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United States
Environmental Protection
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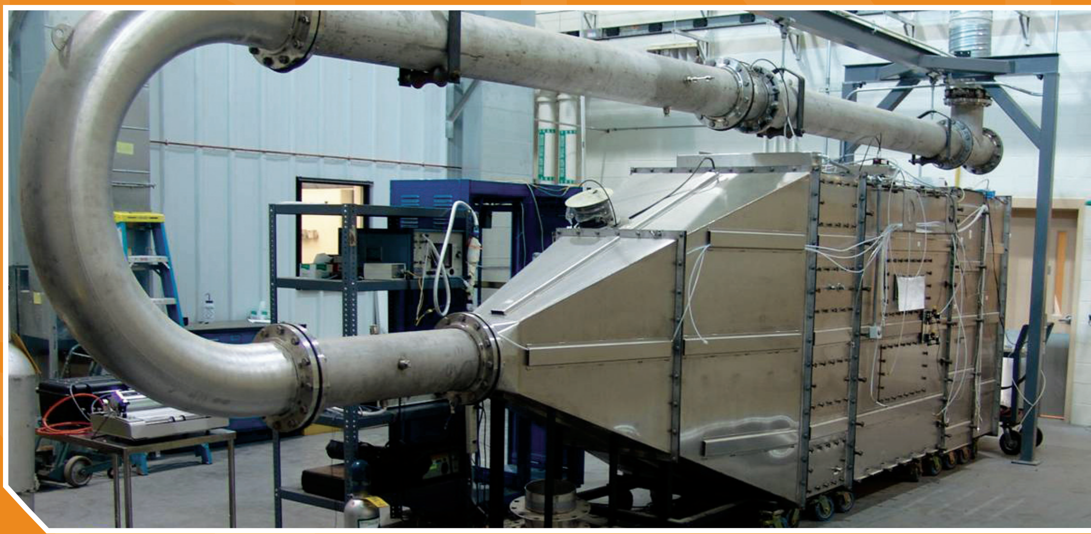
Resuspension of Fibers From Indoor Surfaces Due to Human Activity

FINAL REPORT



Office of Research and Development
National Homeland Security Research Center

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FINAL REPORT ON

Resuspension of Fibers From Indoor Surfaces Due to Human Activity

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Order Number: 3C-R321-NANX

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Notice

This report is submitted in fulfillment of Order Number 3C-R321-NANX by RTI International under the sponsorship of the United States Environmental Protection Agency. This report covers a period from October 2003 to March 2005, and work was completed as of March 4, 2005.

Disclaimer

The U.S. Environmental Protection Agency through its Office of Research and Development funded and managed the research described here under contract to RTI International. It has been subjected to the Agency's review and has been approved for publication. Note that approval does not signify that the contents necessarily reflect the views of the Agency.

Abstract

This research was directed toward 1) determining the quantity of asbestos simulant fibers resuspended (emitted) as normalized by the amount deposited, and 2) calculating asbestos simulant fiber emission factors at two heights while walking on and vacuuming seeded carpet. The asbestos fiber simulant selected for this research was calcium silicate, commonly known as Wollastonite. Three methods for measuring the quantity available for resuspension were studied:

a. MicroVac method following a modified version of ASTM D5755-95,

b. Ultrasonication method developed by Millete et al. (1993),

c. Individual carpet fiber analysis via scanning electron microscopy.

Wollastonite resuspension during walking and vacuuming was studied. Total quantity and size dependent fractions of resuspended Wollastonite were measured gravimetrically and with real-time aerodynamic particle instrumentation, respectively. Established experimental procedures were followed to seed new and old carpet with Wollastonite, characterize the quantity and size distribution of simulant fibers deposited on the carpet, resuspend the simulant fibers within an exposure chamber, and collect representative samples of resuspended fibers. The research defined a fractional carpet resuspension emission factor as ratio of Wollastonite resuspended and Wollastonite available for resuspension on the surface. The best method for estimating the amount available for resuspension was the modified MicroVac technique. This simple method only collected Wollastonite from the upper carpet fiber surfaces that were potentially available for resuspension; Wollastonite fibers embedded deep in the carpet with low probability of being resuspended were not collected. SEM analysis of individual carpet fibers worked only for new carpet fibers. Old carpet samples typically had too many "background" particles that confounded the analysis. The Millete et al. ultrasonication method poorly estimated the quantity available. The removal of a carpet plug and sonic bath released a very high number of carpet material particles that completely overwhelmed the ability to detect Wollastonite. Simulant fiber emission factors ranged from < 0.01 to 0.45, with the majority falling between 0.01 and 0.10. As expected, experimental conditions (primarily resuspension method, carpet age, and relative humidity) affected the emission factors. The majority of Wollastonite fibers resuspended from carpets were between 2 and 10 mm, with particles between 2 and 6 mm yielding the highest mass emission factors. The vacuum beater bar did resuspend a significant number of sub-micrometer particles that did not contribute much to the mass resuspended. Emission factor testing did not elucidate the influences of electrostatic and surface tension adhesion forces between the Wollastonite and carpet fibers in determining the amount available for resuspension. Further investigation of these mechanisms and their influence on emission factors will provide the requisite data needed for robust modeling exposure to resuspended particles.

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1.0 Introduction

1.1 Scope

The events of 9/11 and the subsequent related activities released an enormous particulateload into the environment proximal to the WTC complex. This aerosol burden included building material fragments that contained asbestos and other mineral fibers known or suspected to be health hazards. Although much of the aerosol subsequently deposited outdoors, a significant portion penetrated into nearby residences and businesses. The size distributions and quantity of the aerosol relative to the outside environment were strongly affected by the filtration ability of the ventilation system and building envelope. The model of Thornburg et al. (2001) provides a means of predicting the resultant aerosol sizes and quantities that would have been found in these buildings. A large fraction of the aerosols that penetrated these buildings deposited onto horizontal and vertical surfaces. Normal occupant activities can resuspend portions of the deposited aerosol on horizontal surfaces. Walking on medium pile carpeting is known to resuspend particles in the 2 to 10 mm range (Rodes and Wiener, 2001). This aerosol can result in unhealthful asbestos and other mineral fiber aerosol concentrations within the general vicinity of the activity and translocate the aerosol to other locations and surfaces within the building.

The research described here seeks to relate concentrations of asbestos-type fibers deposited upon carpeting by processes similar to those that occurred after 9/11 to the airborne concentrations that may have resulted from normal resident activities, such as walking and vacuuming. The general focus of this pilot effort was problem-identification rather than phenomenon characterization, since a) it is clearly retrospective, b) only simulants representing the real aerosol are available, and c) only a limited number of samples will be collected and analyzed within the resources available. This work built upon dust resuspension characterization methods for generic PM on carpeting studying the resuspension of generic particulate matter and metals (respectively) from flooring surfaces due to human activity (Rodes and Thornburg, 2004; Thornburg and Rodes, 2004). These pilot efforts provided the fundamental experimental methodologies and limited data to determine whether the resuspension of a tracked-in particles and metals from soil dust deposited on medium pile carpeting was significant and warrants further study. An important outcome of this research was collection of data that could be used in subsequent multi-pathway exposure modeling. This focus involved an experimental design that carefully considered how lifestyle factors such as adult and children's activity levels, residence volumes, fraction of flooring with carpeting, etc. could be used in exposure models in conjunction with the more fundamental data from this study.

1.2 Research Objectives

1. Determine quantity (mass and number) of simulant fibers available for resuspension, as compared to deposited mass, using a variety of techniques that included:
    a. MicroVac method following a modified version of ASTM D5755-95.
    b. Ultrasonication method developed by Millete et al. (1993).
    c. Individual carpet fiber analysis via scanning electron microscopy method (Thornburg et al., 2006)
2. Calculate simulant fiber emission factors at two heights while walking on and vacuuming seeded carpet. Aggregate and size dependent emission factors were calculated on a mass and count basis.

1.3 General Approach

The key elements of the research approach defined to address the objectives given in Section 1.1 were:

1. Select an appropriate asbestos fiber simulant
2. Develop or identify a methodology to deposit and embed (seed) known quantities of fiber simulant on carpet that emulates probable post-9/11 activities.
3. Select a vacuum cleaner representative of a homeowner quality unit rather than a HEPA unit that would be used in remediation efforts.
4. Develop a project Quality Assurance Project Plan before beginning experimental work (see: "Indoor PM Resuspension Testing of Fibers - Quality Assurance Project Plan For Basic Research Projects, EPA Order No. 3C-R321-NANX, EPA/NRMRL under Contract No. QT-OH-03-00572 RTI Project No. 08924)
5. Obtain new and old carpet for experimental use. Characterize background loading of particles on carpet. Condition carpet as necessary to obtain acceptable background levels.
6. Use existing RTI standardized test methodologies, incorporate other established procedures, and devise new methods as necessary that consider fiber simulants by particle size that define:
    a. How to characterize the fiber simulant loadings on carpet fibers by methods specified in the project objectives that consider how much dust is available for resuspension, as a function of particle size.
    b. How to characterize carpeting in terms of pile height (fiber length), age, soiling history, and surface loading level.

c. How to resuspend particles in a controlled environment with minimal interference from background particles. load carpeting with defined areal loadings of a selected dust,

d. How to quantify air concentrations as function of height, fully correcting for transmission line losses between the measurement points and the sensing zone, thus facilitating mass balance closure by accounting for the (large) fraction of particle mass often lost to internal surfaces

7. Conduct controlled walking and vacuuming experiments on new and/or old carpet loaded with up to three different quantities of fiber simulant.

1.4 Underlying Variables

Two variables that probably influence resuspension of particles from carpets were not studied during this project because of the limited scope of work. However, our hypotheses and suppositions regarding these variables based on our carpet research experience are presented below because these concepts aid in the interpretation of the data collected during these experiments.

1.4.1 Flooring Surfaces

Previous RTI resuspension data showed that as the pile height decreased, the level of resuspension decreased substantially from normal walking. No measurable dusts were observed from dusts 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. Thus, the current work focused only on medium pile carpeting (~70% of all new carpeting sold) which has been shown to contribute significantly to resuspension.

1.4.2 Particle Adhesion

An important factor felt to be extremely important in understanding resuspension of particles from carpet fibers is adhesion. Adhesion of particles to carpet fibers is influenced by relative humidity (Rodes and Thornburg, 2004), thought to be controlled primarily by electrical charging of both the fibers and the particles. Very low humidities are routinely found to increase the charging of certain formulations of carpet fibers. An additional adhesive force considered here is surface tension: particle-to-particle and particle-to-fiber. Surface tension forces bonding particles together or to the fibers is felt to be very important at relative humidities above ~45%. At 45% Rh, sufficient water is present to increase the surface adhesion force by increasing the contact angle between the particle and a second surface (Ranade, 1987). Both of these types of adhesive forces work together to bond particles to surfaces. Undoubtedly, resuspension occurs when sufficient energy is imparted to exceed the cumulative force levels.

Our extensive scanning electron imaging of carpet fibers has shown that as carpeting ages or becomes significantly soiled (including coating of the fibers over time by grease aerosol from cooking), the carpet fibers ability to generate static charging appears to decrease substantially. This substantial change in potential adhesion characteristics for particles to fibers between new and old carpeting was addressed in the current research by considering either new, unsoiled carpeting, or soiled carpeting that was at least 1 year (or substantially more) old as a binomial variable.

No efforts were made to measure either type of adhesion in these experiments, but temperature and relative humidity were recorded during all tests to determine if the influences from these types of adhesions could be estimated categorically. Successful modeling of particle resuspension will at some point require more detailed investigation of the relationships among these factors.

1.5 Data Presentation

The wide array of methods used to measure the asbestos fiber simulant size distribution and concentration on the carpet fibers and resuspended required selection of a reference metric.

Asbestos simulant size was measured via microscopy to yield a projected area diameter, and via aerosol instrumentation to yield an aerodynamic diameter. In addition, the bulk asbestos fiber simulant size distribution was measured in terms of optical diameters. For the purposes of this research, aerodynamic diameter was selected to characterize the asbestos simulant size distribution. Aerodynamic diameter is the standard reference for all aerosol research. As such, factors are available for converting other diameter measurements to aerodynamic diameter. For example, projected area diameters can be converted to aerodynamic diameters using established conversion factors as described in Section 2.1.9. However, a conversion between optical and aerodynamic diameters does not exist because of the complexity surrounding particle refractive indices. Therefore, a basis does not exist for comparing the aerodynamic diameters reported from the microscopy measurements and aerosol instrumentation with the optical diameters used to characterize the bulk asbestos simulant size distribution.

Similarly, microscopy measurements provided asbestos simulant fiber count data, realtime aerosol instrumentation provided either count or mass concentration data, and gravimetric analysis yielded mass concentration data. Gravimetric analysis determined the quantity of asbestos simulant deposited on the test surfaces and one method for measuring the quantity of simulant resuspended during the experiments. Without a priori knowledge of the bulk simulant aerodynamic size distribution (due to the lack of an optical-aerodynamic conversion discussed above) an established method for converting mass data to count data was not available. Asbestos simulant count data from microscopy and real-time aerosol instrumentation easily were converted to a mass basis from the volume and density of the measured particles. To provide an estimate of the deposited and resuspended asbestos simulant count concentrations, regression curves relating the mass to the count concentrations are presented in Section 3.1.

2.0 Experimental Methods

2.1 Instrumentation & Procedures

The instrumentation and procedures selected determined the particle aerodynamic diameter and concentration, either mass or number, of the particles resuspended from the carpet or embedded on the carpet fibers.

2.1.1 Asbestos Fiber Simulant

Calcium Silicate ($CaSiO_3$), commonly known as Wollastonite, was the asbestos fiber simulant selected. Wollastonite fibers were the simulant of choice for asbestos occupational exposure studies because of their acicular nature. Nyglos M3 (NYCO Minerals, Willsboro NY) was used (Table 2.1). Wollastonite fibers had a mean aspect ratio of 3.33 ± 1 and density of 2.9 g/cm^3.

2.1.2 Carpet Characteristics

New and old carpets were obtained for the resuspension experiments (Table 2-2). New carpet was beige, medium pile carpet manufactured by Shaw Carpets or Beaulieu. The carpet was purchased retail and was removed directly off the main roll. New carpet was vacuumed multiple times with a standard household vacuum to remove excess loose fibers and dirt. Old carpet was obtained from the same retailer after removal from unknown private residences. The age, use, manufacturer, and history of the old carpet was unknown. Old carpet exhibiting normal wear and soiling were selected; carpets with excessive wear and obvious soiling were avoided. Old carpet was cleaned thoroughly with a rental hot water carpet cleaner and vacuumed multiple times with a standard vacuum before experimental use.

2.1.3 Deposition Chamber

New and old carpet was seeded with Nyglos M33 Wollastonite fibers using a flow through deposition chamber (Figure 2-1). Simulant dust was aspirated and dispersed into a laminar flow transport pipe that carried the fibers to the injection head at the top of the chamber. A mixing baffle at the injection head evenly dispersed the fibers across the cross section of the chamber. The velocity at the injection head outlet was balanced with the downward air velocity generated by a fan that pulled the fibers into the carpet.

A known mass of Wollastonite was injected into the chamber. 47 mm Teflo® filters placed in a 9-point grid pattern across the surface of the carpet collected samples of deposited Wollastonite to determine gravimetrically the total mass deposited. Mass deposited on the carpet was calculated by taking the average mass loading (mg/in^2) measured per filter and multiplying by the area of exposed carpet (A_c),

$$Mass = A_c \frac{\sum \frac{4F_m}{\pi d^2}}{9} \qquad (2\text{-}1)$$

where F_m is the filter mass and d^2 is the filter diameter.

Carpet loadings in the chamber were found to be linear with injected dust mass, and predictable, having an R^2 value of 0.96. Figure 2-2 illustrates the experimental utility of the chamber, showing the linearity and strong correlation of the regression of injected mass versus deposited mass. Without demonstrating this linearity, it would have been inappropriate to normalize the emission factors by loading. Note a leak in the injection nozzle was identified after all experiments were completed. This leak limited the percentage of Wollastonite deposited to 2%. However, the percentage deposited was linear with quantity injected. As a result, the quality of the Wollastonite resuspension data was not compromised.

Table 2-1. Nyglos M3 Wollastonite fiber size distribution. Median diameter = 2.5 µm by Cilas Granulometer

Diameter (µm)	Mass Fraction	Cumulative Fraction
<0.5	0.09	0.09
1	0.11	0.20
2	0.22	0.42
3	0.16	0.58
4	0.14	0.72
5	0.09	0.81
7	0.08	0.89
10	0.07	0.96
>10	0.04	1

Table 2-2. Carpet characteristics

Carpet	Mfg	Material	# Fibers/in^2	Pile Height	Test Use
New #1	Shaw	Nylon 6,6	4000	10 mm	Walking
New #2	Beaulieu	Nylon 6,6	4000	8 mm	Vacuuming
Old #1	unknown	unknown	3000[a]	10 mm	Walking
Old #2	unknown	Nylon 6,6	2500[a]	12 mm	Walking & Vacuuming

[a]Estimated by counting number of fibers per loop and number of loops per in^2.

2.1.4 Exposure Chamber

All tests were conducted in the RTI Large Dynamic Chamber (Figure 2-3). This positive pressure chamber equipped with six pre-filters and six ultra low penetration air (ULPA) filters can provide essentially particle-free air at flows ranging from 0.25 to 80 m^3/min. For these tests, the flow was 13.2 m^3/min; equivalent to a linear face velocity in the test section of 10 cm/s. A flow distribution baffle preceding the filters creates a uniform velocity profile through the chamber. The test space within the chamber is 4 ft wide x 7 ft long x 6 ft high. Carpet (3 x 3 ft) samples were placed in this space. A contraction of 12° over 2.4 meters with a mixing baffle immediately upstream of the 20 cm diameter outlet pipe uniformly concentrates the aerosol generated in the test space. Mass samplers were installed in this section to collect PM_{10} filter samples isokinetically for gravimetric analysis. Sampling ports in the contraction allow direct sampling from within the test space at the desired heights and with multiple instruments. A Model 3321 Aerodynamic Particle Sizer (TSI Inc., Minneapolis MN) was connected to sample ports in the outlet pipe for isokinetic collection of resuspended PM samples for size distribution measurements. Temperature and relative humidity were monitored with a HOBO H8 Data Logger (Onset Computer Corp., Bourne MA) installed in the test space. Preliminary tests confirmed air entering the chamber and activities conducted by test personnel wearing cleanroom coveralls inside the chamber did not generate a significant number of particles above background. As an extra precaution the chamber test section surfaces were vacuumed and wiped with clean, damp cloths prior to each test.

2.1.5 Resuspension Methods

Walking and vacuuming were the resuspension methods selected. A single volunteer walked randomly across the carpet area for 5 minutes during an experiment. The volunteer was a 73 inch, 170 lb male with size 12 shoes. A particle free cleanroom garment was worn for all tests. The same shoes were worn during all walking experiments. A pedometer worn by the volunteer determined the number of steps taken by the volunteer during the experiment. The volunteer walked across each test carpet for 3 minutes prior to seeding with Wollastonite to determine the background resuspended particle concentration. The subject attempted to apply a constant foot pressure (energy) to the carpet during since previous work showed emission factors varied with energy level. A standard 13 amp Mach 2.1 Hoover (Model # U5330-900) upright vacuum with beater bar was used. The entire vacuum was cleaned thoroughly prior to the experiments. A new Hoover Type Y Allergen® vacuum bag (99.98% filtration efficiency) was installed for each experiment. The vacuum was ON for approximately 5 minutes before an experiment began to allow particles generated from the starting of the motor to leave the chamber. A different volunteer, wearing a particle free cleanroom garment, randomly moved the vacuum across the carpet in all directions for 5 minutes during a test. The volunteer did not walk on the carpet during the tests.

2.1.6 Carpet Fibers

Individual carpet fibers were collected from two locations within each piece of test carpet after seeding with Wollastonite. Fibers were analyzed via SEM to quantify the size distribution of the Wollastonite on the carpet fibers available for resuspension. A dial micrometer was used to estimate the carpet pile height at multiple locations for each type of carpet.

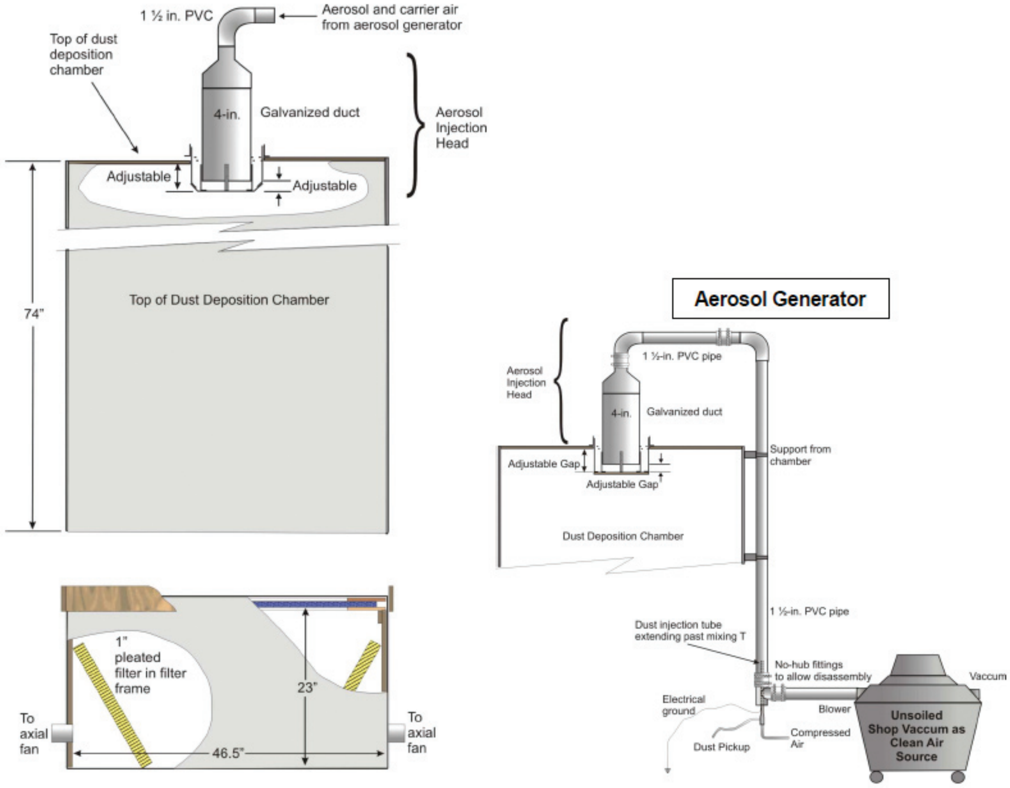

Figure 2-1. Aerosol generator and deposition chamber used to load Wollastonite on carpet

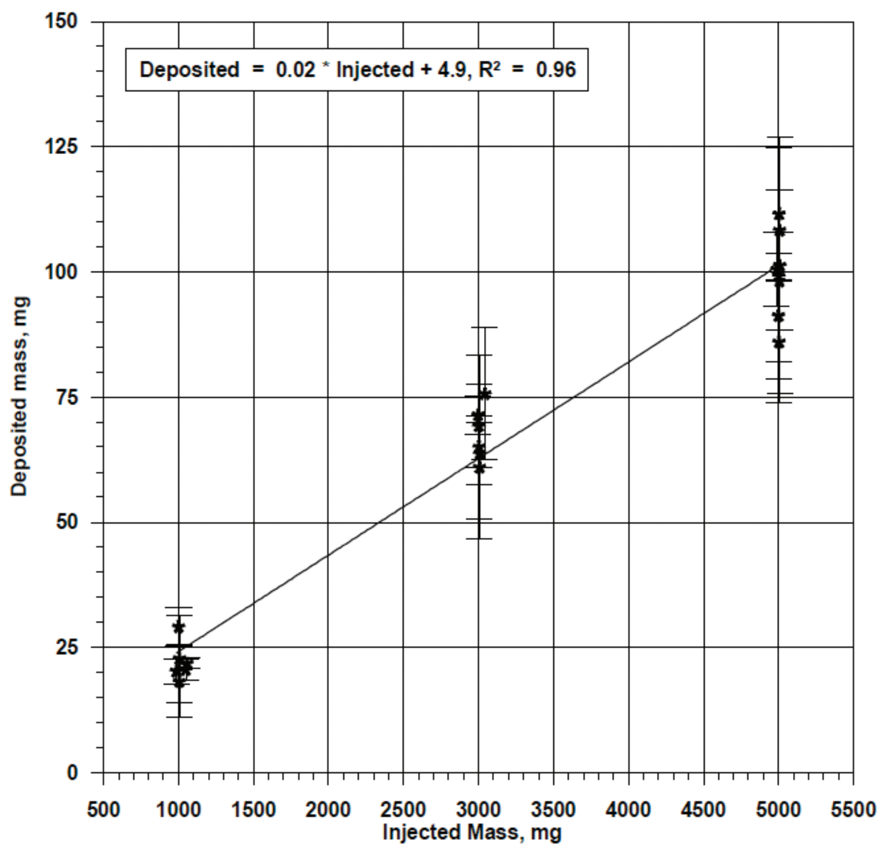

Figure 2-2. Relationship between mass injected into deposition chamber with mass deposited on carpet surface.

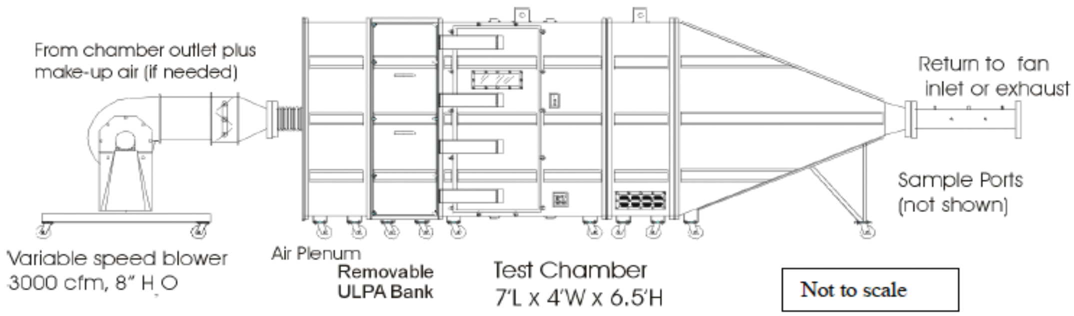

Figure 2-3. Schematic of Large Dynamic Chamber used in resuspension tests.

2.1.7 Carpet Vacuum Samples

The quantity of particulate matter potentially available for resuspension was estimated by collecting two vacuum samples onto 47 mm Teflo® filters from an area adjacent to where the carpet fibers were extracted per Section 2.1.6. The vacuum used was custom designed by RTI. A modified ASTM method D5755-95: Standard Test Method for Microvacuum Sampling and Indirect Analysis of Dust by Transmission Electron Microscopy for Asbestos Structure Number Concentrations was followed for the sample collection. The RTI modifications included: using a brush on the vacuum nozzle to trap carpet fibers, reducing the sampling velocity to 45 cm/s to minimize the aggressiveness of the procedure, manual removal of obvious (visible to naked eye) carpet fibers collected on the filter, and gravimetric analysis of the filter instead of liquid extraction for microscopic analysis.

2.1.8 Ultrasonication Method

Samples of carpet for ultrasonic extraction of particles were collected following a modified version of Millette *et al.* (1993). Approximate 20 cm^2 pieces of carpet were carefully removed from the test carpet following seeding with Wollastonite fibers for the ultrasonic extraction. Carpet pieces were immersed fibers down in a 1 L beaker containing 100 ml of a 0.002% solution of methyl cellulose surfactant in particle free water. The entire beaker was placed in an ultrasonic bath for 30 minutes. The carpet piece then was removed and rinsed with 100 ml of particle free water, raising the total volume to 200 ml. The entire solution was shaken vigorously to disperse particles then allowed to sit for 2 minutes. Only 50 ml aliquots of solution were extracted from ¼ to ½ inch below the surface. Smaller aliquots did not yield sufficient number of particles for accurate SEM image analysis. The 50 ml aliquot was passed through a coarse metal screen to remove large carpet material pieces placed over a buchner funnel. The coarsely screened aliquot was filtered through a 47 mm, 0.2 µm pore polycarbonate filter, backed by a 0.45 µm pore cellulose ester filter placed inside the funnel. The filters were equilibrated inside a temperature (23°C) and humidity (35%) controlled chamber for at least 24 hours before transfer to U.S. EPA for SEM imaging. A subset of the ultrasonication filters underwent gravimetric analysis to provide comparative data for the Wollastonite fiber mass measured via SEM.

2.1.9 SEM Image Analysis

Mantech Environmental (METI) provided scanning electron microscopy (SEM) images of individual carpet fibers and the ultrasonication filters. The aerodynamic diameter of each particle contained in the images was determined using image processing software and established algorithms. The algorithms disregarded particles with aspect ratios less than 2 (non-Wollastonite fibers) and converted the measured particle projected area to an equivalent diameter then an aerodynamic diameter using standard dynamic shape and volume shape factors for fibers (Hinds, 1982). SEM images at 880x magnification were provided, equivalent to 5.059 pixels per micrometer, providing a particle minimum detection limit of 0.4 mm. Additional details are provided in Appendix A.

2.1.10 Aerodynamic Particle Sizer

The Aerodynamic Particle Sizer was used to obtain re-suspended PM mass and count size distribution data from 0.5 to 20 µm. The instrument was operated according to the instructions provided by the manufacturer. Isokinetic samples were collected through the sample probe installed in the outlet pipe. Particle losses within the sampling tube, shown in Figure 2-4, were estimated using standard aspiration and transport equations for laminar flow accounting for gravitational and inertial deposition losses (Brockman, 2001). Counting efficiency errors were corrected using the data from Peters and Leith (2003).

2.1.11 URG Mass Sampler

URG mass samplers (University Research Glassware, Chapel Hill, NC) collected PM_{10} samples isokinetically at 16.7 Lpm within the test chamber. Two samplers were used per test: one at 18" and the other at 36" above the floor. However, mixing within the chamber probably eliminated any gradient in resuspended PM concentration. Samples were collected on 47 mm Teflo® filters. Filter mass was determined gravimetrically.

2.1.12 Gravimetric Analysis

Aerosol mass collected on filters were weighed in RTI's temperature and humidity controlled (23°C, 35% Rh) weigh chamber on a Mettler Toledo MT2 balance with 0.1 µg resolution.

2.1.13 Temperature & Relative Humidity

Temperature and relative humidity within the homes was measured with a HOBO H8 Data Logger. Temperature and relative humidity were recorded at 1-minute intervals.

2.1.14 Statistical Analysis

All statistical analyses were performed using SAS version 9.1 (SAS Inc., Cary NC). The General Linear Models module was used to determine the significance of experimental parameters on emission factors. Forward addition and backward subtraction methods were used to identify the statistical significance of the experimental parameters.

2.2 Tests Conducted

The experimental design selected provided Wollastonite fiber emission factor data for various resuspension mechanisms, carpet characteristics, and environmental conditions. Walking and vacuuming were the resuspension mechanisms. Carpet characteristics encompassed new/unmatted carpet with strong static charge and old/soiled/matted carpet with little static charge. Humidity ranged from typical, indoor air conditioned values to extremely high simulating buildings without air conditioning during precipitation events. Potential variations in emission factors as a function of Wollastonite loading were investigated as well. Total Wollastonite mass deposited on the carpet surface varied from ~25 mg to ~60 mg to ~100 mg, representing low, medium, and high loading levels, respectively.

Emission factors were calculated multiple ways. Resuspended Wollastonite concentrations were measured with the APS and URG instruments. The Wollastonite available for resuspension was calculated from vacuum samples, SEM images, and ultrasonication of carpet sections.

2.3 Emission Factor Calculations

Emission factors were calculated multiple ways. Resuspended mass concentrations were measured with the APS and URG instruments. Corresponding resuspended Wollastonite count data were provided by the APS or calculated from the URG gravimetric data. The mass available for resuspension was calculated from vacuum samples, SEM images, and ultrasonication of carpet sections. SEM images provided available Wollastonite count data directly. Wollastonite count data from gravimetric samples were estimated. Emission factors were normalized by the number of steps made during an experiment.

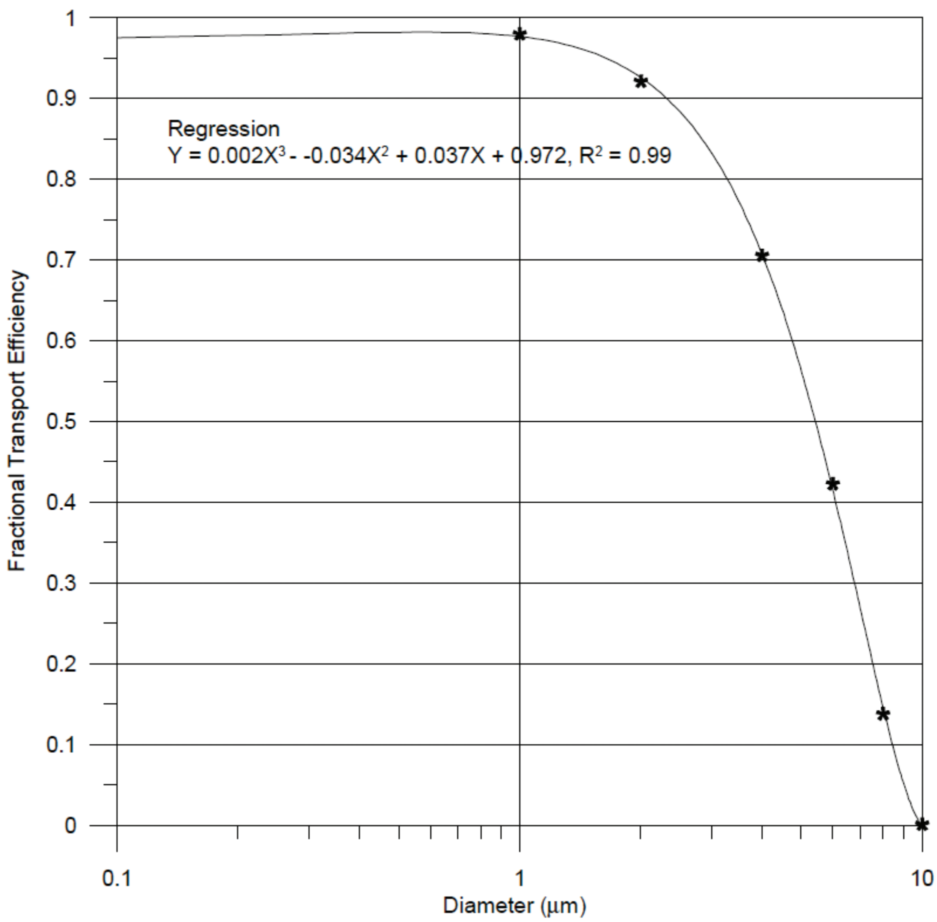

Figure 2-4. Particle transport efficiency in APS isokinetic sample line in Large Dynamic Chamber.

Table 2-3. Description of tests conducted in RTI exposure chamber.

Test #	Carpet	Method	Loading	Humidity
1	New #1	Walk	Low	Low
2	New #1	Walk	Medium	Low
3	New #1	Walk	High	Low
4	Old #1	Walk	Low	Low
5	Old #1	Walk	Medium	Low
6	Old #1	Walk	High	Low
7	New #1	Walk	Medium	High
8	Old #2	Walk	Medium	Low
9	New #2	Vacuum	Low	Low
10	New #2	Vacuum	High	Low
11	Old #2	Vacuum	Low	Low
12	Old #2	Vacuum	High	Low
13	New #2	Vacuum	High	High
14	Old #2	Vacuum	High	High
15	Old #1	Walk	Medium	High

2.3.1 Wollastonite Resuspended by APS

Mass resuspended measured by APS was calculated using Eq. 2-2. The mass concentration in each size bin (C_R) corrected for the background resuspended particle concentration (C_{Bkg}) and transport efficiency into the APS (η) were summed to yield a total concentration. This concentration was multiplied by the flow through the chamber (Q_c = 0.013 Lpm), the total time particles were resuspended (t), and a correction factor for APS counting efficiency (χ =2). The total time particles were resuspended was not constant across all tests because of depletion of the particles available for resuspension.

$$\overline{M}_{APS} = \left[\sum \left(C_R - C_{Bkg}\right) \times \eta\right] \times Q_c \times t \times \chi \qquad (2\text{-}2)$$

The APS also provided resuspended Wollastonite number concentration data. The total counts resuspended (C_{APS}) were calculated using an equation similar to Eq. 2-2.

$$\overline{C}_{APS} = \left[\sum \left(C_R - C_{Bkg}\right) \times \eta\right] \times Q_c \times t \times \chi \qquad (2\text{-}3)$$

2.3.2 Wollastonite Resuspended by Gravimetric Data

Mass resuspended as measured by the URG samplers was calculated from the gravimetric mass collected on the filters, M_{filter} divided by the URG sample flow (Q_{URG} = 20 Lpm) and multiplied by the flow through the chamber (Q_c = 0.013 Lpm). Mass resuspended was not corrected for background because concentrations either were not statistically different from zero or contributed less than 5% of the total mass collected (as measured by APS).

$$M_{URG} = M_{filter} \times \frac{Q_c}{Q_{URG}} \qquad (2\text{-}4)$$

Resuspended Wollastonite number concentrations (C_{URG}) were estimated from the gravimetric mass and APS mass size distribution data. The cumulative gravimetric mass (M_{URG}) was multiplied by the mass fraction in each APS size bin (f_i) then converted to particle counts assuming each fiber was an aerodynamic sphere.

$$\overline{C}_{URG} = \sum \left(f_i M_{URG}\right) \frac{6}{\pi d^3} \rho \qquad (2\text{-}5)$$

2.3.3 Wollastonite Available by MicroVac

Mass available by MicroVac was calculated from the gravimetric mass collected on the filters, M_{filter} divided by the total area vacuumed (A_{vac} = 9 in^2) and multiplied by the area of the test carpet piece (A_c = 1296 in^2).

$$\overline{M}_{Vac} = M_{filter} \times \frac{1}{A_{vac}} \times A_c \qquad (2\text{-}6)$$

The number of Wollastonite fibers available for resuspension was calculated from the MicroVac mass using an equation similar to Eq. 2-5. The Wollastonite size distribution data measured by the SEM images of the carpet fibers determined the mass fraction in each size range.

$$\overline{C}_{VAC} = \sum \left(f_i M_{VAC}\right) \frac{6}{\pi d^3} \rho \qquad (2\text{-}7)$$

2.3.4 Wollastonite Available by Carpet Fiber SEM Images

Fiber SEM images provided cumulative and size dependent estimates of the Wollastonite mass available for resuspension. From the size distribution calculated in each image, the total mass, M_{SEM}, of particles on the 36" x 36" carpet section was calculated based on the incremental mass in each size interval (i) via the following equation,

$$\overline{\boldsymbol{M}_{SEM}} = \Sigma \boldsymbol{M}_{\boldsymbol{F}_i} \times \frac{1}{\boldsymbol{N}} \times \boldsymbol{N}_f \times \boldsymbol{L}_f \times \boldsymbol{A}_c \qquad (2\text{-}8)$$

where *MFi* is the incremental particle mass divided by the total number of images processed, ***N*** is the fiber length visible per photo (101 µm), $\boldsymbol{N_f}$ is the number of millimeters of fiber available for resuspension, $\boldsymbol{L_f}$ is the number of fibers per unit area of carpet, and $\boldsymbol{A_c}$ is the area of carpet tested (36" x 36"). A $\boldsymbol{N_f}$ value for each carpet type was estimated by scanning the entire length of the fiber and determining the distance from the fiber tip that Wollastonite fibers were no longer present. Maximum N_f value was 4 mm, or 50% of the fiber length.

The number of Wollastonite fibers available for resuspension (C_{SEM}) was determined directly from the incremental count data in each size interval (C_{Fi}) provided by the SEM images.

$$\overline{C_{SEM}} = \Sigma C_{F_i} \times \frac{1}{N} \times N_f \times L_f \times A_c \qquad (2\text{-}9)$$

2.3.5 Wollastonite Available by Ultrasonication

SEM images of ultrasonication filters provided a second cumulative and size dependent estimate of the Wollastonite mass available for resuspension. One photo per buchner funnel hole was collected. Usually 5 to 10 holes were photographed. The number of holes photographed depended on the number of particles surrounding the hole. A sufficient number of particles were desired to insure an accurate size distribution. From particle size distribution calculated from each image, the total mass, M_{SON}, on the 36" x 36" carpet section was calculated via the following equation,

$$\overline{M_{SON}} = \Sigma M_{F_i} \times \frac{A_{photo}}{N_{photo}} \times A_{hole} \times N_{hole} \times \frac{A_c}{A_{sam}} \qquad (2\text{-}10)$$

where M_{Fi} is the incremental particle mass per size bin, A_{photo} is the image area, N_{photo} is the number of photos collected, A_{hole} is the area of a buchner funnel hole, N_{hole} is the total number of buchner funnel holes (91), A_c is the carpet section area tested, and A_{sam} is the carpet area sonicated. Additionally, gravimetric analysis of the ultrasonication filters provided another estimate of the Wollastonite mass available for resuspension.

A similar equation estimated the total number of Wollastonite particles available for resuspension using the particle count data from the SEM images.

$$\overline{C_{SON}} = \Sigma C_{F_i} \times \frac{A_{photo}}{N_{photo}} \times A_{hole} \times N_{hole} \times \frac{A_c}{A_{sam}} \qquad (2\text{-}11)$$

3.0
Results & Discussion

3.1 General Results

The background mass of particles available for resuspension from the carpet and resuspended by walking and vacuuming were measured for all four carpets tested. The background mass does not contain Wollastonite particles, but may contain other fibrous particles that affected the SEM analysis. Background particle mass data affecting the mass available in the carpet is presented in Table 3.1. All resuspension data for a respective metric were corrected for the background mass.

As expected, the old carpets yielded higher background particle mass, even after extensive cleaning. The MicroVac yielded a significant quantity of particles in addition to carpet fiber fragments. The destructive ultrasonication method yielded a very high mass of particles as measured gravimetrically and via SEM. The high mass measured via SEM for ultrasonication filters resulted from a large number of fibrous type particles being collected on the filter. Fiber SEM analysis provided a much smaller background particle mass because it is a non-destructive technique. The differences between the two types of old carpet was caused by the presence of high concentrations of sawdust in Old #2 that presented as fibrous particles with an aspect ratio similar to Wollastonite.

On the other hand, new carpets yielded much lower mass by all methods. The small quantity collected by the MicroVac probably was carpet fiber fragments. The gravimetric analysis of the ultrasonication filters from new carpets showed a significant mass of carpet backing is generated during the procedure. However, SEM analysis of these filters showed these particles were not fibrous (aspect ratios < 2) such that a mass and size distribution could not be determined. Similarly, the lack of any particles on the new carpet fibers prevented quantification of the mass and size distribution by the Fiber SEM method.

Resuspension tests to characterize the background concentration of particles generated during walking and vacuuming were conducted. The background resuspended particle mass was less than 0.05 mg, equivalent to a concentration of 3 $\mu g/m^3$. Background concentrations were 10 times, minimum, lower than the concentration resuspended during a test. Resuspended fiber mass data measured by APS and URG systems were corrected for this background mass.

General experimental conditions for all tests are presented in Table 3-2. Note that depletion occurred during resuspension tests with low Wollastonite mass loadings. Depletion of the Wollastonite during these tests was accounted for in the data analysis via Eqs. 2-2 and 2-3. Also, some of the mass deposited estimates were invalid due to movement of deposition coupons within the chamber during the carpet loading.

The mass available and mass resuspended data from each test are presented in Table 3-3. Overall, data quality objectives for each metric were achieved except for the ultrasonication SEM mass measurements. The total mass and number of particles collected on the ultransonication polycarbonate filters was sufficiently high that valid photographs over buchner funnel holes could not be obtained. The particle loading around the holes was sufficiently large for all filters that it was impossible to accurately assess the size distribution because of particle overlap. Only by moving the image away from the buchner funnel holes could image be collected of individually isolated particles so the size distribution could be assessed.

Table 3-1. Background particle mass found in tested carpets by multiple methods for determining mass available for resuspension. Mass data presented in mg. Mass median diameter (MMD) and geometric standard deviation (GSD) data are in mm.

Carpet	MicroVac	Ultrasonication				Fiber SEM		
		Grav Mass	SEM Mass	MMD	GSD	Mass	MMD	GSD
New #1	9.0	482	Unable to Quantify			Unable to Quantify		
New #2	4.6	238						
Old #1	194	-	1161	5.05	2.01	7	7.29	1.88
Old #2	916	2049	3066	5.09	1.87	84	3.52	1.76

Ultrasonication gravimetric mass for Old #1 was invalid.

Otherwise, only a few data points noted by asterisks, collected during the experiments were invalid. Typical reasons included movement of filters during Wollastonite deposition on carpet, lost samples (Test 7a), accidental destruction of polycarbonate filters during the ultrasonication extraction procedure, or insufficient particles were measured via SEM on carpet fibers for a statistically valid assessment of mass and size distribution. Other samples, noted by dashes, were collected but not analyzed because analytical protocols were changed during sample analysis. The first couple ultrasonication filters were not gravimetrically analyzed until an adequate procedure for removal of electrostatic charge was developed. Other ultrasonication filters were not analyzed via SEM to expedite the data analysis and limited resources.

Table 3-4 is similar to Table 3-3, except all data are presented as Wollastonite counts. Because of the error in the ultrasonication measurements, these data were not included in the table.

As discussed in Section 1.5, the relationship between mass and count is required to link the data collected by the gravimetric and particle counter metrics. The Wollastonite mass loaded on the carpet and the calculated number of Wollastonite particles loaded onto the carpet is presented in Figure 3-3. Similarly, the relationship between the Wollastonite mass and number of Wollastonite particles resuspended is shown in Figure 3-4. The regression equations presented provide a conversion for comparison of the data collected presented here with current occupational exposure standards. The conversion from mass to counts per 1296 in^2 of carpet as measured by SEM images of carpet fibers is shown.

3.2 Wollastonite Available Method Comparison

3.2.1 Mass Comparison

Table 3-5 presents correlation coefficients for the various estimates of Wollastonite mass available for resuspension. The primary correlation of interest is the comparison between the mass deposited and the mass available. Direct correlations between the various methods determining mass available are shown for completeness. Since the background particle and fiber masses associated with new and old carpets were drastically different, correlations also are presented separated by age of carpet.

The MicroVac estimate of mass available correlated best with the mass deposited on the carpet, regardless of carpet age. Fiber SEM method correlated significantly only for new carpet. The insignificant correlation for old carpet indicates a large number of particles with aspect ratios similar to Wollastonite were present. It was noted during carpet preparation that Old #2 had a significant quantity of wood chips, either sawdust or pet bedding, present. These chips possibly degraded into micrometer size fibers indistinguishable from Wollastonite by SEM. Gravimetric mass measured on the ultrasonication filters were not correlated with the mass deposited. The destructive nature of the technique generated a very large quantity of carpet backing particles with a total mass that easily exceeded the quantity of Wollastonite deposited.

Based on these results, the MicroVac provided the best estimate of Wollastonite mass available for resuspension. Therefore, these values will be used when calculating total mass emission factors. Size dependent emission factors can be calculated from the Fiber SEM estimate of mass available, but only for the new carpet tests.

Table 3-2. Experimental conditions recorded during each test. Asterisk (*) denotes invalid data collected.

Test #	Carpet	Resuspension Method	Mass Deposited (mg)	% RH	Temp (°F)	# steps	Notes
1a	New #1	Walk	*	40	72	240	Deposition mass data invalid. Depletion @ 2 min
1b	New #1	Walk	18.2 ± 7.3	45	70	250	Depletion @ 4 min
2a	New #1	Walk	75.7 ± 13.2	37	73	230	
2b	New #1	Walk	65.0 ± 18.2	44	70	240	
3a	New #1	Walk	99.2 ± 17.2	45	70	260	
3b	New #1	Walk	101.3 ± 25.6	45	70	220	
4a	Old #1	Walk	22.7 ± 8.6	51	71	250	
4b	Old #1	Walk	29.1 ± 3.8	47	71	230	
5a	Old #1	Walk	69.2 ± 8.4	51	71	250	
5b	Old #1	Walk	71.4 ± 3.9	47	71	220	
6a	Old #1	Walk	101.6 ± 13.2	48	71	270	
6b	Old #1	Walk	108.3 ± 8.2	50	71	270	
7a	New #1	Walk	*	80	72	250	Deposition mass & MicroVac data invalid.
7b	New #1	Walk	*	90	69	260	Deposition mass data invalid.
8a	Old #2	Walk	63.7 ± 6.2	48	70	220	
8b	Old #2	Walk	60.9 ± 10.2	48	70	270	
9a	New #2	Vacuum	21.8 ± 1.0	41	71	–	Depletion @ 2.5 min
9b	New #2	Vacuum	20.5 ± 2.1	40	72	–	Depletion @ 4 min
10a	New #2	Vacuum	98.1 ± 9.7	41	71	–	
10b	New #2	Vacuum	100.5 ± 7.3	40	72	–	
11a	Old #2	Vacuum	20.3 ± 2.5	41	71	–	Depletion @ 4.5 min
11b	Old #2	Vacuum	*	40	70	–	Deposition mass invalid. Depletion @ 2.5 min
12a	Old #2	Vacuum	86.0 ± 12.2	41	72	–	
12b	Old #2	Vacuum	91.2 ± 12.5	40	72	–	
13a	New #2	Vacuum	31.8 ± 3.0	90	70	–	
13b	New #2	Vacuum	33.9 ± 4.2	90	70	–	
14a	Old #2	Vacuum	41.2 ± 6.2	90	70	–	
14b	Old #2	Vacuum	33.6 ± 18.1	90	70	–	
15a	Old #1	Walk	21.7 ± 6.0	90	70	225	
15b	Old #1	Walk	22.1 ± 1.0	90	70	245	

Table 3-3. General experimental results presented as particle mass. Asterisk (*) denotes invalid data. Dash (-) denotes sample collected, but not analyzed. "NS" denotes no sample collected.

Test #	Mass Deposited (mg)	Mass Available									Mass Resuspended			
		MicroVac Mass (mg)	Sonication Grav	Sonication Filter SEM			Carpet Fiber SEM				URG Mass (mg)	APS Data		
			Mass (mg)	Mass (mg)	MMD (μm)	GSD (μm)	Mass (mg)	MMD (μm)	GSD (μm)			Mass (mg)	MMD (μm)	GSD (μm)
1a	*	10.1	*	*	*	*	107.6	5.7	1.9		0.2	0.2	4.0	1.6
1b	18.2	18.7	-	*	4.1	1.7	53.3	3.1	1.8		1.6	0.3	3.3	1.5
2a	75.7	65.1	-	*	5.8	1.9	69.8	3.6	1.8		2.9	0.5	4.0	1.6
2b	65.0	40.0	926	*	-	-	91.4	4.7	1.6		0.5	2.0	3.9	1.6
3a	99.2	74.7	587	*	4.0	1.7	101.5	2.9	1.8		3.5	1.7	3.6	1.5
3b	101.3	123.8	117	*	-	-	217.2	4.6	1.7		8.9	1.5	3.5	1.6
4a	22.7	72.1	4212	*	5.4	1.9	182.8	8.2	2.1		17.8	5.2	5.0	1.7
4b	29.1	48.6	2779	*	6.4	1.9	154.5	5.9	1.9		27.4	7.1	4.2	1.6
5a	69.2	218	2163	*	4.7	1.7	116.1	7.1	2.0		28.5	17.1	4.5	1.6
5b	71.4	166.7	4837	*	7.2	2.1	177.2	5.5	1.8		40.5	11.6	3.7	1.5
6a	101.6	262.9	6755	*	5.5	1.8	52.2	4.9	1.8		70.9	28.5	4.3	1.6
6b	108.3	250.3	1454	*	6.6	1.9	356.2	6.6	1.8		52.1	17.3	4.2	1.6
7a	*	*	*	*	*	*	*	*	*		18.5	2.8	3.7	1.6
7b	*	52.4	-	*	4.8	1.8	45.7	3.2	1.8		21.2	1.8	3.9	1.5
8a	63.7	211.2	409	*	5.4	1.8	81.6	5.4	1.8		39.5	14.8	3.7	1.6
8b	60.9	159.7	4805	*	5.7	1.8	22.1	3.0	1.9		36.8	18.9	3.9	1.5
9a	21.7	21.7	244	*	4.5	1.7	48.5	4.6	1.9		0.3	0.2	4.8	1.9
9b	20.5	53.4	2953	*	4.8	1.8	104.3	6.0	1.8		3.0	0.1	3.9	1.7
10a	98.1	110.2	1148	*	4.0	1.7	189.0	8.6	2.1		0.9	1.6	3.8	2.1
10b	100.5	139.9	1236	*	5.2	1.8	101.0	5.1	1.7		5.8	0.6	2.5	1.8
11a	20.3	75.1	2860	*	7.0	1.9	*	*	*		5.2	0.3	3.2	2.4
11b	*	64.9	1306	*	6.2	2.0	*	*	*		3.2	0.2	3.3	1.9
12a	86.0	242.4	2595	*	6.1	1.8	*	*	*		4.0	1.2	3.0	1.7
12b	91.2	307.2	3497	*	5.5	1.8	*	*	*		7.7	1.4	3.1	1.7
13a	131.8	73.9	ns	ns	ns	ns	ns	ns	ns		5.8	0.5	2.5	1.7
13b	133.9	101.8	ns	ns	ns	ns	ns	ns	ns		7.3	0.5	1.9	1.7
14a	141.2	190.8	ns	ns	ns	ns	ns	ns	ns		7.3	0.8	1.8	2.1
14b	133.6	389.9	ns	ns	ns	ns	ns	ns	ns		10.1	1.4	3.1	1.6
15a	71.7	99.2	ns	ns	ns	ns	ns	ns	ns		27.2	7.2	3.6	1.5
15b	72.1	168.2	ns	ns	ns	ns	ns	ns	ns		51.7	19.8	3.7	1.5

Table 3-4. General experimental results presented as particle count. MicroVac count data calculated from Fiber SEM or Filter SEM size distribution and MicroVac mass. URG count data calculated from APS size distribution and URG mass. CMD is the count median diameter. Asterisk (*) denotes invalid data. Dash (-) denotes sample collected, but not analyzed. "NS" denotes no sample collected.

Test #	Count Deposited	Count Available							Count Resuspended			
		MicroVac Count (#)	Sonication Filter SEM			Carpet Fiber SEM			URG Mass (#)	APS Data		
			Count (#)	CMD (µm)	GSD (µm)	Count (#)	CMD (µm)	GSD (µm)		Count (#)	CMD (µm)	GSD (µm)
1a	*	1.47E+09	*	*	*	1.56E+06	1.5	2.1	3.34E+06	4.80E+04	2.5	1.7
1b	2.37E+10	2.43E+10	*	1.7	1.9	3.70E+06	1.0	2.0	3.57E+07	2.49E+05	2.2	1.6
2a	2.13E+11	1.83E+11	*	1.6	2.2	3.02E+06	1.2	2.0	4.39E+07	5.45E+04	2.2	1.6
2b	3.45E+10	2.12E+10	*	-	-	1.21E+06	1.7	2.2	6.35E+06	1.84E+05	2.4	1.6
3a	5.78E+11	4.35E+11	*	1.5	1.9	7.92E+06	0.9	2.0	6.98E+07	2.23E+05	2.1	1.5
3b	1.91E+11	2.33E+11	*	-	-	3.30E+06	1.7	1.9	2.30E+08	5.75E+04	2.0	1.5
4a	1.63E+10	5.18E+10	*	1.4	2.1	1.00E+06	1.3	2.9	2.24E+08	4.78E+05	2.7	1.7
4b	2.09E+10	3.49E+10	*	1.8	2.3	1.50E+06	1.5	2.2	4.09E+08	7.66E+05	2.8	1.7
5a	1.61E+11	5.08E+11	*	1.8	1.9	4.23E+06	1.5	2.5	3.97E+08	1.71E+06	2.7	1.7
5b	1.27E+11	2.97E+11	*	1.6	2.2	7.53E+06	1.5	2.4	6.54E+08	1.36E+06	2.7	1.7
6a	5.22E+11	1.35E+12	*	1.9	2.0	2.73E+06	1.2	2.4	1.01E+09	2.92E+06	2.7	1.7
6b	2.22E+11	5.12E+11	*	1.9	2.2	2.08E+06	2.1	2.1	7.50E+08	1.80E+06	2.7	1.6
7a	*	*	*	*	*	*	*	*	3.18E+08	2.85E+05	2.4	1.6
7b	*	1.56E+11	*	1.8	1.9	2.60E+06	1.1	2.0	3.37E+08	2.13E+05	2.5	1.6
8a	1.69E+11	5.59E+11	*	2.0	2.0	1.19E+06	16	2.2	5.22E+08	1.42E+06	2.7	1.6
8b	9.34E+11	2.45E+12	*	1.8	2.0	1.23E+06	1.0	1.8	4.64E+08	1.72E+06	2.8	1.6
9a	1.17E+10	1.17E+10	*	1.7	2.0	1.20E+06	1.4	2.1	4.13E+06	2.48E+04	1.7	2.1
9b	2.71E+10	7.07E+10	*	2.1	1.8	1.72E+06	1.8	1.9	6.39E+07	2.38E+04	1.6	2.2
10a	1.06E+11	1.19E+11	*	1.6	1.8	1.88E+06	1.2	3.2	2.91E+07	4.97E+05	0.7	1.9
10b	1.86E+11	2.59E+11	*	1.8	1.9	1.34E+06	1.5	2.3	2.90E+08	6.12E+05	0.9	1.9
11a	1.31E+10	4.84E+10	*	1.9	2.4	*	*	*	3.81E+08	3.37E+05	0.9	1.9
11b	*	6.66E+10	*	2.0	2.2	*	*	*	6.81E+07	1.15E+05	0.9	2.6
12a	2.73E+10	7.70E+10	*	2.1	1.9	*	*	*	1.30E+08	5.33E+05	1.1	2.0
12b	3.18E+10	1.07E+11	*	1.8	5.0	*	*	*	2.65E+08	4.63E+05	1.4	1.8
13a	-	-	ns	ns	ns	ns	ns	ns	1.47E+09	3.90E+05	0.6	1.7
13b	-	-	ns	ns	ns	ns	ns	ns	1.10E+09	5.16E+05	0.8	1.7
14a	-	-	ns	ns	ns	ns	ns	ns	6.17E+08	4.64E+05	0.9	1.9
14b	-	-	ns	ns	ns	ns	ns	ns	2.98E+08	2.94E+05	1.2	2.0
15a	-	-	ns	ns	ns	ns	ns	ns	4.64E+08	9.01E+05	2.0	1.8
15b	-	-	ns	ns	ns	ns	ns	ns	1.52E+09	1.80E+06	2.2	1.7

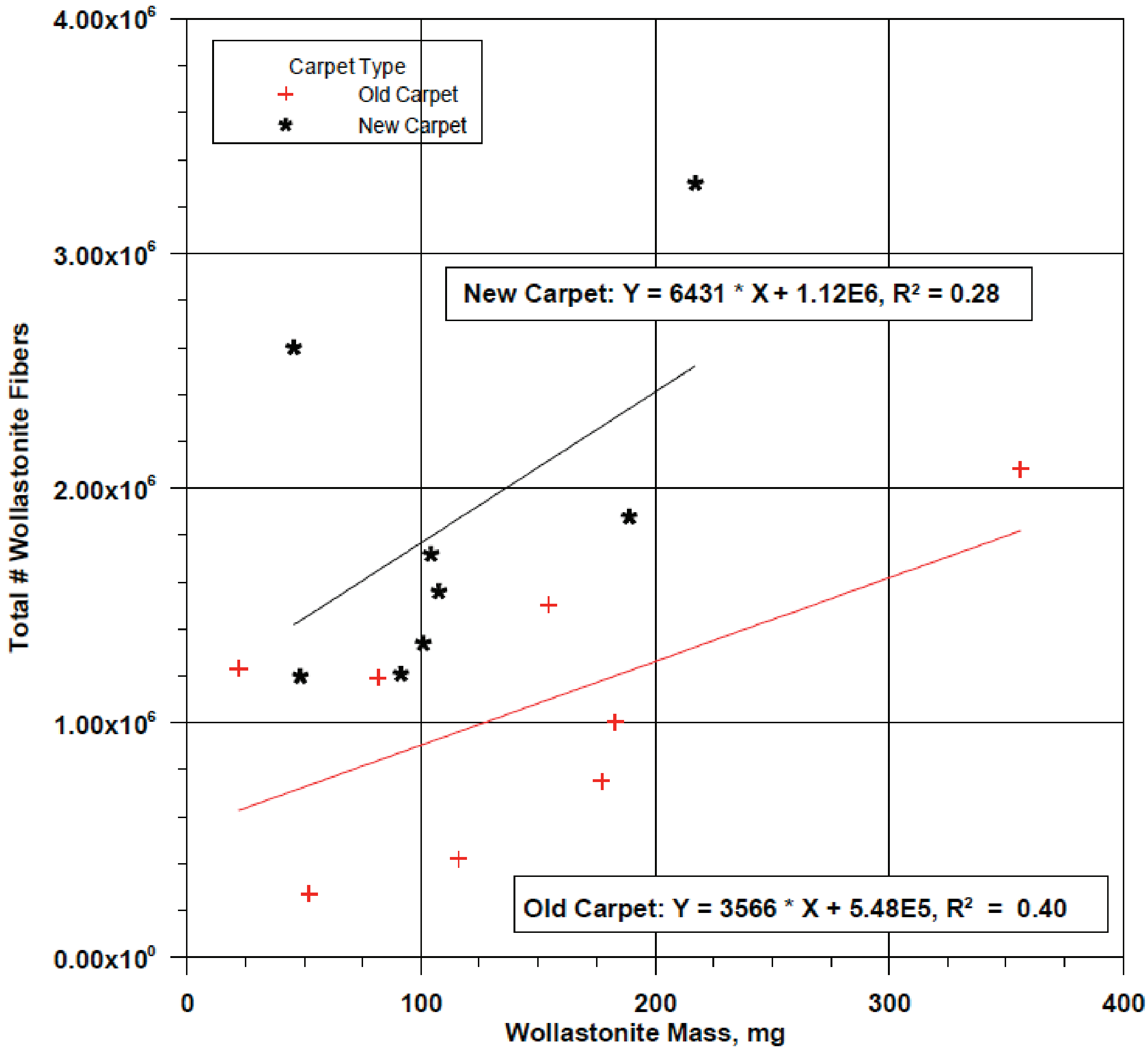

Figure 3-1. Conversion of total Wollastonite mass to total number of Wollastonite fibers per 1296 in2 of carpet. Wollastonite mass data calculated from SEM images of carpet fibers.

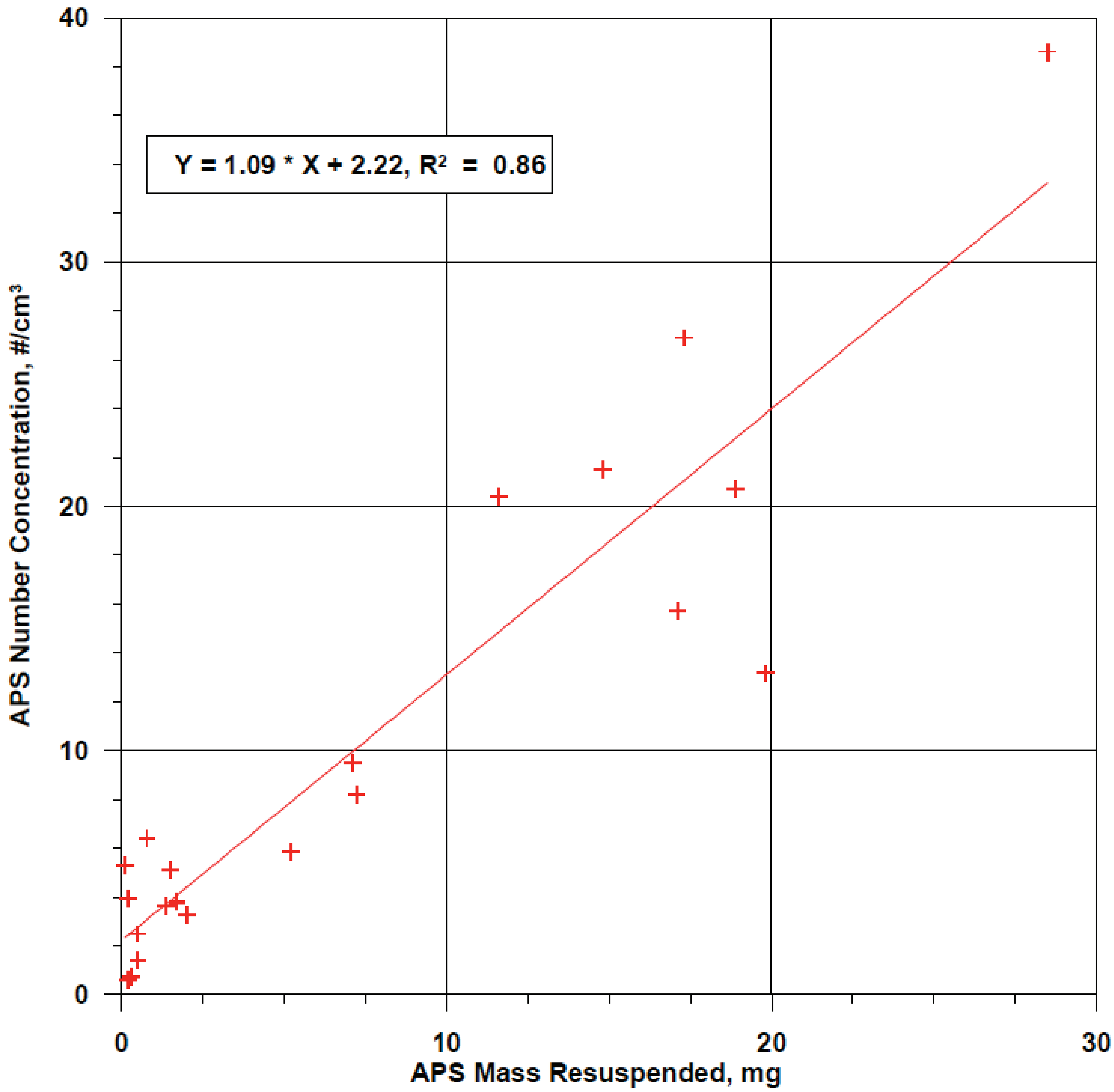

Figure 3-2. Relationship between total Wollastonite mass resuspended during a 5 minute test and the average number concentration. Mass and number concentration data collected by APS.

Table 3-5. Correlation coefficients between different estimates of mass available for resuspension. Statistically significant coefficient (α = 0.95) are italicized.

All Data	**Deposit**	**MicroVac**	**Sonic. Grav.**	**Fiber SEM**
Deposit	1			
MicroVac	***0.64***	1		
Sonic. Grav.	-0.11	0.36	1	
Fiber SEM	0.36	0.32	-0.19	1
New	**Deposit**	**MicroVac**	**Sonic. Grav.**	**Fiber SEM**
Deposit	1			
MicroVac	***0.85***	1		
Sonic. Grav.	-0.42	-0.09	1	
Fiber SEM	***0.64***	***0.66***	-0.14	1
Old	**Deposit**	**MicroVac**	**Sonic. Grav.**	**Fiber SEM**
Deposit	1			
MicroVac	***0.93***	1		
Sonic. Grav.	0.07	0.11	1	
Fiber SEM	0.20	0.01	-0.39	1

Table 3-6. Correlation coefficients between different estimates of counts available for resuspension. Statistically significant coefficient (α = 0.95) are italicized.

All Data	**Deposit**	**MicroVac**	**Fiber SEM**
Deposit	1		
MicroVac	***0.55***	1	
Fiber SEM	0.31	0.25	1
New	**Deposit**	**MicroVac**	**Fiber SEM**
Deposit	1		
MicroVac	***0.65***	1	
Fiber SEM	0.45	0.39	1
Old	**Deposit**	**MicroVac**	**Fiber SEM**
Deposit	1		
MicroVac	***0.52***	1	
Fiber SEM	0.15	0.01	1

3.2.2 Count Comparison

Table 3-6 presents the same correlation coefficients calculated on a count basis. Because of the error associated with the ultrasonication gravimetric mass measurement, these data were not included in the analysis. Count based correlation coefficients followed the same trend as mass based coefficients. However, the magnitudes of the coefficients were somewhat lower, probably due to the error introduced by converting gravimetric data to count data.

3.3 Resuspended Wollastonite Measurement Method Comparison

3.3.1 Mass Comparison

Figure 3-3 shows the relationship between the resuspended Wollastonite mass as measured gravimetrically by the URG sampler and aerodynamically by the APS. The relationship between the two methods is statistically significant (α = 0.95). In general, the APS measured about 30% of the total mass measured gravimetrically. The difference in resuspended mass was caused by the difference between aerodynamic and physical diameter resulting from how the asymmetric Wollastonite fibers align within the sensing volume of the APS. Appendix B provides a more thorough explanation. Therefore, both methods provided a valid estimate of mass resuspended allowing calculation of total mass and particle size dependent emission factors.

3.3.2 Count Comparison

Figure 3-4 illustrates the relationship between the resuspended Wollastonite particle counts as measured by the URG sampler and the APS. Again, there is a strong linear relationship between the two methods. However, the resuspended counts calculated from the URG data were 200 times greater than the APS counts. This dramatic decrease in the regression slope most likely resulted from the conversion of gravimetric data to particle counts because of the cubic influence of particle diameter, especially at smaller sizes.

3.4 Wollastonite Size Distribution

The Wollastonite size distributions deposited on the carpet fibers and resuspended were analyzed to identify any differences between experimental conditions.

The size distribution of the Wollastonite deposited was measured via SEM of the ultrasonication filters and individual carpet fibers (Table 3-7). The resuspended Wollastonite size distribution was measured automatically by the APS. Statistical analysis yielded differences in mass median diameter (MMD) of Wollastonite deposited as a function of carpet age by both techniques. The Wollastonite MMD on old carpet was about 1.3 µm greater than that measured on new carpet. The larger size distribution more than likely was caused by the presence of other fibrous particles in the carpet not removed by the conditioning procedure. The geometric standard deviation (GSD) of the size distribution was consistent across all experimental conditions. There were not any differences in size distribution as measured by SEM analysis of ultrasonication filters andindividual carpet fibers when carpet age was controlled.

The resuspended Wollastonite size distribution as measured by the APS varied between resuspension methods (Table 3-8). Age of carpet did not influence the resuspended size distribution, although the median diameter from the older carpet was slightly larger (2.7 µm vs. 2.3 µm). Walking generated a larger size distribution of particles with a narrower range than vacuuming. The much smaller resuspended CMD from vacuuming indicates many more small particles were generated. The force imparted to the carpet fibers by the vacuum beater bar probably provided sufficient energy to dislodge more particles smaller than 1 µm. This increase in resuspension of 1 µm particles was not evident from the mass data because of their small contribution to the total mass resuspended.

As compared to the size distribution of Wollastonite deposited on the carpet fibers, the resuspended particle size distribution was smaller and narrower. This finding is expected considering only a fraction of the deposited Wollastonite becomes resuspended.

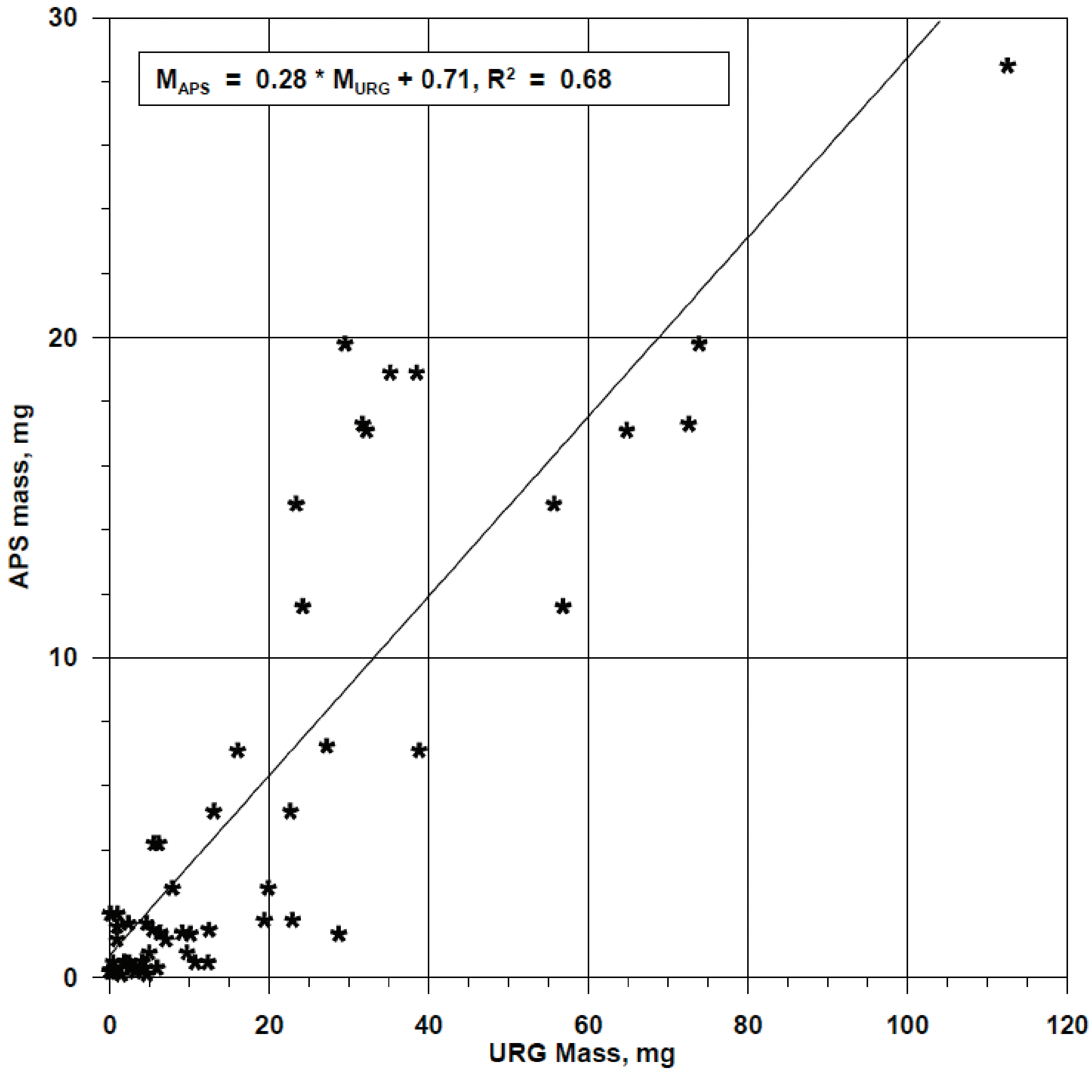

Figure 3-3. Relationship between mass resuspended estimates measured by URG and APS. APS measured approximately 30% of the mass measured gravimetrically.

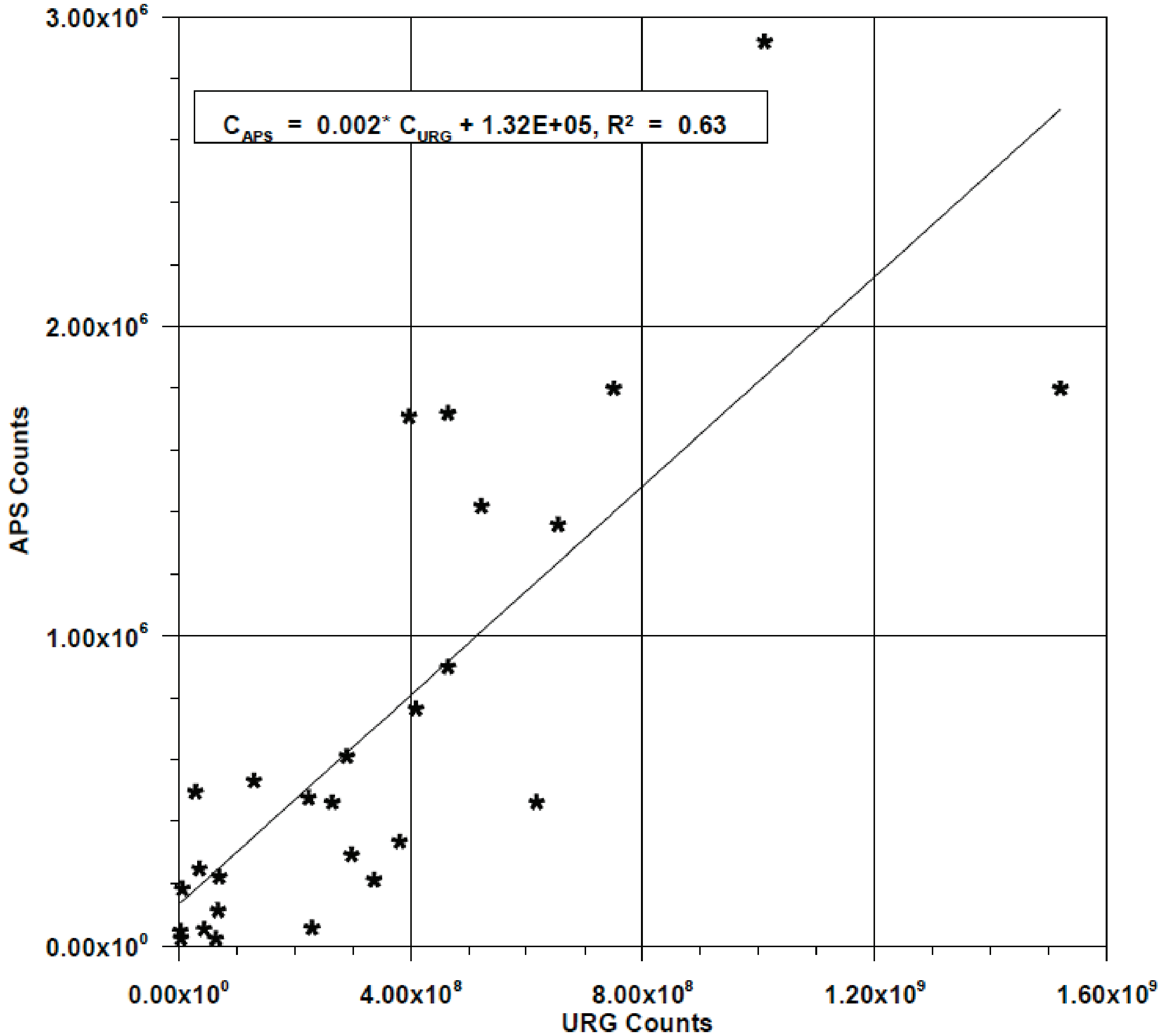

Figure 3-4. Relationship between resuspended Wollastonite counts measured by URG and APS.

3.5 Emission Factors

3.5.1 Total Mass

Emission factors calculated on a total mass basis are presented in Table 3-9. The average plus standard deviation for each experimental condition is presented. Emission factors in the APS/Fiber SEM and URG/Fiber SEM ratios for tests using old carpet were not calculated. As discussed earlier, the Fiber SEM mass available data for tests with old carpet could not be related to the Wollastonite mass deposited because of the presence of other fibrous particles. Any emission factors calculated using this data would be incorrect. Therefore, emission factors using Fiber SEM data for old carpets were not analyzed.

The emission factors in Table 3-9 indicate differences between experimental conditions. Table 3-10 shows the p-values ($\alpha = 95\%$) for each experimental variable calculated using linear regression models as described in Section 2.1.14. However, mixing within the exposure chamber prevented calculation of emission factors as function of height.

3.5.2 Total Counts

Emission factors calculated on a total count basis are presented in Table 3-11. The magnitudes of the count emission factors vary greatly between calculation methods and in comparison with the mass emission factors. The APS/SEM and URG/MicroVac emission factors probably are the most representative of reality because these factors were calculated from count:count or mass:mass raw data. Calculation of emission factors where the numerator and denominator were measured on a different basis (e.g., count:mass or mass:count) introduced significant error into the values. As a result, extremely small emission factors were calculated for the APS/MicroVac. In the other extreme, URG/Fiber SEM emission factors greater than 1 were calculated These emission factors are impossible to achieve given the low background Wollastonite fiber concentrations in the carpet.

Statistical analysis of the APS/SEM and URG/MicroVac count emission factors showed the same influence of the independent variables as the mass emission factors. Table 3-12 shows the p-values ($\alpha = 95\%$) for each experimental variable calculated using linear regression models as described in Section 2.1.12.

Table 3-7. Size distribution of Wollastonite deposited on new and old carpet as measured from ultrasonication filters and individual carpet fibers. Size distribution of bulk Wollastonite shown for comparison.

		Ultrasonication Filter	Carpet Fiber
New Carpet[a]	*MMD*	4.65 ± 0.64	4.74 ± 1.65
	GSD	1.76 ± 0.07	1.81 ± 0.13
	CMD	1.70 ± 0.19	1.37 ± 0.30
	GSD	1.94 ± 0.13	2.15 ± 0.37
Old Carpet[a]	*MMD*	5.98 ± 0.74	5.83 ± 1.56
	GSD	1.87 ± 0.11	1.89 ± 0.11
	CMD	1.80 ± 0.21	1.50 ± 0.29
	GSD	2.10 ± 0.18	2.30 ± 0.26
Bulk Wollastonite[b]	*MMD*	2.5	
	GSD	2.2	

[a]Size distribution presented as aerodynamic diameters

[b]Size distribution measured optically. Data provided by manufacturer.

Table 3-8. Size distribution of Wollastonite resuspended via walking and vacuuming as measured by the APS. Size distribution of bulk Wollastonite shown for comparison.

Walking[a]	*MMD*	3.93 ± 0.40
	GSD	1.57 ± 0.06
	CMD	2.53 ± 0.28
	GSD	1.62 ± 0.06
Vacuuming[a]	*MMD*	2.98 ± 1.06
	GSD	1.90 ± 0.30
	CMD	1.15 ± 0.36
	GSD	2.05 ± 0.26
Bulk Wollastonite[b]	*MMD*	2.5
	GSD	2.2

[a]Size distribution presented as aerodynamic diameters

[b]Size distribution measured optically. Data provided by manufacturer.

Table 3-9. Emission factors calculated on total mass resuspended for each test condition.

Test #	APS/MicroVac	APS/ Fiber SEM	URG/MicroVac	URG/Fiber SEM
1	0.016 ± 0.006	0.003 ± 0.002	0.059 ± 0.040	0.021 ± 0.025
2	0.042 ± 0.040	0.018 ± 0.006	0.034 ±0.031	0.024 ± 0.025
3	0.018 ± 0.009	0.017 ± 0.007	0.072 ± 0.029	0.038 ± 0.017
4	0.124 ± 0.084	*	0.337 ± 0.165	*
5	0.077 ± 0.019	*	0.244 ± 0.120	*
6	0.073 ± 0.039	*	0.203 ± 0.153	*
7	0.022 ± 0.015	0.040	0.233 ± 0.186	0.46 ± 0.05
8	0.117 ± 0.084	*	0.256 ± 0.153	*
9	0.006 ± 0.005	0.002 ± 0.002	0.037 ± 0.035	0.017 ± 0.019
10	0.009 ± 0.007	0.007 ± 0.002	0.023 ± 0.021	0.040 ± 0.031
11	0.004 ± 0.002	*	0.052 ± 0.041	*
12	0.005 ± 0.001	*	0.022 ± 0.014	*
13	0.006 ± 0.001	ns	0.079 ± 0.003	ns
14	0.003 ± 0.001	ns	0.040 ± 0.025	ns
15	0.105 ± 0.044	ns	0.317 ± 0.054	ns

* Emission factors for old carpet were not useable because mass available estimated by SEM could not be related to mass deposited.

ns: No sample collected for analysis

Table 3-10. Table of p-values for each method of calculating mass emission factors (EmFa).

EmFa	Independent Variables					
	Load	Age	Method	Rh	β_o	R^2
URG/MicroVac	0.254	***0.0001***	***0.0002***	***0.0001***	0.240	0.46
APS/MicroVac	0.600	***0.0005***	***0.0002***	0.656	0.089	0.44
URG/Fiber SEM	0.520	–	***0.007***	***0.0001***	0.011	0.94
APS/Fiber SEM	0.160	–	***0.027***	***0.002***	0.010	0.81

3.5.3 Interpretation of Emission Factors

Data from the tables show consistency in parameters influencing emission factors between the different calculation methods. Carpet age (when included as a variable), resuspension method, and chamber relative humidity all influenced the total mass emission factor. Interestingly, the Wollastonite loading did not influence the emission factors. A similar result was discovered for generic Arizona Test Dust (ATD) (Rodes and Thornburg, 2004).

Based on these data, three different emission factor scenarios were statistically different from each other.

1. New carpet versus old carpet at low Rh: With the relative humidity constant at about 40%, emission factors from new carpet were significantly lower than those from old carpet. The lower emission factors possibly were caused by greater adhesion of the particles to the fibers due to electrostatic charging of the fibers. This relationship was consistent with the one between new-old carpet seeded with Arizona Test Dust developed during earlier research.
2. Influence of relative humidity on new carpet: Similar to the relative humidity emission factor influence discovered using ATD, raising the relative humidity within the chamber possibly weakens the static charge on the fibers. As a result, the Wollastonite emission factors from walking and vacuuming are on new carpet are 2-4 times greater at relative humidity levels approaching 90%. Relative humidity did not have a statistically significant influence on walking and vacuuming emission factors from old carpet.
3. Influence of resuspension method: Vacuuming new or old carpet seeded with Wollastonite fibers resuspended significantly less mass than walking. Even with a beater bar, the vacuum efficiently sucked a majority of the particles into the machine for collection in the HEPA type bag and prevented the fibers from reaching the surrounding air. Using a less efficient vacuum bag probably will increase the emission factors as more particles penetrate through and escape into the room air. Also, a different vacuum with less efficient collection of particles by the vacuum head probably will yield higher emission factors.

3.5.4 Size Dependent Emission Factors

Size dependent, mass based emission factors were calculated using the APS/Fiber SEM data for new carpet tests (Table 3-13). Emission factors for 0.5 µm fibers of ~10-9 were obtained. However, these values were not statistically different from zero. The size distribution and mass of Wollastonite available for Test 13 was not determined.

A statistical analysis of these size dependent emission factors did not yield any statistically significant relationships with the test conditions (Table 3-14). However as shown in Figure 3-5, there seems to be a difference in emission factors as function of particle size and relative humidity. At low relative humidity, the emission factor generally decreases as the fiber aerodynamic diameter increases. At high relative humidity, the emission factor peaks at a larger fiber diameter and remains elevated. Although statistically insignificant, these general trends agree with the relationship between particle diameter and emission factor found with ATD. Additionally, the trends may support the validity of the influence of relative humidity on emission factors discussed earlier. High relative humidity possibly decreases influence of electrostatic forces as well as increases the surface tension bond. As a result, smaller particles will have lower emission factors at high relative humidity because the dominant surface tension force is increased by the presence of water. Conversely, the larger particles which adhere to carpet fibers due to electrostatics have lower emission factors because the humidity appears to neutralize some or all of the charge on the carpet fibers.

A similar analysis was conducted for count based emission factors (Table 3-15). Interestingly, vacuuming generated statistically significant count-based emission factors. The vacuum beater bar probably provides sufficient energy to release a large number of sub-micrometer particles that do not contribute significantly to the total mass resuspended. Although the statistical analysis did not indicate any statistically significant variables (Table 3-16), Figure 3-6 does indicate a relationship between count based emission factor and particle diameter may exist due to the resuspension of the submicrometer particles.

3.6 K-Factors

K-factors, ratio of resuspended Wollastonite number concentration and Wollastonite surface loading, were calculated for each test with valid APS and Fiber SEM image data. K-factors provide a widely recognized means for calculating airborne concentrations from surface loading data and the type of activity being performed. In this research, K-factors are a different method for expressing emission factors. For these tests, K-factors were calculated as:

$$Kfactor = \frac{C_{air}}{L_{carpet}} = \frac{\#/cm^3}{\#/cm^2}$$

Aggregate K-factors across all fiber aerodynamic diameters and all test conditions are shown in Table 3-17. Average size-dependent K-factors for new carpet only (Table 3-18) were calculated from data presented in Table 3-15 and the corresponding volumetric airflow and carpet area.

Table 3-11. Emission factors calculated on total count resuspended for each test condition.

Test #	APS/MicroVac	APS/ Fiber SEM	URG/MicroVac	URG/Fiber SEM
1	2.1E-05 ± 1.6E-05	4.9E-02 ± 2.6E-02	1.9E-03 ± 5.7E-04	> 1
2	4.5E-06 ± 5.9E-06	8.5E-02 ± 9.5E-02	2.7E-04 ± 4.2E-05	> 1
3	3.8E-07 ± 1.9E-07	2.3E-02 ± 7.6E-03	5.7E-04 ± 5.9E-04	> 1
4	1.6E-06 ± 8.9E-06	*	8.0E-03 ± 5.2E-03	*
5	4.0E-06 ± 8.6E-07	*	1.5E-03 ± 1.0E-03	*
6	2.8E-06 ± 9.6E-07	*	1.1E-03 ± 5.1E-04	*
7	1.4E-06	8.2E-02	2.2E-03	> 1
8	1.6E-06 ± 1.3E-06	*	5.6E-04 ± 5.2E-04	*
9	1.2E-06 ± 1.3E-06	1.7E-02 ± 4.8E-03	6.3E-04 ± 3.9E-04	> 1
10	3.3E-06 ± 1.3E-06	3.6E-01 ± 1.4E-01	6.8E-04 ± 6.2E-04	> 1
11	4.3E-06 ± 3.7E-06	*	4.5E-03 ± 4.8E-03	*
12	5.6E-06 ± 1.8E-06	*	2.1E-03 ± 5.6E-04	*
13	9.5E-07 ± 2.4E-07	ns	2.9E-03 ± 1.8E-03	ns
14	1.1E-07 ± 1.2E-07	ns	1.5 E-04 ± 1.7E-04	ns
15	1.2E-06 ± 3.1E-07	ns	7.9E-04 ± 7.1E-05	ns

* Emission factors for old carpet were not useable because mass available estimated by SEM could not be related to mass deposited.

ns: No sample collected for analysis

Table 3-12. Table of p-values for each method of calculating count emission factors (EmFa).

EmFa	Independent Variables					
	Load	Age	Method	Rh	β_o	R^2
URG/MicroVac	0.254	***0.0001***	***0.0002***	***0.0001***	0.240	0.46
APS/Fiber SEM	0.604	–	***0.0002***	***0.007***	0.089	0.77

Table 3-13. Table of size dependent APS/SEM Fiber mass emission factors for each test condition using new carpet.

		Test #						
		1	2	3[a]	7[a]	9[a]	10[a]	13
Aerodynamic Diameter (µm)	**10.0**	0	–	–	–	–	0.001 ± 0.001	ns
	8.0	–	–	–	–	0.001 ± 0.002	0.003	ns
	7.0	–	0.012 ± 0.002	0.001	–	0.001 ± 0.001	0.001	ns
	6.0	0.011 ± 0.013	0.020 ± 0.019	0.008 ± 0.010	0.055	–	0.007 ± 0.004	ns
	5.0	0.016 ± 0.021	0.009 ± 0.001	0.021 ± 0.029	0.034	0.001 ± 0.001	0.012 ± 0.009	ns
	4.0	0.054 ± 0.073	0.039 ± 0.028	0.010 ± 0.012	0.045	0.004 ± 0.001	0.016 ± 0.002	ns
	3.5	0.007 ± 0.008	0.029 ± 0.019	0.008 ± 0.009	0.080	0.002 ± 0.001	0.015 ± 0.011	ns
	3.0	0.022 ± 0.028	0.018 ± 0.009	0.007 ± 0.006	0.025	0.002 ± 0.000	0.016 ± 0.006	ns
	2.5	0.019 ± 0.019	0.055 ± 0.067	0.008 ± 0.006	0.028	0.004 ± 0.003	0.044 ± 0.024	ns
	2.0	0.012 ± 0.010	0.015 ± 0.013	0.005 ± 0.001	0.019	0.001 ± 0.000	0.046 ± 0.019	ns
	1.5	0.006 ± 0.004	0.080 ± 0.105	0.007 ± 0.001	0.007	0.007 ± 0.007	0.092 ± 0.033	ns
	1.0	0.001 ± 0.000	0.005 ± 0.006	0.001 ± 0.000	0.001	0.003 ± 0.003	0.168 ± 0.018	ns
	0.5[b]	0	0	0	0	0	0	ns

– = No particles measured by SEM

ns = No SEM fiber sample collected

[a]Emission factors without standard deviations only had one valid measurement per test condition

[b]Emission factors for 0.5 mm particles were not significantly different from zero

Table 3-14. Table of p-values for APS/SEM Fiber mass emission factors including particle diameter as an independent variable.

EmFa	Independent Variables						
	Load	Age	Method	Rh	Diameter	β_o	R^2
APS/Fiber SEM	0.060	–	0.282	0.167	0.122	0.742	0.09

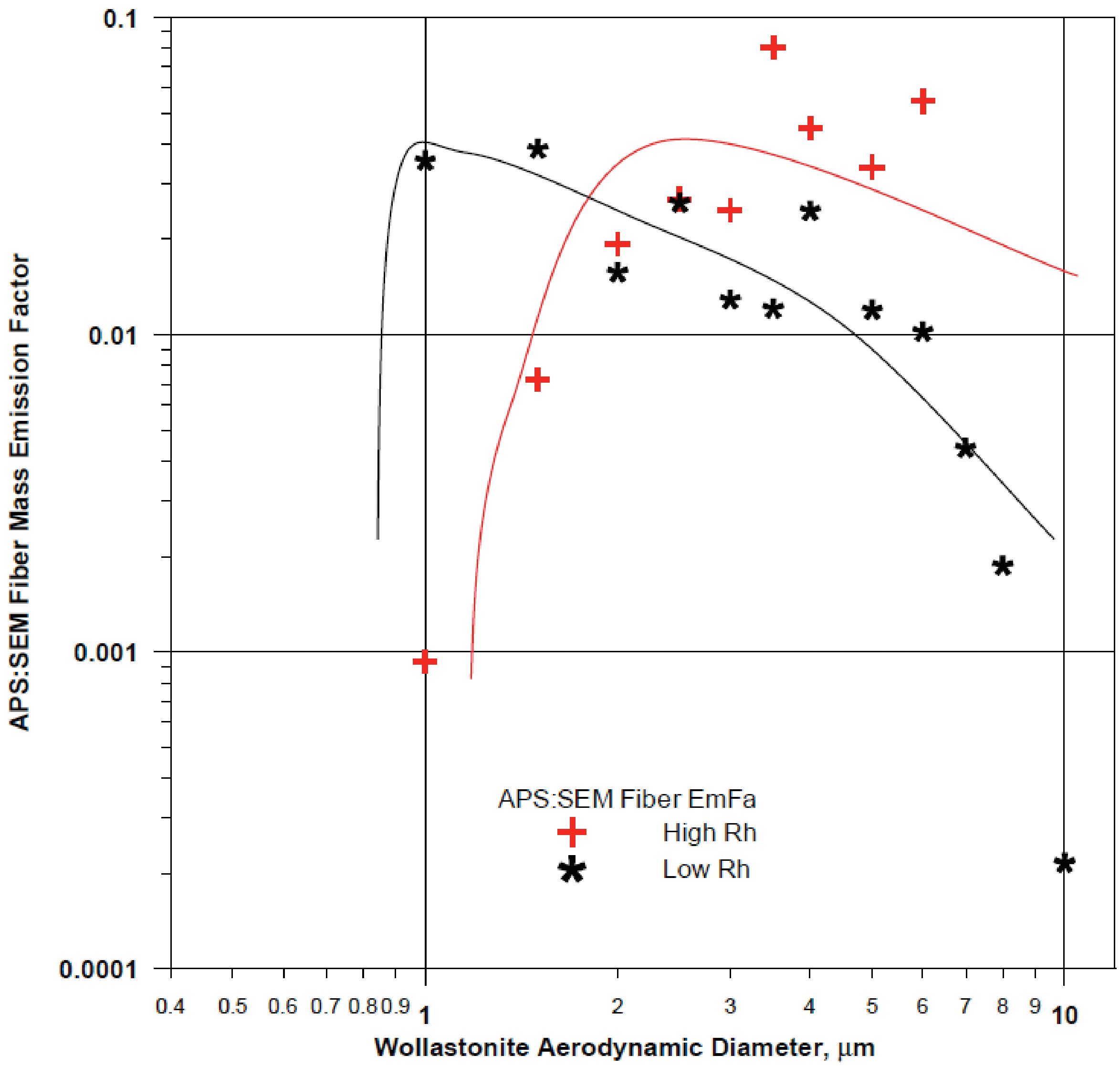

Figure 3-5. Average size dependent, mass based emission factors calculated from APS and SEM Fiber data for high and low relative humidity tests. Curves fitting size distribution are shown for illustrative purposes only. Curves are not statistical regressions.

Table 3-15. Table of size dependent APS/SEM Fiber count emission factors for each test condition using new carpet.

		Test #						
		1	2	3[a]	7[a]	9[a]	10[a]	13
Aerodynamic Diameter (μm)	**10.0**	0	–	–	–	–	0.0001 ± 0.0002	ns
	8.0	–	–	–	–	0.001 ± 0.001	0.004	ns
	7.0	–	0.010 ± 0.010	0.001	–	0.001 ± 0.001	0.002	ns
	6.0	0.031 ± 0.004	0.013 ± 0.002	0.005 ± 0.006	0.097	–	0.003 ± 0.002	ns
	5.0	0.032 ± 0.021	0.006 ± 0.003	0.015 ± 0.020	0.040	0.002 ± 0.001	0.006 ± 0.002	ns
	4.0	0.054 ± 0.050	0.030 ± 0.034	0.007 ± 0.007	0.031	0.001 ± 0.001	0.009 ± 0.009	ns
	3.5	0.012 ± 0.004	0.018 ± 0.017	0.005 ± 0.006	0.060	0.001 ± 0.001	0.006 ± 0.002	ns
	3.0	0.023 ± 0.012	0.010 ± 0.008	0.004 ± 0.004	0.015	0.001 ± 0.001	0.009 ± 0.007	ns
	2.5	0.028 ± 0.012	0.031 ± 0.040	0.005 ± 0.003	0.014	0.0005 ± 0.0004	0.016 ± 0.003	ns
	2.0	0.025 ± 0.019	0.008 ± 0.008	0.003 ± 0.001	0.010	0.001 ± 0.001	0.020 ± 0.002	ns
	1.5	0.026 ± 0.028	0.049 ± 0.067	0.005 ± 0.001	0.005	0.001 ± 0.001	0.067 ± 0.064	ns
	1.0	0.002 ± 0.002	0.002 ± 0.003	0.000 ± 0.000	0.001	0.004 ± 0.003	0.057 ± 0.030	ns
	0.5	0	0	0	0	0.011 ± 0.012	0.080 ± 0.040	ns

– = No particles measured by SEM

ns = No SEM fiber sample collected

[a]Emission factors without standard deviations only had one valid measurement per test condition

Table 3-16. Table of p-values for APS/SEM Fiber count emission factors including particle diameter as an independent variable.

EmFa	Independent Variables						
	Load	Age	Method	Rh	Diameter	β_o	R^2
APS/Fiber SEM	0.130	–	0.141	0.684	0.079	0.005	0.06

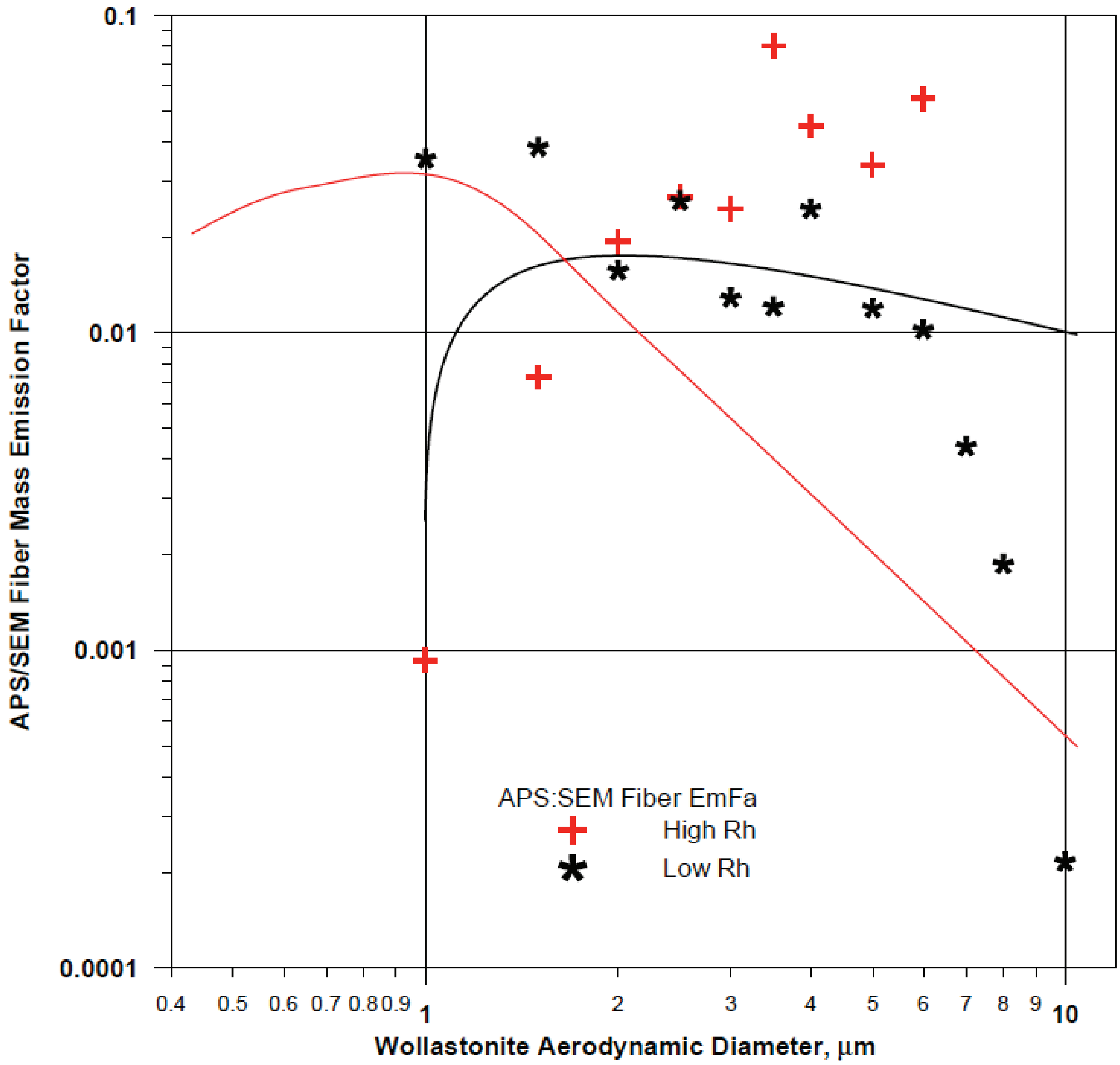

Figure 3-6. Average size dependent, count based emission factors calculated from APS and SEM Fiber data for vacuuming and walking resuspension method tests. Curves fitting size distributions are shown for illustrative purposes only. Curves are not statistical regressions.

Table 3-17. Aggregate K-factors for each test.

Test	Average	Std Dev
1	6.19E-04	3.26E-04
2	2 1.07E-03	1.20E-03
3	2.88E-04	9.59E-05
4	*	*
5	*	*
6	*	*
7[a]	1.03E-03	
8	*	*
9	2.18E-04	6.10E-05
10	4.55E-04	1.72E-03
11	*	*
12	*	*
13	ns	
14	ns	
15	ns	

[a] only 1 valid sample collected

* Emission factors for old carpet were not useable because mass available estimated by SEM could not be related to mass deposited.

ns: No SEM Fiber sample collected for analysis

Table 3-18. Size specific K-factors for each test using new carpet. K-factors calculated from emission factors in Table 3-15.

		Test #						
		1	2	3	7	9	10	13
Aerodynamic Diameter (µm)	10.0	0	–	–	–	–	1.71E-06	ns
	8.0	–	–	–	–	1.22E-05	4.89E-05	ns
	7.0	–	1.30E-04	1.27E-05	–	1.21E-05	2.43E-05	ns
	6.0	3.94E-04	1.58E-04	6.27E-05	1.23E-03	–	3.71E-05	ns
	5.0	4.07E-04	7.92E-05	1.89E-04	5.11E-04	1.90E-05	7.36E-05	ns
	4.0	6.77E-04	3.82E-04	8.21E-05	3.91E-04	1.45E-05	1.19E-04	ns
	3.5	1.55E-04	2.27E-04	6.19E-05	7.64E-04	1.24E-05	7.02E-05	ns
	3.0	2.89E-04	1.22E-04	5.29E-05	1.95E-04	1.26E-05	1.12E-04	ns
	2.5	3.51E-04	3.95E-04	6.27E-05	1.74E-04	6.11E-06	2.06E-04	ns
	2.0	3.14E-04	9.76E-05	4.34E-05	1.23E-04	9.33E-06	2.50E-04	ns
	1.5	3.34E-04	6.23E-04	6.26E-05	6.33E-05	1.29E-05	8.52E-04	ns
	1.0	2.79E-05	3.15E-05	3.47E-06	8.21E-06	5.22E-05	7.19E-04	ns
	0.5	0	0	0	0	1.35E-04	1.01E-03	ns

4.0 Quality Assurance

Quality assurance and quality control measures for the project were outlined in the Quality Assurance Project Plan for basic research projects - "Resuspension of Fibers from Indoor Surfaces Due to Human Activity." Tables 4-1 and 4-2 summarize the QA/QC measures for the project. The QA/QC results for each metric are presented in subsequent sections. Note the detection limits for the URG samplers, MicroVac, and deposition chamber are the same because all rely on gravimetric analysis of the filters collected to determine whether the data quality objectives were achieved. The Mettler Toledo MT2 balance was used for all gravimetric analyses.

4.1 URG Samples

Gravimetric analysis of URG filters determined the mass resuspended from the carpet during experiments. The data quality indicators used to determine whether the data quality objectives for this metric were achieved are listed in Table 4-3.

The number of URG samples attempted and successfully collected determined the completeness percentage. The cumulative completeness percentage, including all blank and collocated samples, was 100% and exceeded the data quality objective. Field and lab filter blanks determined whether handling the filters caused inadvertent contamination. Field blanks were loaded and unloaded with the experimental URG samples. Lab blanks were kept in the gravimetric analysis chamber and were weighed with the experimental and field blank filters. The mean masses collected on the filter blanks were used as correction factors for the experimental samples.

Precision and accuracy were other quality assurance criteria. Precision in the sample collection and gravimetric analysis was assessed by collecting 4 sets of collocated URG samples. Precision was calculated as the percent relative standard deviation (%RSD). Collocated URG samples during experiments could not be collected. Therefore, collocated samples were collected by sampling laboratory air at height of 36 inches for 8 hours. Accuracy of the gravimetric analysis was assessed every session (both pre-weighing and post-weighing) by weighing a 100 µg standard weight. A gravimetric analysis session was not started until the measured weight was within 5% of the stated value.

4.2 MicroVac Samples

Gravimetric analysis of MicroVac filters determined the mass available for resuspension from the carpet. The data quality indicators used to determine whether the data quality objectives for this metric were achieved are listed in Table 4-4.

The number of MicroVac samples attempted and successfully collected determined the completeness percentage. The cumulative completeness percentage, including all blank and collocated samples, was 97.2% and exceeded the data quality objective. Both MicroVac filters from Test 7a were invalid because the samples were dropped during unloading from the cassette after sample collection.

Field and lab filter blanks determined whether handling the filters caused inadvertent contamination. Field blanks were loaded and unloaded with the experimental MicroVac samples. Lab blanks were kept in the gravimetric analysis chamber and were weighed with the experimental and field blank filters. The mean masses collected on the filter blanks were used as correction factors for the experimental samples. Precision and accuracy were other quality assurance criteria. Precision in the sample collection and gravimetric analysis was assessed by collecting duplicate MicroVac samples for each carpet piece. The MicroVac mass collected on each sample was normalized by the mass loaded in that section of carpet to eliminate the variability caused by the Wollastonite loading procedure. Precision was calculated as the percent relative standard deviation (%RSD. Accuracy of the gravimetric analysis was described in Section 4.1. The data listed in Tables 4-3 and 4-4 are identical. The accuracy data in Table 4-4 are included for completeness.

Table 4-1. QA/QC criteria for measurements collected.

Metric	Precision	Accuracy	Completeness	IDL	MDL	MQL
URG	± 20%	± 5%	> 95%	0.1 µg	0.5 µg	1.5 µg
MicroVac	± 20%	± 5%	> 95%	0.1 µg	0.5 µg	1.5 µg
Deposition Chamber	± 30%	± 5%	> 90%	0.1 µg	0.5 µg	1.5 µg
Ultrasonication			> 90%			
SEM Image			> 90%			
APS	± 5%	[a]± 15%	> 95%	0.5 µm	NA	NA
T	NA	± 5%	> 95%	1°C	NA	NA
RH	NA	± 10%	> 95%	1%	NA	NA

NA = not applicable

[a] Determined from manufacturer's calibration certificate.

Table 4-2. Quality control measures to implement during testing.

Metric	Quality Control Evaluation
URG	Precision: Collocated samples 5% of filters collected Accuracy: Asses for =5% filters Field Blanks: =5% of filters collected Lab Blanks: =5% of filters collected Background: Collected prior to each test
MicroVac	Precision: Duplicate samples for each carpet Accuracy: Asses for =5% filters Field Blanks: =5% of filters collected Lab Blanks: =5% of filters collected
Deposition Chamber	Precision: 9 filters for each carpet Accuracy: Asses for =5% filters Field Blanks: =5% of filters collected Lab Blanks: =5% of filters collected
Ultrasonication	Precision: Duplicate aliquots of =5% of extracts Field Blanks: =5% of filters collected Lab Blanks: =5% of filters collected
SEM Image Analysis	Precision: Duplicate analysis of =5% of images Blanks: NA
APS	Precision: Collocated instruments once/week Zero: HEPA filter installed on inlet daily Background: Collected prior to each test
Temp/Rh	Precision: NA Accuracy: Temp = 5%, Rh = 10%

4.3 Deposition Chamber Samples

Gravimetric analysis of deposition chamber filters determined the Wollastonite mass per unit area deposited and the variability in the mass loading for each carpet sample. The data quality indicators used to determine whether the data quality objectives for this metric were achieved are listed in Table 4-5. The number of deposition chamber filters attempted and successfully collected determined the completeness percentage. Nine filters were collected for each carpet sample. The cumulative completeness percentage, including all blank and collocated samples, was 91.3%. Three sets of filters (27 total) were invalid. Two sets were not attached properly to the carpet and moved during the Wollastonite loading. The third set of filters was placed in the wrong locations on the carpet sample.

Field and lab filter blanks determined whether handling the filters caused inadvertent contamination. Field blanks were loaded onto the carpet for five minutes then returned to the filter storage container. Lab blanks were kept in the gravimetric analysis chamber and were weighed with the experimental and field blank filters. The mean masses collected on the filter blanks were used as correction factors for the experimental samples.

Precision and accuracy were other quality assurance criteria. Precision in the sample collection and gravimetric analysis was assessed from the 9 filters deployed per carpet piece. Precision was calculated as the percent relative standard deviation (%RSD). The precision determined the variability in the Wollastonite mass loaded across the surface area of the carpet. The average variability in the mass deposited was 17.4%.Accuracy of the gravimetric analysis was described in Section 4.1.

4.4 Ultrasonication

The ultrasonic extraction of particles was one method for quantifying the amount and size distribution of Wollastonite available for resuspension. The data quality indicators for measurement of particle loading via gravimetric mass using this method are listed in Table 4-6. The data quality indicators for measurement of particle size distribution via SEM image analysis are presented in Table 4-7. As described in Section 3.1, the particle loading (mass or count) could not be determined from SEM analysis of the ultrasonication samples because of the large number of particles collected on the filter. Therefore, QA/QC data for this metric are not presented.

The completeness percentage was 93% for gravimetric and size distribution analyses. Four ultrasonication filters were invalid because filter handling errors. Note that ultrasonication samples were not planned for Tests 13 thru 15 because of budget limitations.

Field blanks were fresh polycarbonate filters that were extracted according to the procedure described in Section 2.1.8. Lab blanks were filters removed directly from the package and either weighed gravimetrically or imaged via SEM to determine the particle size distribution. Both sets of blanks did not show a significant increase in mass because particles were not present on the filter surface. This finding was verified by the SEM image analysis.

Variation in the paired ultrasonication filter particle masses and size distributions for the two samples removed from a single 36” by 36” piece of carpet was measured for each test. The mass extracted from carpet sections removed from different areas varied greatly (RSD = 33%) because of the large amount of (backing material, glue, etc) collected on the filter along with the Wollastonite particles. However, the %RSD is still within the limit set by the author of the method (Millette et al., 1993). Precision in the size distribution measurements was better (RSD = 17.4%).

Variation in the mass and size distribution within a single sample also was measured. The procedure specified removal of one 50 ml aliquot. For three randomly selected samples, a second 50 ml aliquot was collected and filtered. The variation in mass and size distribution within a sample was much smaller, indicating a single aliquot was representative of the carpet extract.

Table 4-3. URG sample completeness, filter blank, precision, and accuracy statistics.

Completeness		Field Blanks		Lab Blanks		Precision		Accuracy	
Valid Samples	72	Number	4	Number	4	Number of Pairs	4	Number Mean (µg)	20 99.6
Planned Samples	72	Mean (µg)	0.2 ± 0.2	Mean (µg)	0.1 ± 0.3	Mean %RSD	6.1%		
% Completed	100%							% Difference	0.4%

[a]Includes 5% field blanks, 5% lab blanks, and 5% collocated samples

Table 4-4. MicroVac sample completeness, filter blank, precision, and accuracy statistics.

Completeness		Field Blanks		Lab Blanks		Precision		Accuracy	
Valid Samples	70	Number	4	Number	4	Number of Pairs	30	Number Mean (µg)	20 99.6
Planned Samples[a]	72	Mean (µg)	0.1 ± 0.2	Mean (µg)	0.1 ± 0.1	Mean %RSD	5.7%		
% Completed	97.2%							% Difference	0.4%

[a]Includes 5% field blanks, 5% lab blanks, and 5% collocated samples

Table 4-5. Deposition chamber filter sample completeness, blank, precision, and accuracy statistics.

Completeness		Field Blanks		Lab Blanks		Precision		Accuracy	
Valid Samples	283	Number	13	Number	13	Number of Sets	22	Number Mean (µg)	20 99.6
Planned Samples[a]	310	Mean (µg)	-0.8 ± 0.5	Mean (µg)	-0.1 ± 0.6	Mean %RSD	17.4%		
% Completed	91.3%							% Difference	0.4%

[a]Includes 5% field blanks, 5% lab blanks, and 5% collocated samples

Table 4-6. Gravimetric mass as measured by ultrasonication: sample completeness, blank, precision, and accuracy statistics.

Completeness		Field Blanks		Lab Blanks		Precision (different section)		Precision (same section)	
Valid Samples	53	Number	3	Number	3	Number of Sets	22	Number of Sets Mean %RSD	3 8.4%
Planned Samples[a]	57	Mean (µg)	-0.3 ± 0.4	Mean (µg)	0.0 ± 0.3	Mean %RSD	33%		
% Completed	93.0%								

[a]Includes 5% field blanks, 5% lab blanks, and 5% collocated samples

Table 4-7. Size distribution from SEM images of ultrasonication filters: sample completeness, blank, precision, and accuracy statistics.

Completeness		Field Blanks		Lab Blanks		Precision		Accuracy	
Valid Samples	53	Number	3	Number	3	Number of Sets	22	Number of Sets Mean %RSD	3 7.3%
Planned Samples[a]	57	Mean (µm)	no particles	Mean (µm)	no particles	Mean %RSD	17.4%		
% Completed	93.0%								

[a]Includes 5% field blanks, 5% lab blanks, and 5% collocated samples

4.5 SEM Image Analysis

Completeness, precision, and accuracy were the QA/QC metrics applicable to the SEM image analysis. Blanks were not needed because particles were not present on clean filters or fibers. Completeness was 100% (416 images) for the SEM image analysis. The high quality of all photographs allowed SEM image analysis to be performed on all. Precision was assessed by repeating the image analysis for particle number and size measurements for 5% (21 images) of the images collected. The %RSD in the particle counts and diameters were 1.3% and 2.8%, respectively. The difference in particle concentration between the SEM image analysis used in this project and the computer controlled SEM measurements (selected as the reference standard) was less than 5%. There was bias in the accuracy of the particle size measured by the analysis of the SEM images. This issue is described in Appendix A.

4.6 Aerodynamic Particle Sizer

The APS measured resuspended particle number and mass concentration at the resuspension area boundary. The QA/QC results for this metric are summarized below.

The number of APS samples attempted and successfully collected is outlined in Table 4-8. The cumulative completeness percentage (100%) exceeded the data quality objective.

Precision and accuracy of the APS measurements were other quality assurance criteria. Precision could not be assessed because only one APS was available. Accuracy was determined to be within specifications because the APS manufacturer's calibration was still valid. The APS was calibrated on December 15, 2004.

The quality control assessment was to make sure the APS measured a concentration of 0 particles per cm^3. A HEPA filter was installed on the inlet to the APS once per day, for a total of 24 samples. The APS always measured 0 particles per cm^3 when the HEPA filter was installed.

4.7 Temperature & Relative Humidity

The HOBO H8 measured the temperature and relative humidity within each house during resuspension and tracking data collection. Only one HOBO was used, so precision was not assessed. Accuracy was measured by placing the unit in a temperature and humidity controlled chamber for 2 hours. The QA/QC results for this metric are summarized in Table 4-9. All data quality objectives were achieved.

Table 4-8. Aerodynamic Particle Sizer sample completeness statistics.

Metric	Background	Test	Cumulative
Valid Samples	30	30	60
Planned Samples	30	30	60
% Completed	100%	100%	100%

Table 4-9. QA/QC results for the HOBO H8 temperature and relative humidity data

Completeness		Accuracy	
	#		%
Valid Samples	24	Temperature	98.8
Planned Samples	24	Rh	97.1
% Completed	100%		

5.0 Conclusions

Asbestos Fiber Simulant Available Estimates

- Neither the MicroVac, Fiber SEM, nor Ultrasonication SEM methods are sufficiently robust to provide accurate mass available measurements for calculation of emission factors. Additional work is needed to develop methods to accurately quantify the mass available.
- The MicroVac method (the RTI-modified version of ASTM D5755-95) had the highest correlations of collections with the Wollastonite mass deposited. Typically, the MicroVac method underestimated the quantity deposited on new carpet. Conversely, the MicroVac method overestimated the amount deposited on older carpet because additional non-Wollastonite particles were collected. This suggests that any more aggressive surface vacuuming method (e.g. HVS3) would exhibit the same or more pronounced problems.
- The Fiber SEM method had a statistically significant correlation with the amount deposited only for new carpet. Fibrous particles originally present that were not removed during the cleaning positively skewed the mass estimate such that a significant correlation could not be obtained. This method generally overestimated the mass deposited.
- The Ultrasonication SEM method had the poorest correlations with the Wollastonite mass deposited. This destructive technique generated many additional particles (fibrous and general). As a result, the method created a positive artifact in the gravimetric and SEM mass estimates that could not be distinguished from Wollastonite mass.

Emission Factors

- Emission factors based on total mass varied from 0.005 to 0.45, depending on the experimental conditions and calculation method. Count based emission factors covered a similar range: 0.0001 to 0.30
- Size dependent emission factors, for new carpet only, varied from 0.0 to 0.17 for fiber aerodynamic diameters from 0.5 to 10 µm.
- Emission factor estimates can be improved by determining the amount available for resuspension as a function of the force applied to the fibers. Additional research is required to account for the influence of electrostatic and surface tension adhesion forces on emission factors.
- Wollastonite emission factors increase with carpet age, consistent with the trend observed for Arizona Test Dust emission factors. Emission factors from old carpet were 2 to 3 times greater than those from new carpet, possibly due to the decreased electrostatic adhesion of large Wollastonite particles (> 3 µm) to the fibers.
- Increasing the relative humidity from ~45% to ~90% increased the Wollastonite emission factors from new carpet 3 to 4 times. It is suspected that the extra moisture neutralizes the electrostatic charge and particles larger than 3.5 µm became resuspended easier.
- Walking generated larger emission factors than vacuuming, especially for older carpet. The vacuum suction efficiently collected particles resuspended by the vacuum beater bar and prevented these particles from becoming airborne.
- Quantifiable count based emission factors for sub-micrometer particles were obtained from vacuuming experiments but not from walking. The energy imparted to the carpet fibers by the vacuum beater bar was sufficient to dislodge these particles. Mass based emission factors for sub-micrometer particles were zero because the mass resuspended was insignificant and difficult to quantify.
- Emission factors for all test conditions were constant at all levels of Wollastonite loading. This finding suggests emission factors can be used to estimate airborne concentrations from the quantity available for resuspension found on the carpet via the MicroVac technique.
- Size dependent emission factors were not influenced by the experimental variables. General trends indicate that emission factors for particles less than 2 µm decrease as relative humidity increases, and emission factors for particles greater than 3.5 µm increase with increasing relative humidity.
- Emission factors as function of height were not calculated because of mixing within the exposure chamber and the contraction of the chamber plenum did not yield the expected concentration gradient.

General Findings

- Wollastonite was a suitable simulant for asbestos fibers. The Wollastonite fibers had a consistent aspect ratio of 1:3 over the range of cross sectional diameters from 1 to 5 µm. Aerodynamically, the Wollastonite fibers covered the size ranges (1-10 µm) that penetrate into the lung during respiration. The Wollastonite dispersed easily and agglomeration was not an issue during seeding of carpets. The only issue may be that Wollastonite aspect ratio was not as large as typical asbestos fibers (> 1:5).

- K-factors ranged from 10^{-3} to 10^{-6}, depending on particle diameter and experimental conditions.
- Depletion of the Wollastonite fibers resuspended during an experiment was noticed, but did not affect the validity of the experiments. The elapsed time before depletion occurred was used as input into Eq. 2-2 to calculate the total mass or counts resuspended.
- New and old carpets could be cleaned sufficiently to minimize the mass resuspended from unseeded carpets to almost the minimum detection limits of the instrumentation. However, the cleaning process did not completely remove all particles from the carpet fibers, as evidenced by the ultrasonication and fiber SEM data.
- Background characterization of the new and old carpet for fibrous particles on the fibers and resuspended during walking/vacuuming significantly improved data quality. Additional characterization samples from old carpet are recommended for future studies to check for spatial inhomogeneity in the background particle loading.
- Theoretically determined correction factors could be applied to the APS mass concentration data to make the values equivalent to the gravimetric data.

6.0 References

Brockman, J.E., "Sampling and Transport of Aerosols", Chapter 6 in Aerosol Measurement: Principles, Techniques, and Applications, 2nd edition, edited by P. Baron and K. Willeke, John Wiley and Son, New York, September, 2001.

Leith, D., "Drag on Nonspherical Objects." *Aerosol Sci. & Technol.*, 6:153–162 (1987).

Hinds, W.C., Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. Wiley Interscience, New York, New York. 1982.

Millette, J.R., Clark, P.J., Brackett, K.A., and Wheeles, R.K., "Methods for the Analysis of Carpet Samples for Asbestos." *Environmental Choices: Technical Supplement*. 1:21–24 (1993).

Peters, T.M., Leith, D., "Concentration Measurement and Counting Efficiency of the Aerodynamic Particle Sizer 3321." *J. Aerosol Sci.*, 34:627–634 (2003).

Ranade, M.B. "Adhesion and Removal of Fine Particles on Surfaces." Aerosol Sci. & Technol., 7:161–176, 1987.

Rodes, C.E., and Thornburg, J. 2004. "Study of Resuspension of Particulate Matter on Flooring Surfaces Due to Human Activity." Final Report, RTI Project 08886. U.S. EPA Contract 3C-R185-NALX.

Rodes, C. E. and R. W. Wiener, "Indoor Aerosols and Exposure Assessment", Chapter 29 in Aerosol Measurement: Principles, Techniques, and Applications, 2nd edition, edited by P. Baron and K. Willeke, John Wiley and Son, New York, September, 2001.

Thornburg, J., Ensor, D.S., Rodes, C., Lawless, P.A., Sparks, L.E., and Mosley; "Penetration of Particles into Buildings and the Influence of Associated Physical Factors, Part I: Sensitivity Model." *Aerosol Sci. & Technol*., 34:284–296, 2001.

Thornburg, J., and Rodes, C.E. 2004b. "Indoor PM Resuspension Testing for Metals." Final Report, RTI Project 08931. U.S. EPA Contract 3C- R340-NALX.

Thornburg, J., Rodes, C.E., Lamvik, M., Willis, R., and Rosati, J., Image Analysis Method (IAM) for Measurement of Particle Size Distribution and Mass Availability on Carpet Fibers. *Aerosol Sci. & Technol.* 40:274–281, 2006.

Appendix A
SEM Image Analysis

Introduction

Determination of the total number of particles available for resuspension from carpet fibers as a function of particle size is important for accurate determination of resuspension emission factors. As part of previous research for Department of Housing and Urban Development, RTI developed a procedure for counting and sizing particles from SEM images. The HUD research focus and optimization of the procedure was for Pb (lead) particles. The developed procedure was modified for EPA funded projects for general particulate matter (PM), fibers, and metals. The modified procedure for general PM is presented here. SEM images and particle size distribution were provided by ManTech Environmental (METI) under contract to EPA. The RTI method for size distribution analysis was compared with the particle size distribution measured automatically during the computer controlled SEM imaging by METI. The results of this comparison are presented in this report.

Procedure

The RTI procedure for measuring the particle size from SEM images is attached. The image analysis procedure to highlight particles from the background was optimized for 6 SEM photographs (500x) provided by METI in August 2004. Several assumptions are required to convert project area measurements from the RTI image analysis to aerodynamic diameters (Hinds, 1982). A volume shape factor of 0.25 was assumed to convert the projected area diameter (d_{pa}) to an equivalent diameter (d_e). A dynamic shape factor of 1.12 was used to convert the de to an aerodynamic diameter (d_{ae}). RTI used a constant particle density of 2.5 g/cm^3.

The procedure used by METI to calculate aerodynamic diameter is unknown, but RTI assumed the actual particle density measured by elemental analysis was used.

Results

One interesting finding between the RTI and METI procedures was immediately evident. The RTI procedure counted 2 to 3 times more particles per image than the METI procedure. The extra particles counted by RTI always were smaller than 2 µm. These extra particles were ignored by RTI. Only the largest RTI particles corresponding to the same number of particles measured by METI were compared.

The RTI and METI aerodynamic diameters calculated from the six 500x images are compared in Figure 1. The linear regression results are shown as well. The slope less than 1 and the intercept greater than 1 indicate a difference in the aerodynamic diameters. However, the high coefficient of determination (R^2) shows the bias is repeatable.

The RTI aerodynamic diameters showed a positive bias for the upper end of the size distribution, and a negative bias for the lower end of the size distribution. This bias is an unavoidable artifact because of the type of particles being measured from the SEM images. Particles containing silicon, calcium, and potassium are more difficult to distinguish from the image background in a backscatter image. Higher molecular weight elements, like lead, are much easier to distinguish and this bias is less pronounced. As a result, the thresholding of the image to separate the particles from the background tends to lose area for smaller particles composed of lower molecular weight elements. Increasing the number of pixels associated with a smaller particle to offset the negative bias leads to the positive bias for the larger particles. Additional pixels cannot be applied solely to the smallest particles. The size of all particles is increased during the procedure. The influence of differences in the RTI and METI procedures for calculating aerodynamic diameters from project areas on the bias needs to be determined too.

Even with the bias in particle size measurements, the calculated size distributions were quite similar. There was a 5% difference in count median diameter. This bias did cause a larger difference in the geometric standard deviation, about 15%.

Conclusions

1. METI should not change their procedure for obtaining SEM images. The RTI image analysis procedure has been optimized for the images being obtained by METI. Changing the SEM image quality would require substantial effort to recalibrate the RTI procedure.
2. Confirm METI and RTI are using the same conversion factors for calculating aerodynamic diameters from projected area measurements.
3. METI used individually calculated particle densities based on the elemental composition of the particles. The METI densities averaged 2.4 g/cm^3 ± 0.2. The difference in RTI and METI densities had a negligible effect on calculated aerodynamic diameter.
4. It is unknown why the RTI procedure was able to detect particles less than 2 µm from 500x images whereas METI did not. Is it possible METI was not looking for particles less than 2 mm during their particle measurements?

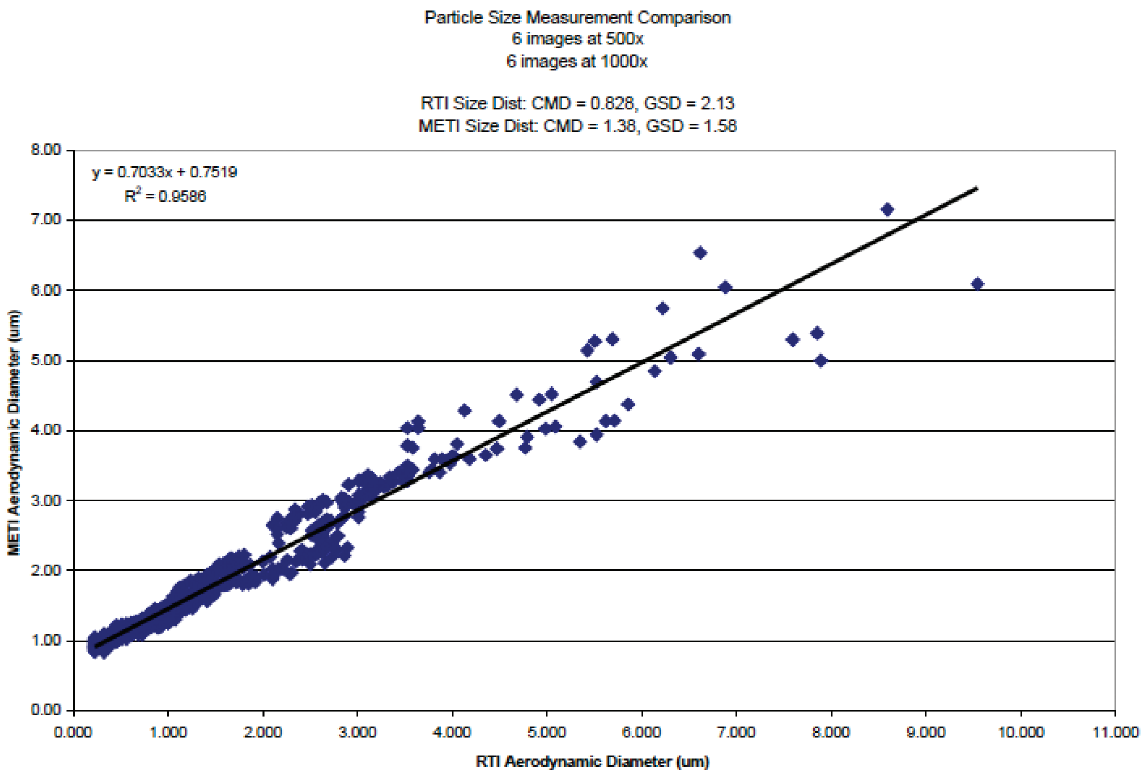

Figure A-1. Comparison of RTI and METI aerodynamic diameters

Particle Size Distribution Measurement Using SEM Image Analysis

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August 19, 2004

This procedure was modified specifically for analysis of METI generated SEM photographs of particles on carpet fibers. Original procedure is located in RTI\CAT Standard Operating Procedure 07061.001, SEM-EDS Analyses, Version 1, 2000. This modified procedure is applicable to RTI projects 08886, 08931, and 08924.

Procedure

1. Use NIH Image Beta V. 4.02, available from Scion Corp. http://www.scioncorp.com/frames/fr_scion_products.htm
2. Open desired photograph in NIH image
3. Select ANALYZE\SET SCALE from menu bar
   a. Select units of scale (micrometers)
   b. Specify # pixels covered by image in known distance box. Move cursor to far right of image and read # pixels in "Info" box
   c. Enter corresponding scale of image in measured distance box.
      i. 500x = 177.8 µm
      ii. 880x = 101 µm
      iii. 1000x = 88.9 µm
4. Select PROCESS\ENHANCE CONTRAST to highlight particles
5. Select OPTIONS\THRESHOLD to highlight particles. Grab threshold intensity bar in LUT window. Move cursor up until threshold value in "Info" window reads 148. **Threshold value of 130 is for METI produced photographs.** Other photographs may need different threshold. Trial and error process to get best
6. Covert photo to binary image by selecting PROCESS\BINARY\MAKE BINARY
7. Remove holes in particles by selecting PROCESS\BINARY\ERODE
8. Remove phantom particles by selecting PROCESS\BINARY\DILATE
9. Remove new holes in particles by selecting PROCESS\BINARY\ERODE
10. Select EDIT\INVERT to make particles black, background white
11. Select ANALYZE\OPTIONS. Check boxes for:
    a. Area
    b. Ellipse major axis
    c. Ellipse minor axis
    d. Include interior holes
    e. Heading
    f. Max Measurements = 1000
    g. Field Width = 9
    h. Digits = 3

12. Select ANALYZE\ANALYZE PARTICLES. Check boxes for:
    a. Label particles
    b. Ignore particles touching edge
    c. Include interior holes
    d. Reset measurement counter
13. Save image of labeled particles
14. Select ANALYZE\SHOW RESULTS. Projected area data for each particle opens in new window.
15. Select EDIT\COPY RESULTS to copy data to clipboard.
16. Copy results into Excel spreadsheet “SizeDist.xls”. Paste into Cell A2.
17. Spreadsheet uses Hinds equations to automatically convert projected area measurements to:
    a. Projected area diameter
    b. Equivalent diameter
        i. Use volume shape factor = 0.25
    c. Aerodynamic diameter
        i. Shape factor = 1.12
        ii. Density = 2.5 g/cm3 for ATD. Use appropriate density for other materials.

User specified size intervals can be used to calculate CMD, GSD, and R2. Upper size of each interval needs entered in Column

Appendix B
Relationship between Aerodynamic and Fiber Diameters

Introduction

Particles with high aspect ratios, like the Wollastonite used in these experiments, present a challenge when trying to interpret mass data based on different measurement techniques. The gravimetric mass measurements depend on the physical volume and true density of the collected particles. On the other hand, the mass measurements from the APS are estimated from aerodynamic diameters and assume unit density. APS mass measurements of fibrous aerosols typically are underestimated because the crosssectional diameter of the fiber is measured due to how the fibers align in the flow field through the APS sensing volume.

To check the accuracy of the APS mass concentrations measured, a theoretical exercise, presented below, provided a correlation between the APS mass measurement (based on aerodynamic diameter) URG mass measurement (based on physical volume).

Procedure

1. **Convert cross sectional fiber diameter to aerodynamic diameter using equations from Leith (1987). See Figure B-1.**

$$d_{ae} = 1.199 d_f \left(\frac{L}{d_f}\right)^{0.25} \rho_w^{0.5} \qquad \text{(B-1)}$$

2. **Relate mass measurements based on aerodynamic (APS) and physical (Gravimetric) data**

$$\frac{M_{APS}}{M_{URG}} = \frac{\frac{\pi d_{ae}^3}{6}\rho_o}{\frac{\pi d_f^2 L}{4}\rho_f} = 0.07\frac{d_{ae}^3}{d_f^3} \qquad \text{(B-2)}$$

Results

Using Figure B-1 and Eq. B-2, the mass measured by the APS will be about 25% of the mass measured gravimetrically (See Eq. B-3). This result agrees with the slope of the linear regression equation shown in Figure 3-1.

$$M_{APS} = \frac{\frac{\pi d_{ae}^3}{6}\rho_o}{\frac{\pi d_f^2 L}{4}\rho_f} M_{URG} = 0.07\frac{d_{ae}^3}{d_f^3} M_{URG} = 0.25 M_{URG} \qquad \text{(B-3)}$$

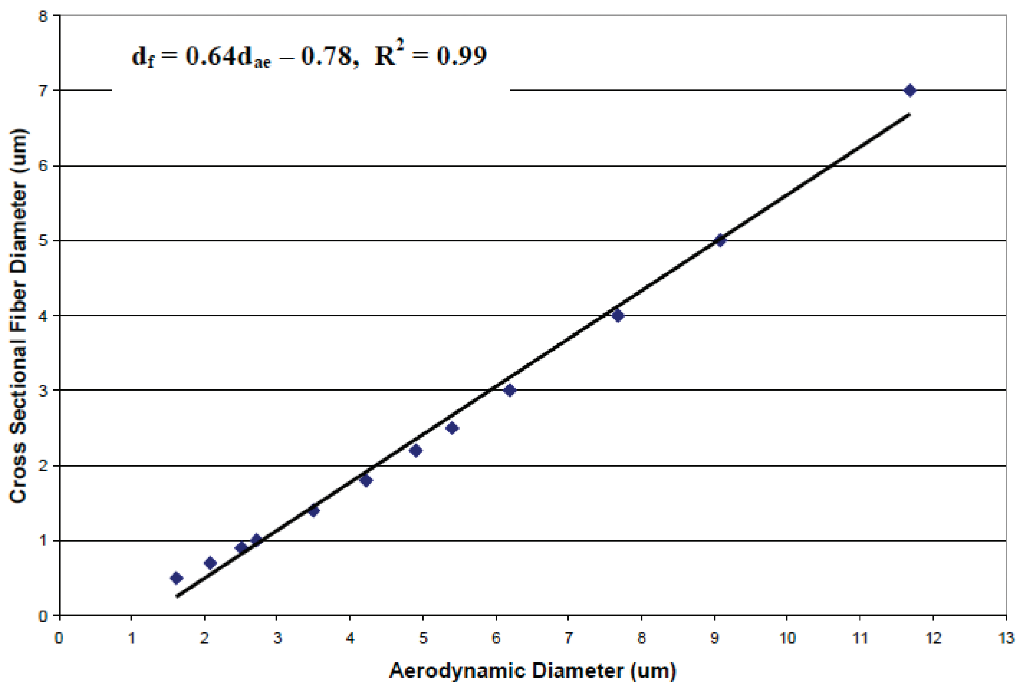

Figure B-1. Comparison of Fiber Aerodynamic (from APS) and Fiber Cross Sectional Diameters.

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