derived from a length of 100 \( \mu \text{m} \) and diameter of 1 \( \mu \text{m} \), which were approximately equal to the maximum length and diameter from the bulk analysis of the chrysotile fibers used in the study.

In addition to considering fibers within the PCME size range, gravitational settling calculations were also performed for fibers with diameters less than the PCME method minimum width of 0.25 \( \mu \text{m} \). For the same fiber lengths of 5, 20, and 100 \( \mu \text{m} \), the following widths were defined: a lower end width of 0.02 \( \mu \text{m} \), which was the minimum diameter measured in the bulk analysis, a mid range of 0.125 \( \mu \text{m} \), which was the midpoint of measured data for the category, and an upper end of 0.25 \( \mu \text{m} \), which was the upper bound for widths below the PCME size range.

Table 2 presents the results of the gravitational settling model calculations for each fiber category (PCME and non-PCME), each fiber length/diameter range (lower, mid, and upper), and each calculation method (Hinds, 1999; Sawyer & Spooner 1978). The most striking finding across the modeling calculations was the tremendous difference observed in calculated settling times when gravitational settling was estimated assuming zero ventilation compared with an appropriate ventilation rate. As shown in Table 2, when ventilation was assumed to be zero, the estimated time to 99% fiber removal ranged from 4 to over 14 000 h (rather than minutes), whereas when ventilation effects were included, the estimated time to 99% removal ranged from 0.99 to 1.32 h (59.4–79.2 min).

Thinner fibers had slower estimated settling velocities than thicker fibers (Table 2), an effect that is directly related to the smaller mass of the thinner fibers compared to thicker fibers of the same length. When ventilation effects were excluded, the slower estimated FS velocities associated with thinner fibers led to longer estimated times to reach 99% removal. Likewise, when ventilation was ignored, the Sawyer and Spooner method yielded longer estimated times to 99% removal compared to the Hinds method. However, when an appropriate ventilation rate was considered in addition to gravitational settling, the effects of gravitational settling model selection and fiber width on the fiber removal rate were minimal (overall time to 99% removal 59–79 min). These results indicate that dilution ventilation had a far greater effect on estimated removal rates than calculated gravitational settling alone.

The gravitational settling velocities estimated for the PCME size fraction spanned a large range from 0.000019 to 0.00076 m/s, which is 4.5-fold to 180-fold slower than the mean observed effective FS velocity of 0.0034 m/s. These findings indicate that simple gravitational FS models do not adequately account for all of the non-ventilation factors that may affect FS and fiber removal from air, and that gravitational settling models alone without consideration of an appropriate ventilation rate are likely to result in fiber removal rates that are significantly longer than measured fiber removal rates.

**Discussion**

This study used measured data from the breathing zone to characterize the removal rate of PCME chrysotile fibers from air in a controlled environment with a measured ventilation rate of 3.5 ACH. To estimate the instantaneous

| General approach | Specific approach | Assumed ventilation rate (ACH) | Estimated time to 99% PCME fiber removal (min) |
|------------------|------------------|-------------------------------|---------------------------------------------|
| 1. Measured concentration data | 1b. Decay curve fit to measured concentration data across all six events | NA (decay curve fit to data, not calculated from ventilation rate) | 32 (95% CI: 22–57) |
| 2. Ventilation versus non-ventilation effects | 2a. Decay curve expected from measured dilution ventilation only | 3.5 (measured ventilation rate) | 79 |
| | 2b. Decay curve attributable to observed non-ventilation effects only | | 0 |
| 3. Calculated gravitational fiber settling rates | 3a. Decay curve based on fiber settling rates calculated by the Hinds model | | 240–8160 |
| | 3b. Decay curve based on fiber settling rates calculated by the Sawyer and Spooner model | | 420–9600 |

*The estimated time to 99% removal is the time required for the initial airborne fiber concentration to decrease by 99%.*
(rather than TWA) fiber concentrations at specific time points, a concentration decay curve was fit to the measured data. This fitted decay curve was used to estimate the time required for the initial concentration to fall by 99%. These measurement-based fiber removal rates were also compared to estimates for fiber removal using dilution ventilation and non-ventilation fiber removal factors (such as agglomeration, impaction, and adherence to surfaces), as well as gravitational settling calculations for similar-sized fibers. Table 3 presents an overall comparison of the three approaches used for estimating the time to 99% removal: (1) reliance on the measured FS data, (2) consideration of effects from measured ventilation versus observed non-ventilation effects, and (3) reliance on calculated gravitational settling velocities, with and without consideration of dilution ventilation.

Based on the data collected in this study and the concentration decay equation (Equation 1) fitted to the measured breathing zone data, 99% of chrysotile fibers in the size range counted using the PCME method (≥5 μm in length, ≥0.25 μm in width, 3:1 aspect ratio) settled out or were removed from air in about a half hour (mean 32 min, 95% CI: 22–57 min) (Table 3). The measured TWA concentrations for the period 15–30 min after fiber generation ceased were reduced 86% on average (range: 80–92%) compared to concentrations during the fiber generation period. This study was conducted under ventilation conditions (3.5 ACH) considered to be representative of indoor conditions in residential structures and some commercial settings, but it is likely to be on the lower end of the ventilation range for many industrial settings. A dilution ventilation rate of 3.5 ACH, without consideration of FS or other removal mechanisms, is expected to yield 99% fiber removal by about 80 min, which was 2.5-fold longer than for the measured data. For the experimental conditions of this study, observed non-ventilation effects (e.g. agglomeration, impaction) appeared to have a larger impact on fiber removal than did ventilation effects (54 min to 99% fiber removal for non-ventilation effects versus 79 min for ventilation only effects). These results suggest that even if the current study had been performed in the absence of ventilation, 99% of the fibers still would have been removed from the air within approximately 1 h on average.

The use of theoretical gravitational settling models without taking into account ventilation yielded unrealistically slow settling rates compared to measured FS rates. Compared to the measurement-based estimates, the time to 99% fiber removal estimated from gravitational FS calculations in the absence of ventilation was more than 7-fold longer for the largest fiber sizes evaluated and up to 300-fold longer for the smallest fiber sizes evaluated (32 min for measurement-based settling versus 240–9600 min for gravitational settling; Table 3). Even when gravitational settling and dilution ventilation were both accounted for, estimated times to 99% removal were more than 2-fold longer than the measurement-based estimates (32 min versus 59–79 min). These findings highlight the likely effect of other known fiber removal mechanisms including agglomeration, impaction, and adherence to surfaces, rather than just gravitational settling.

The exponential decay curve approach used in the study analysis assumed a uniform concentration throughout the study chamber. A detailed spatial fiber dispersion analysis was beyond the scope of this study. Although ventilation and gravitational settling effects models were evaluated in comparison to measurement data collected in the personal breathing zone near a localized emission source, the results suggest that similar trends in fiber removal rates are likely to be seen at other locations in the chamber more distant from the localized emission source. This is evidenced by the finding that the shape of the fiber decay curves was fairly consistent across a range of initial fiber concentrations and did not show a trend associated with initial fiber concentration (Figure 3). Therefore, it is expected that although other locations in the study chamber could have had a different maximum concentration compared to the personal samples, the rate of fiber removal is likely to have been similar.

**Comparison to other published studies reporting measured fiber settling data**

As previously noted, several other studies have been published that have also reported measured data on the rate at which asbestos fibers settle out of the air (Brune & Beltesbrekke, 1981; Burdett & Stacey, 2001; Madl et al., 2008; Moorcroft & Duggan, 1984; Reitze et al., 1972; Sawyer, 1977). These studies are summarized in Table 4 and described below. Of these studies, only one (Reitze et al. 1972) reported data at a sufficient number of points in time (at least 3), and with a sufficient number of sample results per time point (at least 3) to reliably determine the time to 99% removal using an exponential decay curve. The remainder of the studies provided sufficient information to estimate the mean percent decrease in concentration during the FS periods (Table 4). These studies were helpful for the purposes of comparison to the data presented, although none of the other identified published studies discussed below measured asbestos FS in repeated events using PCME measurements, as was done in the current study.

In 1972, Reitze et al. conducted a study in which they reported measurements of FS following the spraying of asbestos insulation. Asbestos fiber type was not specified but appeared to be chrysotile based on the information provided in the study. The authors reported PCM airborne fiber concentrations at 30 and 60 min after insulation spraying operations, but did not report the sample averaging times (see Reitze et al., 1972; Table 3). During spraying operations, area samples collected between 10 and 75 feet from the spraying measured 10–71 f/cc. The room sizes were not specified but were large enough to allow for sampling at 10, 15, 20, 35, and 75 feet from the worker conducting the spraying. The ventilation rates were also not specified but were reported to have varied during sampling. At 30 min after spraying ended, concentrations declined between 1.01 f/cc and 4.22 f/cc and at 60 min, concentrations declined further between 0.26 f/cc and 0.76 f/cc. To characterize the FS rate of the spray application scenario that Reitze et al. analyzed, the exponential decay curve (Equation 1) was fit to their data. The resulting decay curve was used to determine that the estimated time to
| Activity                                                                 | Fiber type           | Sample type       | Post-activity time (min) | n   | Mean concentration ± Std. Dev. (f/cc) | Mean conc. % decrease | Estimated time to 99% removal [95% CI] (min) | Author                      |
|--------------------------------------------------------------------------|----------------------|-------------------|--------------------------|-----|--------------------------------------|----------------------|---------------------------------------------|------------------------------|
| Spraying asbestos insulation from nozzle, unspecified ventilation         | Likely chrysotile    | Area, PCM (≥5 μm) | 0                        | 7   | 45 ± 25                              | –                    | 61 [51–77]                                 | Reitze et al. (1972)        |
|                                                                          |                      |                   | 30                       | 4   | 2.0 ± 1.5                            | 96%                  |                                             |                              |
|                                                                          |                      |                   | 60                       | 5   | 0.47 ± 0.21                          | 99%                  |                                             |                              |
| Removal of dry asbestos-containing ceiling material, "quiet" conditions, or minimal ventilation | Chrysotile (15%)    | Area, PCM (≥5 μm) | 0                        | 1   | 120b                                 | –                    |                                             | NCa                         |
|                                                                          |                      |                   | 30                       | 1   | 65b                                  | 46%                  |                                             | Sawyer (1977)               |
|                                                                          |                      |                   | 45                       | 1   | 40b                                  | 67%                  |                                             |                              |
|                                                                          |                      |                   | 60                       | 1   | 25b                                  | 79%                  |                                             |                              |
|                                                                          |                      |                   | 120                      | 1   | 10b                                  | 92%                  |                                             |                              |
|                                                                          |                      |                   | 300                      | 1   | 4bc                                  | 97%c                 |                                             |                              |
| Dental casting procedure (mold dismantling) using asbestos liner, no local ventilation | Unspecified | Area, PCM           | 0                        | 2   | 24 ± 4b                              | –                    |                                             | NCa                         |
|                                                                          |                      |                   | 10                       | 2   | 1 ± 0b                               | 96%                  |                                             | Brune & Beltsetvikke (1981) |
| Vigorous dust disturbance in classrooms, unventilated with heating system | Amosite              | Area, PCM (≥5 μm) | 0                        | 19  | 0.14 ± 0.19                          | –                    |                                             | NCa                         |
|                                                                          |                      |                   | 45                       | 19  | 0.018 ± 0.015                        | 87%                  |                                             | Moorcroft & Duggan (1984)   |
| Resuspension of fibers using brush in small (~19 m³) polyethylene chamber, no ventilation | Amosite              | Area, PCM (≥5 μm) | 5a                       | 2   | 0.3 ± 0.2b                           | –                    |                                             | NCa                         |
|                                                                          |                      |                   | 15                       | 2   | 0.2 ± 0.2b                           | 22%                  |                                             | Burdett & Stacey (2001)     |
|                                                                          |                      |                   | 25                       | 2   | 0.1 ± 0.0b                           | 82%                  |                                             |                              |
|                                                                          |                      |                   | 35                       | 2   | 0.02 ± 0.0b                          | 93%                  |                                             |                              |
|                                                                          |                      |                   | 45                       | 2   | 0.02 ± 0.0b                          | 93%                  |                                             |                              |
|                                                                          |                      |                   | 55                       | 2   | 0.01b                                | >99%                 |                                             |                              |
| Resuspension of fibers using leaf blower in small (~19 m³) polyethylene chamber, no ventilation | Amosite              | Area, PCM (≥5 μm) | 5a                       | 2   | 0.9b                                 | –                    |                                             | NCa                         |
|                                                                          |                      |                   | 15                       | 2   | 0.8b                                 | 11%                  |                                             | Burdett & Stacey (2001)     |
|                                                                          |                      |                   | 25                       | 2   | 0.6b                                 | 33%                  |                                             |                              |
|                                                                          |                      |                   | 35                       | 2   | 0.4b                                 | 55%                  |                                             |                              |
|                                                                          |                      |                   | 55                       | 2   | 0.5b                                 | 44%                  |                                             |                              |
| Unpacking and repacking boxes of automobile brake shoes and pads (4 or 16 boxes) | Chrysotile (3–60%) | Personal, PCME     | 0                        | 4f  | 0.2 ± 0.2                            | –                    |                                             | NCa                         |
|                                                                          |                      |                   | 7.5                      | 4f  | 0.03 ± 0.04                          | 85%                  |                                             | Madl et al. (2008)          |
| Shake-out and handing of asbestos loaded work clothing, 3.5 ACH            | Grade 7T chrysotile  | Personal, PCME     | 0                        | 6   | (±1.5)²                              | –                    | 32 [22–57]                                 | This study                  |
|                                                                          |                      |                   | 2.5                      | 6   | 1.9 (±1.2)                           | 36%                  |                                             |                              |
|                                                                          |                      |                   | 7.5                      | 6   | 1.3 (±0.8)                           | 58%                  |                                             |                              |
|                                                                          |                      |                   | 22.5                     | 6   | 0.5 (±0.3)                           | 86%                  |                                             |                              |

*The time to 99% removal was calculated when data were available for 3 or more time points, with 3 or more samples at each time point. The “time zero” concentration represents the airborne concentration during the activity. The post-activity times are reported as the mid-point of the start and end sampling time. The airborne concentrations were estimated from figures if not reported in the text.

aNC indicates not calculated.

bAirborne concentrations estimated from plotted data in figure presented in reference.

cA sample was also collected 18 h after ceiling removal, but the resolution of the figure was insufficient to estimate the concentration. The authors noted background conditions occurred within 30 h after removal of the ceiling material.

dSampling time midpoint estimated based on an estimated delay of 30 min between sampling periods, and a total sampling time of approximately 60 min (total settling time of 90 min). Data shown for 19 events with data for both dust disturbance and no dust disturbance periods. The detection limit for one sample with no fibers detected was assumed to be 0.001 f/cc based on minimum detected result.

Based on the text, the first 10-min sample appears to include 5 min of brushing or leaf-blowing.

fThe 4 events from Testing II included pads (4 boxes), pads (16 boxes), shoes (4 boxes), and shoes (16 boxes). The first and second 15-min TWA left and right lapel samples were averaged prior to analysis. Box handling occurred in the first 15-min period. Values in table were calculated from the raw study data and do not appear in Madl et al. (2008).

gConcentration is a weighted average of 0–5 and 0–15 min TWA concentrations. See text.

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99% removal from air for this study was 61 min (95% CI: 51–77 min).

Another study involved collecting airborne fiber measurements under “quiet conditions” for a 3-d period (i.e. assumed to be minimal ventilation) following removal of the ceiling material in a building (Sawyer, 1977). PCM fiber analyses were combined with polarizing light microscopy (PLM) rather than the current technique of TEM to determine asbestos-specific fiber concentrations. It is unknown whether this analytical technique affected the final sample concentration results; this technique was not used in any of the other studies evaluating FS. Sample averaging times were not reported. The decrease in fiber concentration as a function of elapsed time following a 20-min removal procedure was provided in a figure in the published study (Sawyer, 1977, Figure 7). Based on the provided figure, fiber concentrations appeared to decline from a maximum airborne concentration of nearly 120 f/cc to just over 25 f/cc within approximately 1 h, then declined further to approximately 10 f/cc within approximately 2 h, and again to about 4 f/cc by 5 h, ultimately reaching background levels (0.02 f/cc) within 30 h. A sample was also collected 18 h after ceiling removal, but the resolution of the figure was insufficient to estimate the concentration (the concentration appeared to be near 0 f/cc). Although this study was reportedly conducted under “quiet conditions”, it is unclear what these conditions were. Another limitation of the study is that only one sample was taken at each time point. It is also unknown what happened to fiber concentrations between 5 h and 18 h post disturbance, since no additional samples were collected during this period; concentrations could have declined more rapidly than depicted (Sawyer, 1977; Figure 7). And, finally, it is unknown just how far above the reported background level (0.02 f/cc) the fiber concentrations remained between the 5 and 30 h time points (Sawyer, 1977; Table 2).

A simple study was conducted by Brune and Beltesbrekke in 1981 where the airborne concentrations of an unknown asbestos fiber type were measured in a laboratory during dental casting procedures using an asbestos liner. The laboratory was not equipped with local exhaust ventilation. Samples were collected during the dismantling of the mold and during two periods after the task ended, and were analyzed using PCM. Sample averaging times were not indicated. Reported airborne fiber concentrations of 21 f/cc and 27 f/cc were measured during the mold dismantling task. As depicted in the study (Brune & Beltesbrekke, 1981; Figure 4), after approximately 10 min following cessation of the mold dismantling, measured concentrations dropped to approximately 1 f/cc. Concentrations appeared to decline to approximately 0.25 f/cc after 30 min (Brune & Beltesbrekke, 1981). Qualitatively, the rate of decay in airborne concentrations appeared very similar to those observed in our study.

Moorcroft & Duggan (1984) measured airborne amosite concentrations using PCM in four classrooms with no mechanical ventilation during a period of vigorous dust disturbance, and then again approximately 15–75 min after the dust disturbance had ended (the sample duration was approximately 1 h with 5–30 min between sampling periods). Prior to conducting the measurements, the authors used gravitational settling velocity calculations to estimate the settling rate for fibers with a diameter of 1 μm, and reported that the amount of time needed for 50% of the fibers to settle out of the air would be 120 min, and for 90% of the fibers to settle out of air would be 410 min. For fibers with a diameter of 0.5 μm, the gravitational settling velocity estimates increased to 480 min for 50% settling and 1600 min for 90% settling. Similar to the current study, when Moorcroft and Duggan compared these gravitational settling calculations to the samples collected in the field, they noted that airborne fiber concentrations declined far more rapidly than the gravitational settling calculations had predicted. In the samples they collected, less than 25% of the fibers counted had a diameter of greater than 1 μm, and almost all fibers had aspect ratios of greater than 10 to 1. Based on the results of their measurements, they concluded that “theoretical estimates of the reduction expected from gravitational settling and ventilation suggest that these two mechanisms of fiber loss from the air were not sufficient to account for all of the observed reductions in concentrations” (Moorcroft & Duggan, 1984, p. 457). Also consistent with the current study, the authors indicated that “the residence time for the majority of fibers made airborne during our measurements was less than 1 h” (Moorcroft & Duggan, 1984, p. 457).

In 2001, the Health and Safety Laboratory in the UK reported the results of amosite FS measurements collected in a small chamber with polyethylene walls measuring 2.5 × 2.5 × 3 meters with no ventilation (Burdett & Stacey, 2001). To measure FS, the authors reported that the fibers were made airborne by brushing the walls of the chamber with a hand brush for 5 min. Following the end of the disturbance, the authors reported that PCM airborne fiber concentrations had been reduced by a factor of 50% after about 10 min and subsequently decreased by over 90% after 30 min, which was very similar to the decreases in concentrations observed in the measured data presented in this study. In a related test with a leaf blower, by the same authors, it was reported that 40% of the amosite fibers settled out in the first 60 min. There was some discrepancy between the authors’ description of the data and the report figures (Burdett & Stacey 2001; Figures 9 and 10); the data from the figures is summarized in Table 4. It is difficult to extrapolate the results of settling from this study to other situations (or more generally) because of the small chamber size and the polyethylene walls used in the chamber. Known adherence properties of fibers to plastic compared to the wall surfaces in a typical room are likely to have influenced the results. In addition, the rate of decay in concentration should be interpreted with caution because the airborne concentration during the fiber release activity was not reported by the authors. Based on the text, the duration of the suspension activity appears to be 5 min versus sampling durations of 10 min.

In 2008, researchers reported air concentration data that are useful for assessing FS rates as part of a simulation study characterizing airborne chrysotile concentrations involving the unpacking and repacking of unused chrysotile-containing automotive brake components (Madl et al., 2008). Short term personal samples analyzed by PCME characterized a 15-min period of active component handling followed by 15 min of...
inactivity. A total of four events with active and inactive periods were simulated using either 4 or 16 boxes of brake pads or shoes components with average bulk chrysotile concentrations between 31 and 36% by weight. The study was conducted in a 2054 m³ unventilated (0.83 air changes per hour) automotive repair shop with all entry and service doors closed. During first the 15-min period of active component handling, the average personal airborne chrysotile concentration was 0.2 f/cc (range: 0.030 f/cc to 0.541 f/cc). Concentrations decreased on average by 85% during the second 15-min period to 0.03 f/cc (range: 0.001 f/cc to 0.097 f/cc) (raw data requested and received from study authors for this comparative analysis). The observed 85% reduction is consistent with the 58% and 86% reduction rates observed during the first and second 15-min FS periods in the current study.

Evaluation of the studies presented in Table 4 showed that despite potentially large differences in workplace conditions, sizes, and ventilation rates, as well as differences in fiber type and likely differences in PCM fiber dimension profiles, the measured decreases in airborne PCM fiber concentrations in the published literature were consistent across all studies (within the same order of magnitude). Sawyer (1977) reported results that appeared less consistent compared to the other five studies, but previously described questions about this study make it difficult to directly evaluate the results compared to the other studies. Further, the results of Sawyer (1977) did show significant reductions in fiber concentrations over 1 h, consistent with the other studies. Fiber removal rates were similar between studies that measured amosite compared to chrysotile, and, consistent with the current study, both Moorcroft & Duggan (1984) and Burdett & Stacey (2001) reported data indicating that a majority of amosite fiber removal occurred within 60 min, depending on the scenario. In a more formal comparative analysis of the data in the current study and Reitze et al. (1972), which had sufficient measurement data to reliably fit an exponential decay curve to the airborne concentration results over time, the observed time to 99% removal from air ranged from approximately 20 to 80 min. Differences in the mean time to 99% fiber removal between this study (32 min) and the Reitze study (61 min) could have been affected by the specificity of the analytical method for asbestos fibers used in the studies; the current study used the PCME method, which reported only airborne chrysotile concentrations in the size range of interest, compared to the PCM method used in the Reitze study, which reported all airborne fibers in the size range of interest.

Fiber removal mechanisms from air: previous findings and future research priorities

Overall, the results of the analyses conducted in this study point to the influence of factors other than dilution ventilation and gravitational settling in the removal of asbestos fibers from air. Researchers initially identified some of these mechanisms of particle removal from air as early as the 1950s (Drinker & Hatch, 1954). Lists of these factors often include van der Waals forces, electrostatics, impaction on other bodies, centrifugation, agglomeration, Brownian motion, and diffusion (Corn, 1961a,b; Drinker & Hatch, 1954; Hinds, 1982; Zimon & Corn, 1969). In 1982, Hinds stated that “Aerosol particles will attach firmly to any surface they contact” and indicated that when particles contact one another, they will readily form clumps or larger masses in the air (Hinds, 1982, p. 127). According to Reist, in more turbulent airflows, such as what would be expected in a typical workplace, particles are likely to be removed from the air by mechanisms other than settling (Reist, 1984). Drinker and Hatch indicated that diffusion is the primary method by which micron-sized particles are removed from the air. In diffusion, particle momentum is reduced by the slower moving air boundary at the surface of larger objects, and ultimately results in particle adherence. Further, the small size of these particles causes them to be affected by the viscous forces of air, and significantly reduces the distance that they are able to travel (Hinds, 1982). Zimon reported that van der Waals forces, capillary forces due to the cohesion of water molecules in the air, and electrophoresis are all important factors in the adhesion of particles to surfaces and to each other (Zimon & Corn, 1969). As evaluated by Zimon, relative humidity levels above 65% in air can also result in increasing adhesion of particles to surfaces and to each other. Relative humidities above this level were not observed in the current study, as reported in the methods section. Zimon also reported an increase in adhesive forces on a particle as the size decreases, and further stated that for particles in the microscopic range, the variability in adhesive forces among particles was no larger than approximately 20%, and was much lower for smaller particle sizes (Zimon & Corn, 1969).

Regarding fibrous shapes, Zimon stated that, “In addition to the shapes already mentioned, there are also particles of fibrous or acicular form (prisms, needles, fibers, etc.) having one dimension greatly exceeding others. These include particles of zinc oxide, asbestos, tobacco virus, etc. We should expect that the adhesive force of acicular particles would be greater than that of plane and isometric ones, owing to the greater area of contact of the particles with the surface” (Zimon & Corn, 1969, p. 93).

The findings of our study are strongly supported by the work of Drinker and Hatch, Corn, Hinds, Reist, and Zimon, all of whom have concluded that there are many factors other than gravitational settling and ventilation that can influence the rate of particle and fiber settling. Existing models which rely heavily on either gravitational settling velocity or ventilation alone, or even these two factors together, are overly simplistic for estimating the residence time of fibers in air and appear likely to overestimate (at times dramatically) the amount of time that fibers, particularly those in the PCM size range, will remain airborne.

It is important to consider some of the factors that may be worthy of further evaluation based on the results of this study. Going forward, it would be desirable if some of the models which have been used in recent years could incorporate correction factors to account for those additional fiber removal factors beyond gravitational settling and ventilation, as these other factors appear to have a strong effect on the rate of PS. While the Drivas et al. (1996) model is an example of a model that
begins to take some of these factors into account, it could be helpful to further refine and validate this model specifically for use with fibers. Additional measurements of fiber removal under a variety of airborne concentrations and ventilation conditions would allow better characterization of the impact of these factors and help to improve the ability of existing models to more accurately predict fiber removal rates.

Conclusions
This study is the first known research to specifically assess the airborne settling rate of asbestos-specific fibers in the relevant size range of interest to human health (i.e. >5 μm in length and >0.25 μm in width with a 3:1 or greater aspect ratio, or PCME, according to regulatory agencies such as OSHA). There were several important conclusions reached following the data analysis in this study. First, the measured rate of asbestos fiber removal was faster than what was predicted by gravitational settling models commonly used by human exposure assessment and industrial hygiene professionals, particularly when these models included an assumption of limited or no ventilation. Such models do not account for a number of the major fiber removal mechanisms and conditions that have been shown to substantially influence the rate of FS (including agglomeration, diffusion, and electrostatic charge). These models are therefore likely to predict FS times that are longer (or much longer) than what has been measured in this study and other published studies reporting FS measurements in the literature. Second, room ventilation has been shown to be an important factor with respect to the rate of fiber removal. For scenarios where the dilution ventilation rate is 3–4 ACH, it was estimated that the impact of ventilation was similar to but slightly less than other removal mechanisms. The use of settling models with zero ventilation, which is not representative of the vast majority of work or home environments, resulted in unrealistically long estimates of FS times. And third, the measured removal rate from air in this study for asbestos-specific fibers in the size range of interest (i.e. PCME fibers) was consistent with what has been observed in prior peer-reviewed studies, despite the measurement of all fibers rather than asbestos-only fibers in those studies (PCM fibers). Based on the current and previous research, a reasonable estimate of the time necessary for the removal of 99% of relevant fibers from air ranged from approximately 20 to 80 min. For the chrysotile fibers specifically measured in this study, the time for 99% removal was a half hour (mean of 32 min; 95% CI: 22–57 min). This research has important implications for improving the accuracy of human health exposure and risk assessment efforts for airborne asbestos.

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Declaration of interest
The authors’ affiliations are as shown on the cover page. All of the authors are 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 underlying data used in this analysis were generated from a study that was partially funded by John Crane, Inc., a manufacturer of sealing devices which historically manufactured or supplied asbestos-containing gaskets and packing. Cardno ChemRisk has been engaged by John Crane, Inc., as well as other corporations, to provide general consulting, expert advice, and litigation support on scientific matters involving asbestos. The analysis reported in this article and the work associated with preparing this manuscript for publication was conceived and funded entirely by Cardno ChemRisk. This paper was prepared and written exclusively by the authors without any review or input by John Crane, Inc. employees or legal counsel, or any other outside source. Four of the authors (D.J.P., J.L.H., J.S., A.K.M.) have served as expert witnesses regarding historical exposures of various tradesmen to asbestos.

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