EPA/600/R-07/131 | November 2007 | www.epa.gov/ord

United States
Environmental Protection
Agency

Resuspension and Tracking of Particulate Matter From Carpet Due to Human Activity

FINAL REPORT

Office of Research and Development
National Homeland Security Research Center

EPA/600/R-07/131 | November 2007 | www.epa.gov/ord

Resuspension and Tracking of Particulate Matter From Carpet Due to Human Activity
Final Report

Prepared by:

RTI International
Center for Aerosol Technology
Post Office Box 12194
Research Triangle Park, NC 27709
Order Number: 4C-R179-NALX

Submitted by:

Jonathan Thornburg, PhD
Project Manager

Prepared for:

Jacky Rosati, PhD
Project Officer
U.S. Environmental Protection Agency
National Homeland Security Research Center
Research Triangle Park, NC 27711

Office of Research and Development
National Homeland Security Research Center, Decontamination and Consequence Management Division

Notice

This report is submitted in fulfillment of Order Number 4C-R179-NALX by RTI International under the sponsorship of the United States Environmental Protection Agency. This report covers a period from May 25, 2004 to September 30, 2005, and work was completed as of September 30, 2005.

Abstract

Each day adults and children are exposed to particulate matter (PM) from the flooring and other horizontal surfaces in their homes and offices. Potential health risks from inhalation and dermal exposure to this particulate matter exist. This particulate matter can include metals, pesticides, or terrorist-based materials such as anthrax, ricin or radiologics. The PM found on flooring stems primarily from dusts tracked in on shoes and ambient particle penetration from outside that deposits on the flooring and other horizontal surfaces. Once indoors, PM translocates throughout the residence. The major mechanisms of translocation are hypothesized to be resuspension and tracking, but the relative importance of these mechanisms is unknown. The goal of this research was to begin developing a fundamental understanding of generic PM movement within a residence. This project provided resuspension and tracking data to define the approach and scope of future research to determine primary routes of PM translocation within buildings.

The resuspension research measured the magnitude of resuspended PM vertical and lateral concentration gradients within a room, confirmed that PM emission factors calculated from medium pile carpet agreed with laboratory-generated values, and determined whether residential vacuum cleaners were an effective remediation technique. These experiments were conducted inside seven occupied homes in the Research Triangle area of North Carolina. Resuspended PM concentrations exhibited vertical and lateral gradients. On average, the resuspended concentration at 36 inches above the floor was 1.8 times lower than the concentration measured at 18 inches. Spatial-temporal analysis of the data suggested a time lag of 2 to 5 minutes between resuspension at the source and transport to instruments 8 feet away. Depending on the room configuration and size, the concentration 8 feet away was 10% to 50% of the concentration at the source. Calculated emission factors, mass resuspended per step per unit mass available in carpet, varied from 0.001 to 0.06 mg/step-mg, and followed patterns similar to those determined during laboratory experiments. Emission factors between houses were statistically different. Previous research showed variations in particle adhesion and loading characteristics affected emission factors. These data confirm that carpet age is a significant variable, and fiber length becomes more important over time after the carpet has been in place for an unknown number of years. Vacuuming was an effective remediation technique. A residential vacuum reduced the resuspended PM mass by an average of 44%. However, vacuuming increased the measured emission factors by a factor of 4 because of the reduction in mass available for resuspension. Therefore, carpet history and maintenance must be known when applying emission factors to exposure models

Experimental methods were developed to collect dust samples from carpet to determine PM translocation rates via tracking. Field and laboratory experiments used these methods to quantify PM movement rates. Mass movement via tracking from field tests varied between 2.7 and 24.1 μg per in^2-week. The rate was highly dependent on weather conditions and the estimated number of traverses across the carpet, determined from the number of occupants. Laboratory tests showed between 40% and 80% of the mass on a shoe is transferred to carpet on the first step after loading, with subsequent steps transferring about 2%. These tests also showed that approximately 1% of the PM mass in the carpet was transferred to the shoe with each step.

Table of Contents

List of Figures

List of Tables

Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
APS	Aerodynamic Particle Sizer
Avg	average
cm	centimeter
CMD	count median diameter
DI	deionized
EmFa	emission factor
ft	foot
GSD	geometric standard deviation
HEPA	high efficiency particulate air
HVAC	heating, ventilation, and air conditioning
IDL	instrument detection limit
in	inch
lb	pound
Lpm	liter per minute
m	meter
MDL	minimum detection limit
min	minutes
mL	milliliter
mm	millimeter
MQL	minimum quantitation limit
mW	milliwatt
N/A	not applicable
nm	nanometer
OPC	optical particle counter
Pb	lead
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
PM	particulate matter
RH	relative humidity
RSD	relative standard deviation
s	second
Std Dev	standard deviation
T	temperature
α	confidence level in statistical analyses
µL	microliter
µm	micrometer

Symbols

A	sample collection area
A_{vac}	area sampled with microvacuum
A_c	test carpet area
C_{APS}	counts resuspended as measured by APS
C_{Bkg}	background count concentration as measured by instrument
C_{OPC}	counts resuspended as measured by OPC
C_R	count concentration resuspended as measured by instrument
D	dilution volume
V	fluid volume
I	fluorescence intensity
I_{bkg}	fluorescence background intensity
M_{APS}	mass resuspended as measured by APS
M_{Avail}	mass available on carpet for resuspension
M_R	mass concentration resuspended as measured by instrument
M_{Bkg}	background mass concentration as measured by instrument
M_{dep}	mass deposited on surface
M_{filter}	mass on Teflo filter
M_R	mass resuspended as measured by instrument
M_{rem}	mass remaining on shoe
M_{shoe}	mass loaded on shoe
M_{URG}	mass resuspended measured by URG sampler
M_{Vac}	mass available as measured by microvacuum
Q_{APS}	sample flow of APS
t	sample time
χ	instrument counting efficiency
ξ	OPC unit specific correction factor
η	transport efficiency in sample line

1. Introduction

1.1 Scope

Each day adults and children are exposed to particulate matter (PM) from the flooring and other horizontal surfaces in their homes and offices. Potential health risks from inhalation and dermal exposure to this particulate matter exist. This particulate matter can include metals, pesticides, or terrorist-based materials such as anthrax, ricin or radiologics.

The PM found on flooring stems primarily from dust tracked in by shoes and ambient particles that settle on the flooring and other horizontal surfaces. Once indoors, PM translocates throughout the residence. The major mechanisms of translocation are hypothesized to be resuspension and tracking.

Resuspension emission factors express the ratio of the mass *resuspended* to the mass *available* on the carpet. Emission factors can also be expressed as particle count. The mass available does not necessarily equal the total mass in the carpet. Carpet provides depth that may allow migration of the particles, especially those >10 µm, downward toward the backing so that they are not available for resuspension. Also, particles smaller than 1 µm strongly adhered to the fibers are not easily dislodged and may not be "available" for resuspension. Therefore, only particles on the upper portion of the carpet fibers may be available for resuspension.

Previous research conducted by RTI for U.S. EPA developed and refined experimental methods to measure emission factors for generic particulate matter, fibers, and metals in the laboratory and field (Rodes and Thornburg, 2004; Thornburg and Rodes, 2004a, 2004b). Resuspended particle mass and size distribution data can be measured with either an integrated gravimetric-electron microscope combination or with real-time data collected with aerodynamic particle sizing instrumentation. The denominator of the emission factor, mass available, can also be measured by multiple methods. The key is identification of the method that best represents the quantity available. Sample collection mechanisms also affect the mass available estimate. Rodes and Thornburg, 2004, and Thornburg and Rodes, 2004a, using seeded, new carpet, showed that microvacuum sampling and scanning electron microscopy analysis of carpet fibers yielded mass data statistically correlated with the quantity loaded onto the carpet. Hence, both methods provided a good estimate of the mass available.

Previous research showed that walking on medium carpet resuspended almost 2% of the PM between 1 and 10 µm available on the carpet fibers, but up to 40% could be resuspended under the proper conditions. Carpet age, applied force, and relative humidity determined the emission factors. Emission factors of less than 1% were obtained for new carpet at low humidity and low applied force (e.g., walking). Emission factors between 20 and 40% were obtained for older carpet at high force (e.g., stomping) and low humidity. These tests also confirmed that the reservoir of particles available for resuspension is finite. As a result, depletion will occur in lightly loaded carpets and emission factors will drop to zero after five minutes or less of resuspension activity. Because these emission factors were calculated in laboratory experiments, the representativeness of these emission factors for "real" carpet inside homes is unknown.

Whether the resuspended PM rises into the breathing zone to be an inhalation exposure risk and be to carried throughout the residence via general air currents is unknown. Preliminary testing at three residences indicated a majority of the mass traveled less than 2 m laterally or vertically before settling to the floor (Rodes and Thornburg, 2004). Additional testing is required to confirm these initial findings. We hypothesize that the large particle size distribution of the resuspended dust (MMAD ~ 5.5 mm, GSD ~ 2.0, Rodes and Thornburg, 2004) promoted rapid gravitational settling to the carpet and prevented dispersion of the particles to sufficient heights to be convectively transported by the air currents within the homes. In addition, any mass that did migrate away from the location of resuspension was insufficient to raise the PM concentration above background levels because of the low emission factors and the large mixing volume. Additional research is needed to determine the amount of translocation of resuspended PM to different areas of the residences.

An unknown fraction of the PM on carpet fibers also will adhere to shoe soles and be carried throughout the home as the residents move from room to room. Whether or not the PM is dislodged from the shoe soles onto other surfaces needs to be investigated. PM dislodged from shoe soles onto carpet in other rooms may then become available for resuspension by walking or other activities. Remediation methods such as vacuuming may have a significant influence on translocation and exposure, depending on the type and frequency of the activity. A literature review indicates that tracking as a translocation mechanism has not been studied previously. The exploratory research into tracking will develop sampling methods, a better understanding of parameters affecting tracking, and a range of tracking translocation rates (mass per unit of time).

1.2 Research Objectives

The goal of this pilot effort was to begin developing a fundamental understanding of generic PM movement within a residence. The relative importance of resuspension and tracking for PM translocation is unknown. This project provided resuspension and tracking data to define the approach and scope of future research to determine primary routes of PM translocation within buildings. Specific objectives of this project were:

1) To measure PM resuspension emission factors from walking on medium-pile carpet (of various ages and fiber lengths) in private homes at ambient relative humidity (40%–60%) to confirm that laboratory-generated emission factors are representative of real environments
2) To measure resuspended PM concentrations at two heights to obtain vertical gradient data
3) To monitor PM concentrations in areas/rooms surrounding the test area to quantify the amount of translocation from resuspension
4) To initially characterize the magnitude of tracking as a method for PM translocation within a residence
5) To evaluate whether vacuuming can significantly reduce PM resuspension and translocation within a residence

This research provided improved input data for the inhalation and dermal exposure models used in risk assessments for metals, allergens, biologics, and pesticides associated with particles.

1.3 General Approach

The key elements of the research approach to address the objectives given in Section 1.2 were:

1) Develop a project Quality Assurance Project Plan (QAPP) before beginning experimental work. (See "Resuspension of Particulate Matter on Flooring - Quality Assurance Project Plan for Basic Research Projects," EPA Order No. 4C-R179-NALX, EPA/NHSRC under Contract No. QT-OH-04-00315 RTI Project No. 09188.)
2) Identify seven homes with medium-pile carpet of various ages for collecting resuspension data for calculation of emission factors.
3) Obtain particle counters suitable for measuring vertical and horizontal concentration gradients of resuspended PM.
4) Select a vacuum cleaner representative of a homeowner quality unit rather than a HEPA unit that would be used in remediation efforts.
5) Conduct controlled walking experiments pre- and post-vacuuming in each residence to measure emission factors and particle translocation vertically and laterally.
6) Develop procedures and methods for tracking tests in homes and the laboratory.
    a) Identify four homes for deployment of a 12-ft long piece of new, medium-pile carpet. Collect microvacuum samples every week at 3-ft intervals to monitor for PM mass loading increases over time.
    b) For laboratory tests, identify fluorescent tracers and develop shoe/carpet loading procedures to quantify the mass dislodged per step.

1.4 Underlying Variables

Carpet pile height and particle adhesion are two variables that probably influence resuspension and tracking of particles from carpets. However, these variables were not studied during this project because of the limited scope of work. 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

RTI data from previous projects showed that as the pile height decreased, the level of resuspension and tracking from normal walking decreased substantially (Rodes, 1998). Tracking decreased because of the reduction in contact area between the shoe and the surface. No measurable resuspension was observed from dust on bare flooring. Resuspending dust from bare floors may require 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 resuspension. Thus, the current work focused only on medium-pile carpeting (~70% of all new carpeting sold), which has been shown by RTI and others to contribute significantly to resuspension (Rodes, 2001; Ferro et al., 2004).

1.4.2 Particle Adhesion

A potentially important factor in understanding resuspension of particles from carpet fibers is adhesion. Adhesion of particles to carpet fibers has been reported to be influenced by relatively humidity, controlled primarily by electrical charging of both the fibers and the particles. Very low humidity is 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. This latter type of force bonding particles together or to the fibers is potentially important when the relative humidity exceeds ~45%. Adhesion literature states that 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. 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 adhesive force levels.

RTI also has observed that as carpet ages or becomes significantly soiled (including coating of the fibers over time by aerosolized grease from cooking), its ability to generate static charging appears to decrease substantially. The coating of grease may increase the surface adhesion for larger particles. 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 whether the influences from these surface forces could be estimated categorically. Successful modeling of particle resuspension will require more detailed investigation of the relationships among these factors.

2.0
Experimental Methods

2.1 Resuspension Instrumentation and Procedures

The instrumentation and procedures selected for resuspension tests determined the particle aerodynamic diameter and concentration (either mass or number) of the particles resuspended from the carpet and available for resuspension.

2.1.1 Instrumentation and Materials

The instrumentation used to collect the emission factor and translocation data from the residences is described below. A brief summary of the resuspension method is provided also.

2.1.1.1 Carpet Pile Height - A dial micrometer was used to estimate the carpet pile height at multiple locations within the residences.

2.1.1.2 Carpet Microvacuum Samples - The quantity of particulate matter available for resuspension was estimated by collecting two vacuum samples onto 47-mm Teflo filters. The vacuumed area was a 3-in by 3-in square. 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, manually removing obvious carpet fibers collected on the filter, and using gravimetric analysis of the filter instead of liquid extraction for microscopic analysis.

2.1.1.3 MetOne Optical Particle Counters -The MetOne GT-521 is an optical particle counter that uses light scattering principles; it operates a 30-mW laser diode that emits 785 nm of light with a nominal flow rate of 2.831 Lpm. However, in its application here, the flow rate was reduced to ~1.9 Lpm to improve the counting efficiency of the unit. Two MetOne GT-521 units were deployed at the edge of the resuspension area. One unit sampled at 18 inches above the floor, and the other sampled at 36 inches above the floor. The units collected data continuously in two channels: >1 μm and >5 μm. One data point was collected every 6 seconds.

2.1.1.4 Climet 4302 Optical Particle Counters - Six Climet 4302 optical particle counters were located at various locations within the test room. All monitors were within 8 feet of the resuspension source. The instruments collected particle concentration data every 60 seconds. Two channels measured the cumulative number >0.5 μm and >5 μm, respectively. Instruments were operated according to manufacturer's instructions. All data were corrected for background aerosol levels. Data were used for translocation hypothesis testing.

2.1.1.5 Aerodynamic Particle Sizer - The TSI Aerodynamic Particle Sizer (Model 3321) was used to obtain resuspended PM mass and count size distribution data from 0.5 to 20 μm. The APS was operated according to manufacturer's instructions . Counting efficiency errors were corrected using the data from Peters and Leith (2003).

2.1.1.6 URG Mass Sampler - URG mass samplers (University Research Glassware, Chapel Hill, NC) collected PM_{10} samples isokinetically at 20 Lpm. Two samplers were used per test: one at 18 in and the other at 36 in above the floor. Samples were collected on 47-mm Teflo filters. Filter mass was determined gravimetrically.

2.1.1.7 Temperature and Relative Humidity - Temperature and relative humidity within the homes were measured with a HOBO H8 Data Logger (Onset Computer Corporation, Bourne, MA). Temperature and relative humidity were recorded at 1-minute intervals.

2.1.1.8 Gravimetric Analysis - Aerosol mass collected on filters was weighed in RTI's temperature and humidity controlled (23 °C, 35% RH) weighing chamber on a Mettler Toledo MT2 balance with 0.1 μg resolution.

2.1.1.9 Statistical Analysis - All statistical analyses were performed using SAS version 9.1 (SAS Inc., Cary, NC). The General Linear Mixed model (Proc Mixed) was used to determine the significance of experimental parameters on the resuspended dust. This model structure allowed statistical analysis of the random and fixed effects for their influence on the resuspended dust. The statistical models evaluated for the dependent variables are listed below. The statistical models included the first order independent variables and all second order interactions (listed below collectively as INTERACTIONS).

$$\log\left(\frac{M_{URG}}{Step}\right) = Age + Vacuum + Length + Height + INTERACTIONS \quad (2\text{-}1)$$

$$\log\left(M_{Avail}\right) = Age + Vacuum + Length + Height + INTERACTIONS \quad (2\text{-}2)$$

$$MMD = Age + Vacuum + Length + INTERACTIONS \quad (2\text{-}3)$$

$$CMD = Age + Vacuum + Length + INTERACTIONS \quad (2\text{-}4)$$

$$\log\left(\frac{M_{URG}/Step}{M_{Avail}}\right) = Age + Vacuum + Length + Height + INTERACTIONS \quad (2\text{-}5)$$

where:

- M_{URG} = mass collected by URG filter
- Step = numbers of steps made during the five-minute test
- Age = carpet age
- Vacuum = carpet was vacuumed (e.g., remediated) before test ("Yes" = 1; "No" = −1)
- Length = carpet fiber length (pile height)
- Height = sampling height
- M_{Avail} = mass available on carpet for resuspension
- MMD = mass median diameter
- CMD = count median diameter
- M_{URG}/M_{Avail} – Step = emission factor

One source of experimental variability that could be controlled during the statistical analysis was the number of steps per test. Therefore, the resuspended mass was normalized by dividing the measured value by the number of steps.

The collected data for the normalized "resuspended mass" and "mass available" variables were not normally distributed because of the small dataset (n<55) and the large variation in masses between houses. The "log" transformation was required to normalize the data.

2.1.2 Tests Conducted

PM resuspension and translocation experiments were conducted in seven private residences with medium-pile carpet. RTI recruited volunteers for the residential testing. Houses with pets (dogs, cats) were included in the study. Volunteer residences had at least 36 ft^2 of open space in a frequently used room to increase the probability of obtaining detectable resuspended PM concentrations. The area and frequency of use specifications attempted to equalize the dust reservoir and carpet characteristics within a house. Four different carpet sections, one for each experiment, were tested to avoid depletion of the dust reservoir. The HVAC system in each home was deactivated and all windows were closed during the tests to remove these variables from the statistical analysis. Natural and HVAC-induced ventilation could increase the between-house variability in the resuspended and translocated concentrations. Experience gained during RTI Project 0886 showed that the HVAC system can supply sufficient quantities of "clean" air that dilutes the resuspended PM and introduces experimental error. Open windows could introduce either "clean" or "dirty" air that could confound the experimental data.

The home and test room characteristics for each residence were recorded (see Appendix A). Each home was assigned a unique identification number linked to the address. Information recorded covered home occupants, carpet characteristics, cleaning history, and interior and exterior surveys. This information provided a qualitative understanding of the carpet condition and PM loading to relate measured emission factors to the corresponding laboratory-generated values.

Four resuspension tests per home were conducted. Two resuspension tests were conducted on the carpet "as is." The carpet was cleaned with a standard residential vacuum prior to the remaining two resuspension tests to test the efficacy of simple remediation efforts. The vacuum was a 13-amp Mach 2.1 Hoover (Model # U5330-900) upright vacuum with beater bar. The entire 9 ft^2 area was vacuumed two times from each direction (left to right, right to left, top to bottom, bottom to top). 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.

A single volunteer walked randomly within the 3-ft by 3-ft carpet area for five minutes during an experiment. The volunteer was a 71 inch, 165-lb male with size 12 shoes (120 in^2). A pedometer worn by the volunteer determined the number of steps taken during the experiment. The subject walked so that a constant foot pressure (energy) was imparted to the carpet since previous work showed emission factors varied with energy level. There is no way to ensure each step applied the same foot pressure. Any variability in foot pressure contributing to experimental error was minimized by the large number of steps possible in a five-minute period (~ 250 steps). Also, the highest possible foot pressure imparted by walking still should be much less than the foot pressure generated by "stomping."

Microvacuum samples characterized the quantity of PM available for resuspension (Table 2-1, Figure 2-1). Resuspended PM concentrations and size distributions were measured with the time-of-flight instrument (APS), optical particle counters (Climet OPCs and MetOne OPCs), and gravimetric samplers (URG units) listed in Table 2-1 and shown in Figures 2-2 and 2-3. APS and Climet sampling artifacts were accounted for when calculating PM emission factors. Large particles suffered deposition losses within the sampling lines leading to both instruments. These losses were characterized for both instruments during RTI Project 0886. The same sampling lines were used in this research. In addition, the APS does not count every particle that enters the instrument. The correction factor developed by Peters and Leith (2003) was used.

Table 2-1. PM measurements during each resuspension test.

Carpet/House Characteristic	Collection Method	Number per instrument	Analysis
Background PM concentration and size distribution	APS x 1	10 files over 10 minutes	Calculation of total and size dependent mass and number concentration using Excel® correcting for instrumentation artifacts
	Climet x 6	10 files over 10 minutes	
	MetOne x 2	10 files over 10 minutes	
Resuspended PM concentration and size distribution	APS x 2	10 files over 10 minutes	
	Climet x 6	10 files over 10 minutes	
	MetOne x 2	10 files over 10 minutes	
	URG x 2	1 filter over 10 minutes	Gravimetric analysis for mass and SEM analysis for size distribution
PM reservoir strength: concentration and size distribution	Microvac	2 filters per test area	Gravimetric analysis for mass

Figure 2-1. Collection of microvacuum samples to characterize the PM mass available for resuspension. Template area is 9 in^2. Fourteen passes were made across the template. Samples were collected prior to walking in test area.

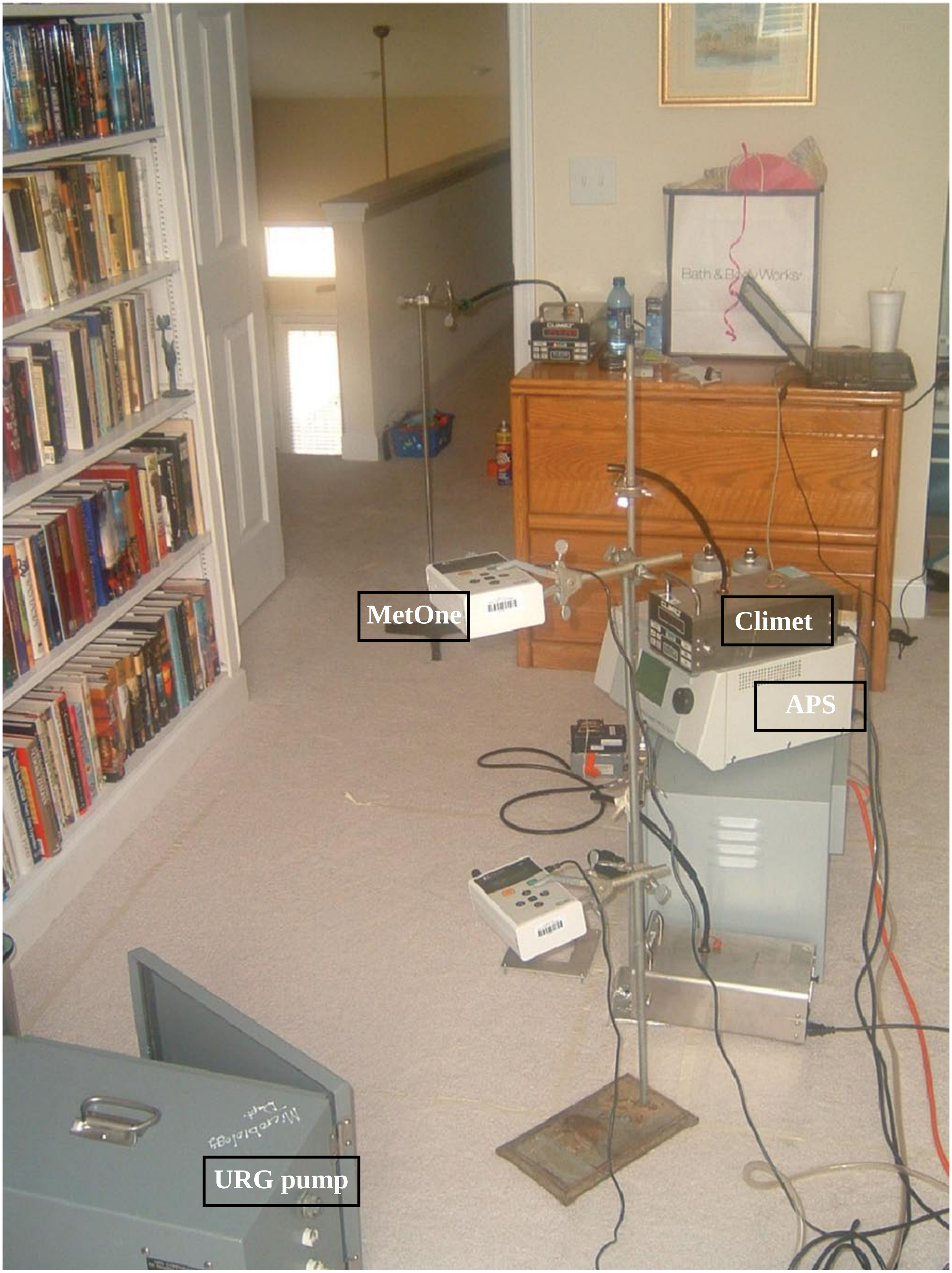


Figure 2-2. Arrangement of sample collection equipment around 9 ft^2 resuspension test area. Note that instruments were located at 18 inches and 36 inches above the floor. URG filter samplers were not installed. Also, note that Climet was located at entry into room.

Figure 2-3. Sample collection during resuspension experiment.

A preliminary experimental protocol is presented in Table 2-2. The 9 ft^2 test area was outlined in masking tape. All sampling instruments were positioned around the edge of the template in the direction of most likely air movement. The sample inlet height for the four Climets set up away from the test area boundary was 36 in. Presence of furniture, walls, or other obstructions to airflow sometimes required Climet inlets to be as low as 32 in or as high as 40 in, depending on professional judgment. These changes were noted on the test datasheets.

Once all equipment was ready, movement within the house ceased to allow the PM concentration to return to quiescent levels prior to collection of the background PM samples with the APS, Climets, and MetOnes. All instrumentation within the house was programmed to start after 15 minutes of quiescent conditions. After collection of 10 minutes of background data at each sampling height, the PM mass samplers were started and the test volunteer began the scripted activity within the template. The volunteer wore a particle-free clean room suit to prevent the "personal cloud" from biasing the data. The volunteer walked for 5 minutes, then waited for another 10 minutes to allow the PM concentration to return to background levels. After the 10 minutes allocated for the PM resuspension expired, all instrumentation was stopped, mass samples collected, and data files saved. Ancillary indoor temperature and relative humidity data were collected during each test. One experiment required about 60 minutes to prepare for the test and about 60 minutes to collect the data.

Table 2-2. Procedure for collecting PM resuspension data from private residences.

Step	Description	Time
1	Deploy HOBO temperature and relative humidity monitor.	5 min
2	Outline 3 ft by 3 ft resuspension area.	5 min
3	Vacuum test area if remediation evaluation test is being conducted.	5 min
4	Collect two microvac samples in two separate 9 in^2 sections within test area.	10 min
5	Set up APS, Climet, MetOne, and URG units at the boundary of the area. Sampler inlets, one of each type, should be at 18 inches and 36 inches above the floor. APS only at 24 inches.	10 min
6	Set up remaining four Climets no more than 8 feet from area boundary and with sample inlets at about 36 inches above the floor or as determined by professional judgment accounting for obstacles and expected air movement.	10 min
7	Allow PM concentrations to return to background levels.	10 min
8	Start background sample collection with all APS and Climets. Collect data for 5 minutes.	5 min
9	Reset all instrumentation for resuspension test.	10 min
10	Allow PM concentrations to return to background levels.	5–10 min
11	Start all APS, Climet, and URG samplers.	1 min
12	Begin walking within test area to resuspend PM. Walk for 5 minutes.	5 min
13	Stop movement and allow PM to settle. Wait for 10 minutes.	10 min
14	Stop all sample and data collection instrumentation.	1 min
15	Retrieve URG filters and save APS and Climet data files.	15 min
16	Retrieve HOBO temperature and relative humidity monitor.	5 min
	TOTAL	**120 min**

2.1.3 Data Reduction

Emission factors were calculated in multiple ways. Resuspended mass concentrations were measured with the URG and APS instruments. Corresponding resuspended count data were provided by the APS, Climet, and MetOne units. The mass available for resuspension was calculated from microvacuum samples.

2.1.3.1 PM Resuspended by APS - The mass resuspended as measured by APS was calculated using Eq. 2-6. 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_{APS} = 5.0 Lpm), the total time particles were resuspended (t), and a dimensionless correction factor for APS counting efficiency (χ=2). Total time particles were resuspended was not constant across all tests. Depletion occurred within three minutes during some experiments because of low mass load in the carpet. Other experiments had airborne concentrations greater than background that lingered for up to five minutes past the end of the resuspension activity because of high mass load in the carpet and low air exchange rate. These factors were accounted for in the data analysis.

$$\overline{M}_{APS} = \left[\sum \left(M_R - M_{Bkg}\right) \times \eta\right] \times Q_{APS} \times t \times \chi \qquad (2\text{-}6)$$

APS also provided resuspended PM number concentration data. The total counts resuspended (CAPS) were calculated using an equation similar to Eq. 2-6.

$$\overline{C}_{APS} = \left[\sum \left(C_R - C_{Bkg}\right) \times \eta\right] \times Q_{APS} \times t \times \chi \qquad (2\text{-}7)$$

2.1.3.2 PM Resuspended by Gravimetric Data - Mass resuspended as measured by the URG samplers was equal to the gravimetric mass collected on the filters, Mfilter. 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).

$$M_{URG} = M_{filter} \qquad (2\text{-}8)$$

2.1.3.3 PM Resuspended by Optical Particle Counters - Resuspended PM counts (C_{OPC}) were calculated from the number concentrations measured by the Climets and MetOnes (C_R) and their respective sample flow (Q_{OPC}). Measured concentrations were corrected for background PM concentration (C_{Bkg}), sample line transport efficiency (η), and a unit-specific correction factor (ξ). Collocated sampling (as part of the quality control procedures outlined in the QAPP) for the Climets and MetOnes indicated concentrations measured by individual units differed by up to a factor of 10. Reference instruments for calculation of the correction factors were Climet #958304 and MetOne #01.

$$\overline{C_{OPC}} = \left[\sum \left(C_R - C_{Bkg}\right) \times \eta\right] \times Q_{OPC} \times t \times \xi \qquad (2\text{-}9)$$

2.1.3.4 PM 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 (Ac = 1296 in^2).

$$\overline{M_{Vac}} = M_{filter} \times \frac{1}{A_{vac}} \times A_c \qquad (2\text{-}10)$$

2.2 Tracking Instrumentation and Procedures

Two experimental approaches determined whether PM moves through a residence via tracking. The first approach used real homes to bracket the range of expected translocation rates via tracking. These tests were followed by laboratory experiments that identified the salient parameters influencing particle translocation via tracking.

2.2.1 Instrumentation and Materials

The residential and laboratory tracking tests required different experimental methods. Whether a method was used for a residential or laboratory experiment is clearly delineated in the subsection heading.

2.2.1.1 Carpet Microvacuum Samples (Residential) - The quantity of particulate matter available for tracking on the test carpet placed within each residence was determined by collecting microvacuum samples. PM available for tracking was collected on 47-mm Teflo filters. The vacuumed area was a 3-in by 3-in square. The locations sampled on the carpet each week are described in Section 2.2.2. 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, manually removing obvious carpet fibers collected on the filter, and using gravimetric analysis of the filter instead of liquid extraction for microscopic analysis.

2.2.1.2 Gravimetric Analysis (Residential) - Aerosol mass collected on filters was weighed in RTI's temperature and humidity controlled (23 °C, 35% RH) weighing chamber on a Mettler Toledo MT2 balance with 0.1 µg resolution.

2.2.1.3 Fluorescent Particles (Laboratory) - The test dust used was amorphous silica (Syloid, W.R. Grace Co., Baltimore, MD) tagged with Uranine (Fisher Scientific, Fair Lawn, NJ) or Tinopal (Ciba-Geigy, Greensboro, NC). Uranine and Tinopal are tracers that fluoresce at different wavelengths. Uranine particles determined the quantity of dust dislodged from the shoe onto the carpet. Tinopal particles determined the amount of particulate matter transferred from the carpet to the shoe sole. This dust had a median diameter of ~2.5 µm and a standard deviation of ~2.7 µm when aerosolized or applied to the surface. This size distribution had 10% of the mass contained in 10 µm particles. An established RTI procedure was used to generate the dust.

2.2.1.4 Fluorometer (Laboratory) - A GENios TECAN fluorometer using XFLUOR v4.51 software measured the intensity of the fluorescence emitted from the samples. This system analyzed 96 100 µL samples for both Uranine and Tinopal fluorescence in one batch. The instrument software was automatically programmed to change the excitation and emission wavelengths to the desired wavelength. The Uranine excitation wavelength was 485 nm and the emission wavelength was 535 nm. The Tinopal excitation wavelength was 360 nm and the emission wavelength was 465 nm. Dilution of samples was sometimes necessary to stay below the upper detection limit of the fluorometer. Progressive dilutions of 1/10, 1/20, and 1/30 were used until a valid fluorometer reading was obtained. Calibration curves relating the fluorescence intensity to the fluorescent particle mass concentration were generated for each batch. All measurements were corrected for residual fluorescence from the sample collection fluid (0.01 N NaOH solution) and the well-plate. The Uranine and Tinopal detection limits were 0.2 μg/mL and 0.7 μg/mL, respectively.

2.2.1.5 Statistical Analysis (Residential and Laboratory) - The nonlinear, spatial-temporal autoregressive analysis necessary to analyze the tracking data required use of the Proc Mixed procedure in SAS version 9.1 (SAS Inc., Cary, NC). The spatial-temporal analysis accounted for the variability in conditions influencing the loading on the carpet sections or shoe over time. The autoregressive structure controlled for the variability in experimental conditions found between houses or laboratory test conditions so that comparisons between these independent variables could be made. The Tukey-Kramer least squares analysis procedure identified whether differences between houses existed.

2.2.2 Residence Experiments

Farfel *et al*. (2001) showed significant increases in lead (Pb) mass within 3 ft of the home main entry after 3 weeks of deploying a walk-off mat to collect lead particles. This work extended the size of the walk-off mats to cover a larger area of the residence and extended the sampling period to provide estimates of tracking translocation rates. Walk-off mats were installed inside four volunteers' residences. One residence (H1) participated in the resuspension testing, and the other three participated only in the tracking study. Walk-off mats were new, medium-pile carpet about 30 in wide and at least 144 in long. The walk-off mats were located immediately inside the main entry of the home. Home selection criteria for installation of the walk-off mats depended on: 1) resident participation, 2) space availability, 3) number of people living in the home, 4) absence of dogs inside the home, and 5) main entry being not through the garage. Volunteers were instructed <u>not</u> to vacuum or clean the walk-off mat. Characteristics of these houses are presented in Appendix B.

Walk-off mats were deployed inside the home for four weeks. Figure 2-4 summarizes the details of the walk-off mat data collection. Microcvacuum samples were collected in each of four segments of the carpet immediately after deployment and at the end of each week. All microvacuum samples were collected in situ. The four segments of the walk-off mat corresponded to specified distances, 3-ft increments, from the main entry into the home. Microvacuum samples were collected using a 30-in by 36-in metal template consisting of ten 9-in^2 sample points. The corners of the template had "feet" to raise the grid above the carpet surface to avoid cross-contamination between segments. Ten sample points allowed collection of duplicate samples per week, one sample per row. Each sample grid per walk-off mat segment was used only once per residence. The grids were spaced to match the normal adult step width of ~ 18 in. Two background samples were collected from each carpet segment.

The PM mass collected each week, in each segment, required spatial-temporal statistical analysis. The statistical model accounted for the number of people inside the homes, segment number, and week number. Due to the small sample of four houses and data collection over five weeks, the particulate matter masses collected were not normally distributed. Several transformations of the data were considered. The "log" transformation provided the appropriate correction and parametric tests were performed under normal assumptions.

2.2.3 Laboratory Experiments

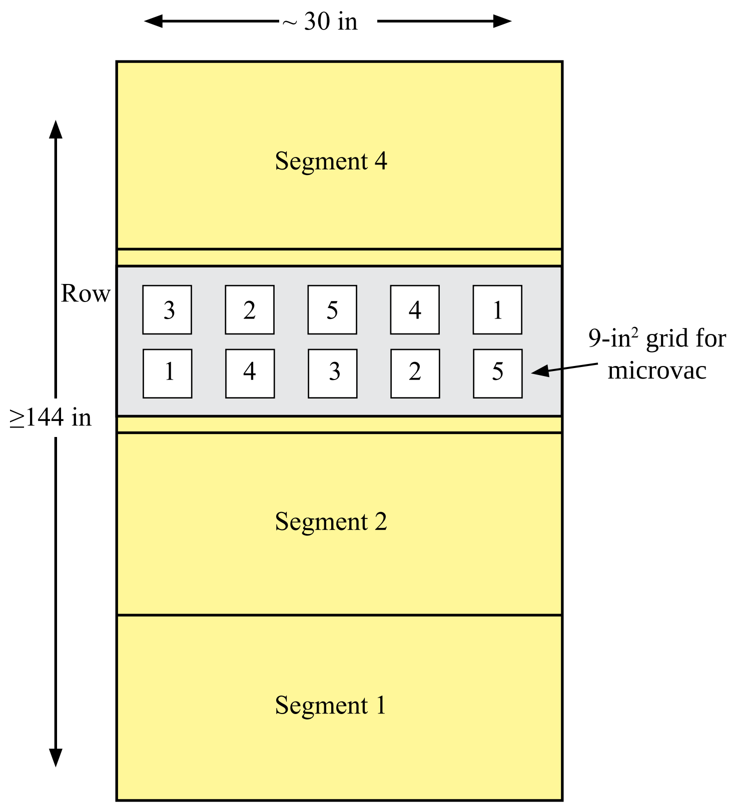
2.2.3.1 Sample Collection and Analysis - Additional tracking experiments were conducted in the laboratory. These tests identified salient parameters affecting translocation and quantified the range of particle translocation rates for comparison with the field tests. Because little is known about the mechanism of particle adhesion/removal on surfaces (e.g., shoes, carpet fibers), this exploratory effort required the development of sampling methods and judicial selection of test conditions.

One challenge was determining how to uniformly load a known quantity of the fluorescent tracer to a surface. The best approach was to suspend a known mass of tracer in 25 mL of DI water, then apply 2 mL aliquots to the surface by syringe. The aliquots were dispersed evenly in a 1.5-in diameter circle outlined by a piece of PVC pipe. As the DI water evaporated, the fluorescent particles were deposited uniformly across the 1.5-in circle. Eleven aliquots were applied to each surface. Eight aliquots were applied into an area matching the shoe sole area. The other three aliquots were applied outside the shoe sole area to quantify the amount deposited.

Uranine and Tinopal particles were applied as follows. Uranine tracer was applied indirectly to the shoe sole. The above procedure was used to load Uranine onto a 9-in by 13-in cookie sheet (Figure 2-5). Once the Uranine solution dried, the shoe was evenly pressed into the cookies sheet to evenly coat the sole surface (Figure 2-5). The shoe surface was marked with eight 1.5-in diameter circles to correspond to the sample locations. Following this step of the procedure, the three wash samples outside the footprint were collected to quantify the amount deposited. [A wash sample was collected with 10 mL of 0.01 N NaOH solution (twice), a disposable pipette, and a piece of 1.5-in diameter PVC pipe. The PVC pipe was held firmly against the flat shoe sole by the technician. Using the other hand, the same technician poured 10 mL of the NaOH solution into the PVC pipe, mixed the solution with the pipette, and then pipetted the solution back into the vial. The area on the shoe sole was washed twice with 10-mL aliquots of the NaOH solution.] Also, the eight wash samples within the footprint were collected to calculate the amount transferred to the shoe via a mass balance. Tinopal particle solution was applied to the carpet (Step 1 location) using the above procedure and allowed to dry. Tinopal particles were transferred from the carpet to the shoe during a normal step on the first location only. Again, the three samples outside the footprint quantified the amount deposited and the eight samples within the footprints were used to calculate the amount transferred to the shoe via a mass balance. As discussed below, carpet samples were removed to extract the Tinopal for quantification. Subsequent steps transferred Tinopal from the shoe sole to the carpet.

The sample collection procedure for the tracking tests is described below. The test volunteer was a 6-ft, 170-lb male wearing size 10 shoes (160 in^2) with flat, smooth soles. The volunteer stepped onto the Uranine-coated cookie sheet to evenly load the shoe sole of his right foot (Figure 2-5). Then, he stepped onto the Step 1 template (Figure 2-6). After the step, the volunteer stopped movement, lifted his foot and a wash sample was collected from the specified location on the shoe sole (Figure 2-7). Steps 2–6 followed this same procedure. After the last step, the shoe was removed and the remaining two shoe wash samples were collected.

Figure 2-4. Illustration of walk-off mat and microvac sample collection template. Sample collection template is shown in Segment #3. Numbers within boxes correspond to order of sample collection:
b = background, # = week number.



Following the steps, carpet squares were removed to extract the fluorescent particles for measurement of the amount remaining in the carpet (Tinopal: Step 1 only) or transferred to the carpet (Uranine: all steps; Tinopal: Steps 2–6). Squares approximately 1 inch by 1 inch were cut from the carpet (Figure 2-8). The squares corresponded to the marked sample collection point on the carpet. The squares were placed in a disposable beaker filled with 40 mL of 0.01 N NaOH solution and sonicated for 20 minutes. Then, the carpet squares were removed from the beaker. The sonication extracted the fluorescent particles from the carpet fibers and suspended them in the fluid.

Once samples for two tests were collected (96 samples: 48 per test), the samples were transferred to the well-plate for fluorometry. Each sample was mixed for five seconds to resuspend the fluorescent particles in solution immediately before 100 μL was pipetted into the well-plate (Figure 2-9). If necessary, 1/10, 1/20, or 1/30 dilutions of a sample were prepared to obtain a measurement below the maximum detection limit of the fluorometer.

2.2.3.2 Data Reduction - The fluorescent particle mass loadings (µg/in^2) on the shoe and carpet following each step were calculated directly from the fluorescence intensity data from the fluorometer (I) corrected for the background fluorescence (I_{bkg}), any dilutions (D), fluid volume (V), and sample collection area (A).

$$Mass = \frac{(I - I_{bkg}) \times D \times V}{A} \tag{2-11}$$

Mass loaded onto the shoe (µg/in^2) was calculated via a mass balance between the average quantities deposited minus the average amount remaining following the step.

$$\overline{M_{shoe}} = \frac{\sum^{i=1\text{-}3} M_{dep,i}}{3} - \frac{\sum^{i=1\text{-}8} M_{rem}}{8} \tag{2-12}$$

Figure 2-5. Example of uniform loading of shoe with Uranine from stepping firmly onto cookie sheet with uniform deposits of Uranine dust. Left picture shows clean shoe and cookie sheet prior to step. Right picture shows loading of shoe following step.

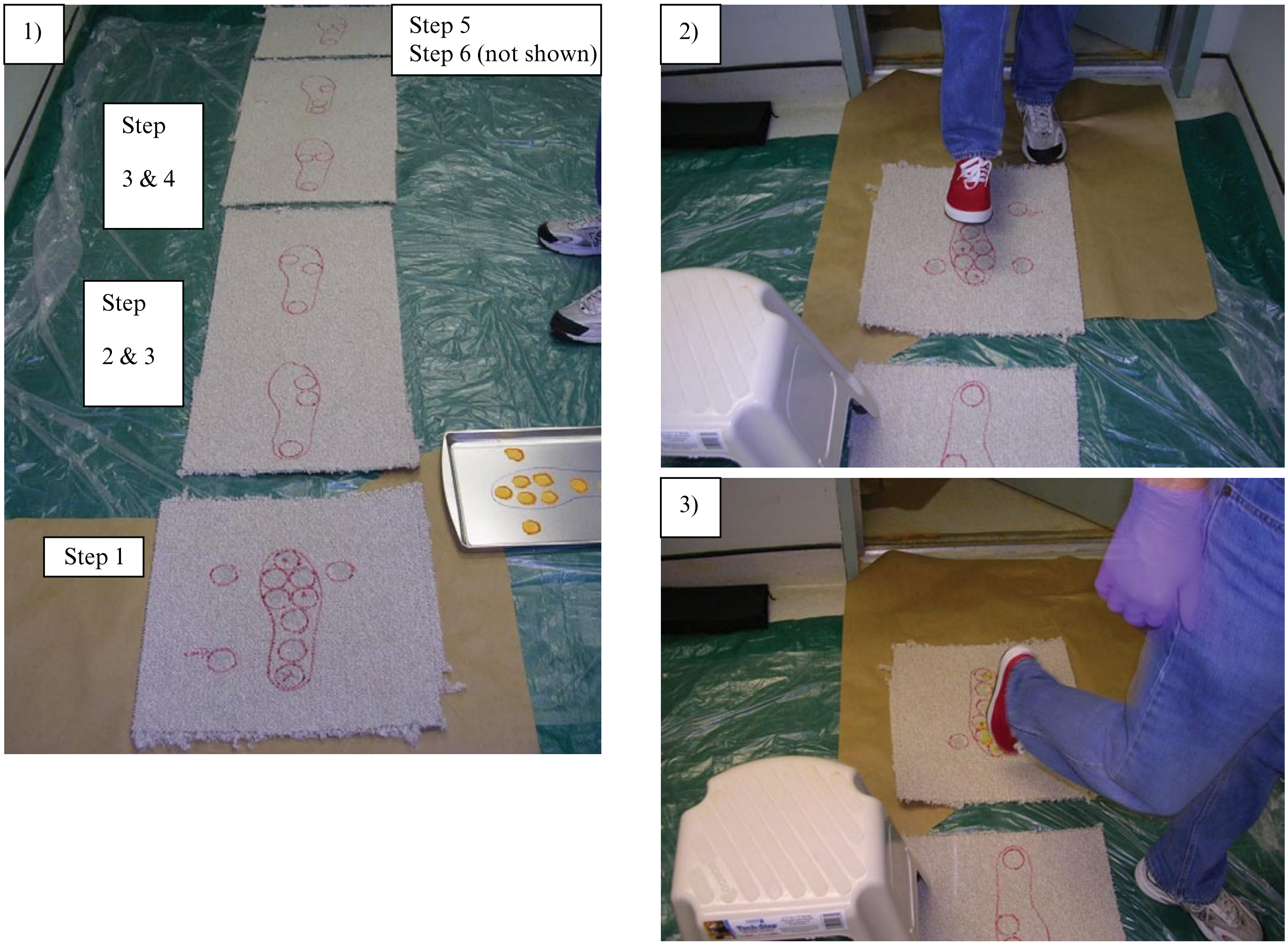


Figure 2-6. Walking path and example steps during laboratory tracking experiments. 1) Target walking path. Shoe template shows where each step should occur. Circles indicate where Tinopal loaded onto carpet (Step 1 only) and where carpet and shoe wash samples were collected after each step. 2) First step onto carpet. Notice alignment of shoe and the template to identify where carpet samples should be collected and to ensure Tinopal is loaded onto shoe. 3) Normal step off carpet.

Figure 2-7. Shoe wash collection after a step. Each circle on shoe corresponds to a sample to be collected after the appropriate step. Only one location sampled per step. 10 mL of 0.01 N NaOH was poured into PVC pipe firmly held against shoe sole to prevent leaks. Solution mixed and pipetted back into sample vial. Procedure repeated with another 10 mL of fluid. 20 mL of fluid extracts > 99% of fluorescent particles off surface. All fluid combined for fluorometric analysis.

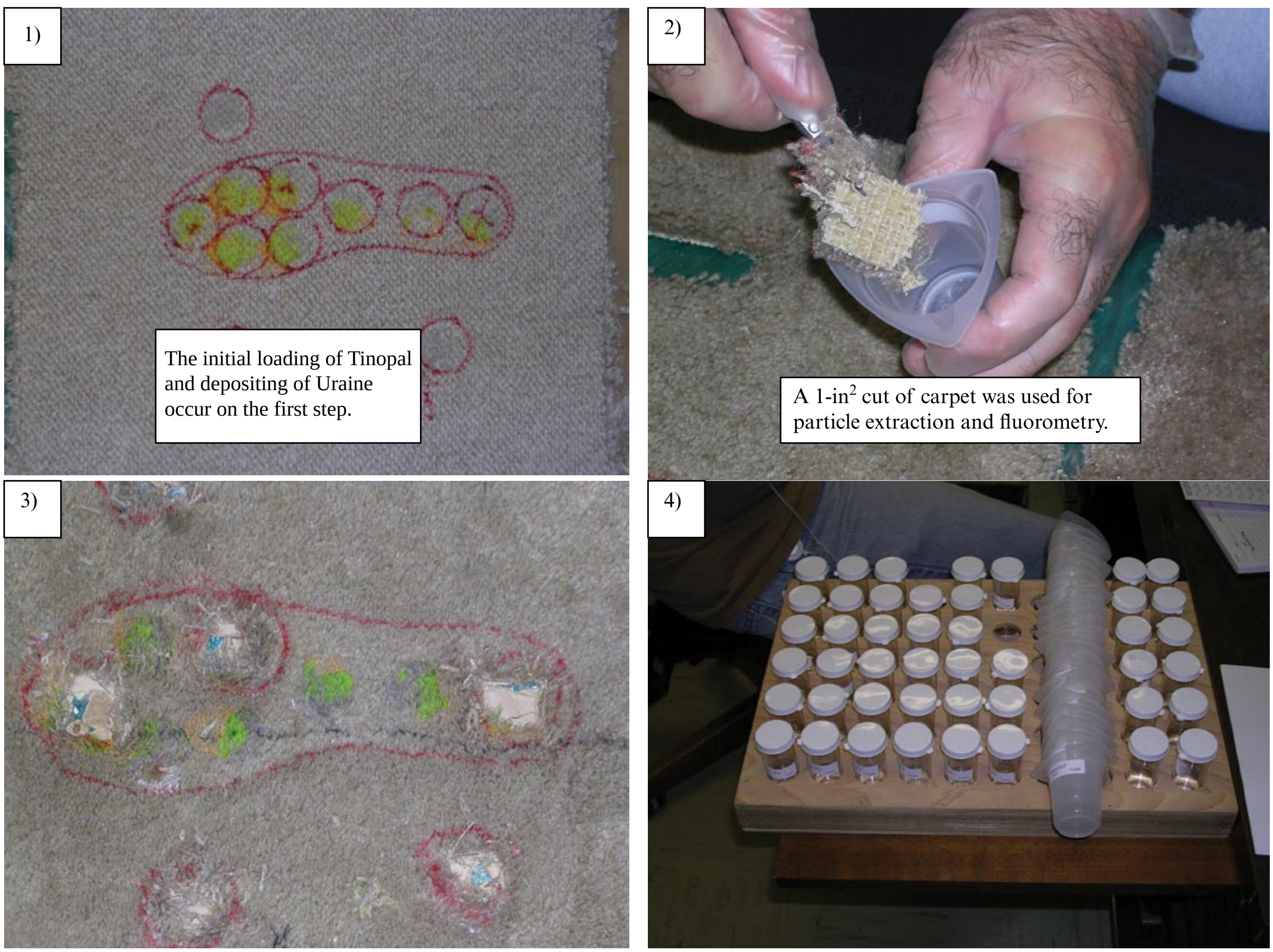


Figure 2-8. Carpet sample collection. 1) Uranine deposited on carpet following Step 1. 2) Removal of 1-in^2 carpet sample for sonic extraction then fluorometry. 3) Step 1 carpet after removal of all samples. 4) Number of wash, carpet, and QA/QC samples collected per experiment.

Figure 2-9. Fluorometer well-plate template identifying the type and quantity of samples analyzed per test.

	1	2	3	4	5	6	7	8	9	10	11	12
A	UCal 100/0	UCal 80/20	UCal 60/40	UCal 40/60	UCal 20/80	TCal 100/0	TCal 80/20	TCal 60/40	TCal 40/60	TCal 20/80	Blank NaOH	Blank NaOH
B	Load-U-W1	Load-U-W2	Load-U-W3	Load-T-Se1	Load-T-Se2	Load-T-Se3	Shoe-Bkg	Car-U-Bkg	Car-T-Bkg	CS-Bkg	Shoe-W6	Shoe-W8
C	Step1-W1	Step1-Se1	Step1-Se5	Step1-Se8	Step2-W3	Step2-Se3	Step2-Se5	Step2-Se8	Step3-W2	Step3-Se2	Step3-Se5	Step3-Se8
D	Step4-W4	Step4-Se4	Step4-Se5	Step4-Se8	Step5-W7	Step5-Se7	Step5-Se5	Step5-Se8	Step6-W5	Step6-Se7	Step6-Se5	Step6-Se8
E	Load-U-FP1	Load-U-FP2	Load-U-FP3	Load-U-FP4	Load-U-FP5	Load-U-FP7	Load-U-FP1	Load-U-FP2	Load-U-FP3	Load-U-FP4	Load-U-FP5	Load-U-FP7
F	Load-U-W1	Load-U-W2	Load-U-W3	Load-T-Se1	Load-T-Se2	Load-T-Se3	Shoe-Bkg	Car-U-Bkg	Car-T-Bkg	CS-Bkg	Shoe-W6	Shoe-W8
G	Step1-W1	Step1-Se1	Step1-Se5	Step1-Se8	Step2-W3	Step2-Se3	Step2-Se5	Step2-Se8	Step3-W2	Step3-Se2	Step3-Se5	Step3-Se8
H	Step4-W4	Step4-Se4	Step4-Se5	Step4-Se8	Step5-W7	Step5-Se7	Step5-Se5	Step5-Se8	Step6-W5	Step6-Se7	Step6-Se5	Step6-Se8

UCal 100/0	Calibration ratio: Uranine/NaOH
UCal 80/20	
UCal 60/40	
UCal 40/60	
UCal 20/80	
TCal 100/0	Calibration ratio: Tinopal/NaOH
TCal 80/20	
TCal 60/40	
TCal 40/60	
TCal 20/80	
Blank NaOH	Blank fluid

Load-U-W#	Uranine loading on cookie sheet
Load-T-Se1	Tinopal loading on carpet - Core sample
Load-T-Se1a	Tinopal loading on carpet - Core sample
Step#-W#	Wash sample from shoe sole
Load-U-FP1	Cookie sheet loading in foot print following step.
Step#-Se#	Core sample from area of step.
Shoe-Bkg#	Background shoe contamination. 2 per shoe
CS-Bkg	Cookie sheet background
Car-Bkg-Se#	Background carpet contamination by core sample
Shoe-W#	Shoe wash samples following all steps

Odd # tests
Even # tests

3.
Results and Discussion

3.1 Resuspension Experiments

3.1.1 General Findings

All experiments successfully provided data to achieve the research objectives, although several experiments lacked one or more types of data. General experimental conditions for all tests are presented in Table 3-1. Table 3-2 summarizes the data collected at each house. As described in Section 4.0, data quality objectives were achieved for all metrics except the MetOnes. Reduction of the MetOne data showed the expected vertical concentration gradients were not present. Therefore, MetOne data are not included in Table 3-2 and were not included in any statistical analyses. More information on the MetOne data quality is presented in Section 4.5.

All equipment was not available for testing at each house. Experiments at two houses were conducted before the Climets were received as Government Furnished Equipment. Study of PM translocation via resuspension was not hindered by the lack of the Climets for experiments at these two houses. Climet data from five houses were sufficient for achieving this study objective. The MetOnes were not available for use at three houses. The MetOnes' availability for this project was a matter of convenience. The instruments were purchased for another project and were available for the resuspension studies only when not needed for their primary project. However, the poor quality data obtained limited their value for achieving the study objectives.

Table 3-3 contains the statistical analysis of the data examined for influence of different carpet ages, fiber lengths, vacuuming, and sampling height on the resuspended PM concentration and size distribution, and the quantity of PM available for resuspension. The statistical models used were listed in Eqs. 2-1 thru 2-4. The quantity of mass resuspended followed the expected trends. The differences in carpet age, quality, and maintenance between houses definitely had an impact. Older homes with poor maintenance released more PM during the resuspension tests than homes with new, clean carpet (Table 3-3, Appendix A). Vacuuming the carpet also decreased the amount of mass resuspended by an average of 44%, independent of sampling height and mass available for resuspension. Only if the carpet was new and already extremely clean did vacuuming not have an influence. There was a significant difference in the PM mass available for resuspension (as measured by the microvacuum) between houses, with the houses with the newest, most frequently cleaned carpet having the lowest values. The PM mass resuspended also followed the expected gradient as a function of height from the floor. More details on the vertical gradient in resuspended PM concentrations are discussed in Section 3.1.3. Statistical analysis of the resuspended PM size distribution gave conflicting results. The mass median diameter of the resuspended PM was not statistically associated with the carpet age, carpet pile height, sample height, or whether or not the test area had been vacuumed (remediated). However, the count median diameter was statistically influenced by the carpet age.

Table 3-1. Experimental conditions recorded during each test. Pre-vacuum indicates test occurred prior to simple remediation (cleaning). Post-vacuum indicates the test area was remediated via vacuuming with a regular household unit.

House #	Test #	Conditions	% RH	Temp (°F)	# steps	Notes
1	1	Walk, pre-vacuum	54	73.2	350	
	2	Walk, post-vacuum	52	75.2	400	
	3	Walk, pre-vacuum	51	77.7	325	
	4	Walk, post-vacuum	52	78.0	und	Pedometer not reset before test.
2	1	Walk, pre-vacuum	56	72.1	250	No Climets or MetOnes. Climets not received as GFE. MetOnes being used on primary project.
	2	Walk, pre-vacuum	57	72.3	275	
	3	Walk, post-vacuum	55	72.4	240	
	4	Walk, post-vacuum	55	72.6	280	
3	1	Walk, pre-vacuum	59	74.5	300	18-in URG mass data invalid. Pump shut off early.
	2	Walk, post-vacuum	58	75.2	280	
	3	Walk, pre-vacuum	57	76.8	260	
	4	Walk, post-vacuum	57	77.3	340	
4	1	Walk, pre-vacuum	60	77.3	300	
	2	Walk, pre-vacuum	59	78.0	260	
	3	Walk, post-vacuum	60	79.5	260	
	4	Walk, post-vacuum	59	80.8	260	
5	1	Walk, pre-vacuum	45	68.1	275	No Climets or MetOnes. Climets not received as GFE. MetOnes being used on primary project.
	2	Walk, pre-vacuum	45	68.1	300	
	3	Walk, post-vacuum	46	68.3	290	
	4	Walk, post-vacuum	45	68.5	310	
6	1	Walk, pre-vacuum	41	73.3	320	No MetOnes. MetOnes being used on primary project.
	2	Walk, pre-vacuum	40	73.8	340	
	3	Walk, post-vacuum	41	74.1	350	
	4	Walk, post-vacuum	40	74.1	330	
7	1	Walk, pre-vacuum	46	74.4	280	
	2	Walk, pre-vacuum	47	75.9	295	
	3	Walk, post-vacuum	49	78.7	300	
	4	Walk, post-vacuum	49	79.4	240	

Table 3-2. Summary of data collected at each house. Microvacuum, URG, and APS data presented.

House 1

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm³)		URG Mass (mg)		APS Data CMD (µm)	APS Data MMD (µm)	APS Data GSD (µm)	APS Data Count Conc (#/cm³)	APS Data Mass Conc (µg/m³)	Notes
1	Walk, pre-vacuum	0.078	**18"**	3.0	**18"**	0.047	2.04	4.63	1.68	1.06	20.3	
		0.051	**36"**	1.0	**36"**	0.039						
2	Walk, post-vacuum	0.016	**18"**	2.4	**18"**	0.026	1.48	4.59	1.76	1.10	16.2	
		0.008	**36"**	1.2	**36"**	0.014						
3	Walk, pre-vacuum	0.018	**18"**	2.4	**18"**	0.003	1.91	4.13	1.66	1.12	15.4	18-in URG data invalid. Pump shut off early.
		0.026	**36"**	1.2	**36"**	0.036						
4	Walk, post-vacuum	0.007	**18"**	2.1	**18"**	0.027	1.78	4.66	1.80	0.99	13.5	
		0.008	**36"**	0.9	**36"**	0.020						

House 2

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm³)		URG Mass (mg)		APS Data CMD (µm)	APS Data MMD (µm)	APS Data GSD (µm)	APS Data Count Conc (#/cm³)	APS Data Mass Conc (µg/m³)	Notes
1	Walk, pre-vacuum	0.080	**18"**	None	**18"**	0.012	1.88	7.64	2.48	0.11	10.6	
		0.072	**36"**	None	**36"**	0.007						
2	Walk, post-vacuum	0.084	**18"**	None	**18"**	0.008	1.88	5.41	2.26	0.12	8.6	
		0.038	**36"**	None	**36"**	0.006						
3	Walk, pre-vacuum	0.007	**18"**	None	**18"**	0.001	1.84	4.95	2.42	0.02	6.1	
		0.009	**36"**	None	**36"**	<MDL						
4	Walk, post-vacuum	0.032	**18"**	None	**18"**	0.004	1.84	3.36	2.29	0.03	4.4	
		0.010	**36"**	None	**36"**	0.002						

House 3

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm³)		URG Mass (mg)		APS Data CMD (µm)	MMD (µm)	GSD (µm)	Count Conc (#/cm³)	Mass Conc (µg/m³)	Notes
1	Walk, pre-vacuum	0.107	**18"**	1.9	**18"**	0.024	2.17	5.20	1.71	0.58	14.5	
		0.068	**36"**	1.1	**36"**	0.009						
2	Walk, post-vacuum	0.006	**18"**	0.7	**18"**	0.038	1.94	4.29	1.65	0.50	8.1	
		0.006	**36"**	0.6	**36"**	0.025						
3	Walk, pre-vacuum	0.060	**18"**	1.6	**18"**	0.032	2.14	5.34	1.73	0.50	3.0	
		0.071	**36"**	0.8	**36"**	0.024						
4	Walk, post-vacuum	0.008	**18"**	0.6	**18"**	0.021	2.12	4.75	1.65	0.20	4.1	
		0.008	**36"**	0.4	**36"**	0.018						

House 4

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm³)		URG Mass (mg)		APS Data CMD (µm)	MMD (µm)	GSD (µm)	Count Conc (#/cm³)	Mass Conc (µg/m³)	Notes
1	Walk, pre-vacuum	0.085	**18"**	1.2	**18"**	0.023	2.22	5.67	1.55	0.60	3.6	
		0.039	**36"**	0.5	**36"**	0.010						
2	Walk, post-vacuum	0.097	**18"**	0.5	**18"**	0.016	2.26	4.99	1.67	0.40	6.1	
		0.046	**36"**	0.2	**36"**	0.013						
3	Walk, pre-vacuum	0.008	**18"**	0.7	**18"**	0.043	1.89	4.46	1.73	0.70	6.0	
		0.017	**36"**	0.4	**36"**	0.015						
4	Walk, post-vacuum	0.017	**18"**	0.3	**18"**	0.011	1.81	4.33	1.71	0.20	1.7	
		0.006	**36"**	0.1	**36"**	0.015						

House 5

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm^3)		URG Mass (mg)		APS Data					Notes
							CMD (µm)	MMD (µm)	GSD (µm)	Count Conc (#/cm^3)	Mass Conc (µg/m^3)	
1	Walk, pre-vacuum	0.330	**18"**	None	**18"**	0.088	1.41	5.61	2.08	1.50	19.6	
		0.194	**36"**	None	**36"**	0.068						
2	Walk, post-vacuum	0.277	**18"**	None	**18"**	0.073	1.40	5.63	2.13	1.50	21.1	
		0.201	**36"**	None	**36"**	0.035						
3	Walk, pre-vacuum	0.011	**18"**	None	**18"**	0.032	1.90	5.23	1.77	1.90	15.3	
		0.020	**36"**	None	**36"**	0.012						
4	Walk, post-vacuum	0.007	**18"**	None	**18"**	0.009	1.95	5.10	1.71	1.10	14.7	
		0.015	**36"**	None	**36"**	0.005						

House 6

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm^3)		URG Mass (mg)		APS Data					Notes
							CMD (µm)	MMD (µm)	GSD (µm)	Count Conc (#/cm^3)	Mass Conc (µg/m^3)	
1	Walk, pre-vacuum	0.692	**18"**	None	**18"**	0.171	2.38	6.08	1.76	6.20	68.9	
		0.557	**36"**	None	**36"**	0.134						
2	Walk, post-vacuum	0.584	**18"**	None	**18"**	0.163	2.25	5.98	1.78	4.50	47.8	
		0.772	**36"**	None	**36"**	0.119						
3	Walk, pre-vacuum	0.397	**18"**	None	**18"**	0.139	2.29	5.35	1.80	4.10	38.5	
		0.178	**36"**	None	**36"**	0.040						
4	Walk, post-vacuum	0.260	**18"**	None	**18"**	0.096	2.21	4.94	1.83	5.40	27.0	
		0.288	**36"**	None	**36"**	0.081						

House 7

Test #	Conditions	Micro-vacuum Mass (mg)	Climet Conc (#/cm³)		URG Mass (mg)		APS Data CMD (µm)	MMD (µm)	GSD (µm)	Count Conc (#/cm³)	Mass Conc (µg/m³)	Notes
1	Walk, pre-vacuum	0.259	**18"**	5.4	**18"**	0.029	2.238	5.154	1.696	1.100	28.800	
		0.291	**36"**	1.1	**36"**	0.010						
2	Walk, post-vacuum	0.194	**18"**	5.4	**18"**	0.043	2.234	4.802	1.658	1.000	23.100	
		0.163	**36"**	4.3	**36"**	0.022						
3	Walk, pre-vacuum	0.014	**18"**	1.0	**18"**	0.006	2.243	5.844	1.734	0.100	2.600	
		0.012	**36"**	0.7	**36"**	0.006						
4	Walk, post-vacuum	0.042	**18"**	1.8	**18"**	0.011	2.165	4.397	1.622	0.600	10.900	
		0.022	**36"**	0.4	**36"**	0.006						

Table 3-3. P-values for resuspension data collected at the seven residences. The mass resuspended as measured by the URGs, the microvacuum mass available, and resuspended PM median diameter (mass and count) measured by the APS are the dependent variables. Statistically significant parameters ($\alpha = 0.05$) are shown in bold-italics.

Independent Parameters	Dependent Variables: Mass Resuspended per Step	Mass Available	Mass Median Diameter	Count Median Diameter
Age	***< 0.0001***	***< 0.0001***	0.1183	***0.0069***
Vacuum	***0.0002***	< 0.0001	0.6501	0.7285
Height	***0.0061***	na	na	na
Length	0.087	0.234	0.9785	0.8624
Age * Vacuum	***< 0.0001***	0.1238	0.6147	0.8839
Age * Height	***0.0167***	na	na	na
Age * Length	***0.006***	***< 0.0001***	0.9044	***0.0009***
Vacuum * Height	0.9966	na	na	na
Length * Vacuum	0.3304	0.0878	0.9499	0.8627
Length * Height	0.7077	na	na	na

3.1.2 Resuspension Emission Factors

Statistical analysis of the calculated emission factors using Eq. 2-5 identified carpet age, vacuuming, and the carpet age–fiber length interaction as significant variables (Table 3-4). Previous field and laboratory tests showed emission factors typically were between 0.01 and 0.1 but could be as high as 0.4 or as low as 0.001 under the proper conditions (Rodes and Thornburg, 2004; Thornburg and Rodes, 2004a; Thornburg and Rodes, 2004b). These experiments showed that emission factors from a wide variety of houses varied between 0.001 and 0.064 (Table 3-5), and were within the previously identified typical range.

Table 3-4. P-values for calculated emission factors. Statistically significant parameters (α = 0.05) are shown in bold-italics.

Dependent Variable	Emission Factor (p-value)
Age	***0.0059***
Vacuum	< ***0.0001***
Height	0.4972
Length	0.9770
Age * Vacuum	0.3388
Age * Height	0.6959
Age * Length	0.0047
Vacuum * Height	0.8413
Length * Vacuum	0.7934
Length * Height	0.9999

Table 3-5. Average emission factors per test at each house.

House	Pre-Vacuumed		Post-Vacuumed	
	EmFa	Std Dev.	EmFa	Std Dev.
1	0.0048	0.0012	0.0124	0.0064
	0.0117	0.0027	0.0210	0.0035
2	0.0011	0.0005	0.0081	0.0055
	0.0009	0.0010	0.0121	0.0061
3	0.0014	0.0008	0.0369	0.0092
	0.0030	0.0006	0.0170	0.0022
4	0.0021	0.0014	0.0189	0.0141
	0.0016	0.0007	0.0097	0.0055
5	0.0082	0.0059	0.0222	0.0155
	0.0033	0.0005	0.0198	0.0133
6	0.0025	0.0020	0.0177	0.0090
	0.0045	0.0008	0.0110	0.0068
7	0.0198	0.0103	0.0640	0.0344
	0.0237	0.0105	0.0471	0.0205
Average	**0.0063**		**0.0227**	
Std Dev	**0.0072**		**0.0160**	

Emission factors were expected to vary between houses, as indicated by the statistical significance of the carpet age and the carpet age–pile height interaction term. We hypothesize that older carpet had higher emission factors because of the weaker adhesion forces between the dust and carpet fibers. Adhesion forces present on new carpet should not vary as function of fiber length. Hence, fiber length was not significant individually. The interaction between age and length was required to influence the emission factor. We hypothesize that after carpet loses its electrostatic adhesive force (after an unknown period of time), emission factors will increase with increasing fiber length, as shown by Rodes (1998). Future research should be conducted to confirm these two hypotheses.

Vacuuming also influenced the emission factors. Emission factors post-vacuuming were about 4x greater than those pre-vacuuming (Table 3-5). Emission factors pre-vacuuming were lower even though more mass is resuspended during the pre-vacuum experiments, regardless of carpet age or fiber length. The change in emission factors was driven by the mass available on carpet, which was included in the denominator of the emission factor equation. Across all houses, vacuuming decreased the mass available for resuspension by an order of magnitude, but the total mass resuspended decreased by a factor of 2.5, thereby resulting in a net increase in the emission factors.

3.1.3 Resuspended PM Vertical Gradients

Confirmation of the vertical gradient in resuspended PM concentration was referred to in Section 3.1.1. Table 3-6 provides additional evidence. For all experiments except one, the resuspended PM mass at 18 in was always greater than the mass measured at 36 in. The probability that the average ratio across all experiments was greater than unity was statistically significant at $\alpha = 0.05$.

Table 3-6. Average ratio of resuspended mass at 18 in versus 36 in separated into pre-vacuumed and post-vacuumed conditions.

House	Mass 18 in : Mass 36 in Ratios	
	Pre-Vacuumed	Post-Vacuumed
1	1.16	1.84
	..[a]	1.33
2	1.71	..[b]
	1.33	2.00
3	2.76	1.55
	1.33	1.25
4	2.42	2.93
	1.24	1.39
5	1.29	2.67
	2.09	1.80
6	1.28	3.48
	1.37	1.19
7	3.09	0.87
	1.95	1.93
Mean	**1.77**	**1.86**
Std Dev	**0.64**	**0.76**
Probability (p-value) that the Ratio is > 1	**< 0.0001**	**< 0.0001**

[a]No ratio because 18-in mass invalid. Pump shut off during sample collection.

[b]No ratio because 36-in mass was below gravimetric analysis minimum detection limit.

3.1.4 PM Translocation

PM translocation within a house was measured with the Climets. Climet concentration data were not normally distributed. A "log" transformation of the Climet data satisfied the normality parametric tests. The results from the spatial-temporal autoregressive analysis of the transformed database are shown in Table 3-7. Location stratified the Climet locations into two categories: within 1 ft of the resuspension area boundary or greater than 1 ft from the boundary. The spatial-temporal analysis of the dependent variables "house," "vacuum," and "height" independently confirms their statistical significance on the resuspended PM concentration measured by the Climets. The analysis also shows that resuspended PM concentrations varied spatially and temporally.

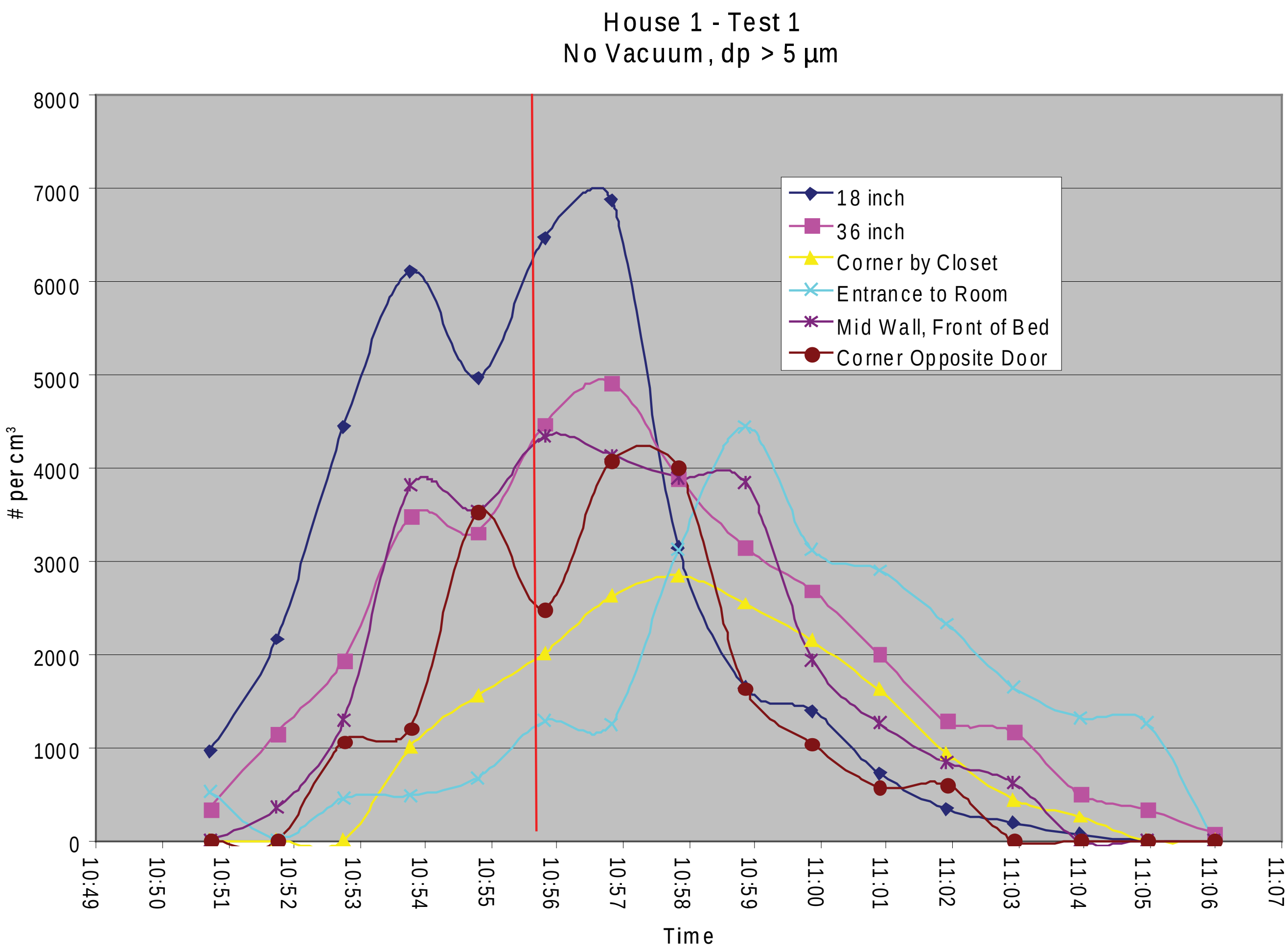
Table 3-7. P-values for spatial-temporal differences in Climet concentrations. Statistically significant parameters ($\alpha = 0.05$) are shown in bold-italics.

Dependent Variable	Emission Factor (p-value)
House	< ***0.0001***
Vacuum	< ***0.0001***
Height	***0.0225***
Location	***0.0032***
House * Location	0.1181
Vacuum * Location	0.2135

Time-series plots of resuspended PM concentrations were prepared (see Appendix C). An example plot for discussion purposes is shown in Figure 3-1. These plots do show the expected trend that Climets farther from the source experienced a delay before detecting the PM cloud and the total particle concentration measured was lower. Figure 3-1 indicates the 18-in Climet at the resuspension area boundary responds first, followed by the 36-in Climet at the boundary and the Climet at the mid-wall (the next closest unit). The resuspended PM cloud then moved counterclockwise through the room until reaching the door.

A more complicated spatial-temporal analysis is required to develop statistical regression contour plots showing the spatial-temporal evolution of the resuspended PM concentration within a test house. Such an analysis was not within the scope of this project, but the data are available for such an endeavor. However, simple ratios estimated from the graphs included in Appendix C suggest 10% to 50% of the resuspended PM migrates the approximate 8 ft to the entry to adjacent rooms. These data also could validate more complicated, three-dimensional indoor dispersion models.

Figure 3 1. Climet data collected at House 1, Test 1, showing the temporal and spatial dispersion of the resuspended PM larger than 5 µm. Red vertical line demarcates when resuspension activity stopped.



3.2 Household Tracking Experiments

Particulate matter data collected at each house, each week, and each segment are presented in Appendix D.

Particulate matter mass tracked into the four houses was not normally distributed due to the small sample of test houses. The "log" transformation provided the appropriate correction, and parametric tests satisfied normal distribution assumptions. Two sets of data were considered. All data were used in one analysis for a total of 160 data points. The second set removed the data from House 1, Week 1, for a total of 150 data points. There was heavy rainfall the day before Week 1 data collection and thus heavy soiling of the carpet.

The statistical output from the analysis of both datasets is shown in Table 3-8. The full dataset and the reduced dataset indicated only "week" and "house" variables were statistically significant. This finding means there was a temporal component to the mass loading and the mass loading was dependent on the number of people living in the residence.

Table 3-8. Results from the spatial-temporal autoregressive analysis of the full and reduced datasets. Statistically significant variables (95% confidence) listed in italics.

	All Data		Rain Event Excluded	
Variable	**Degrees of Freedom**	**p-value**	**Degrees of Freedom**	**p-value**
Segment	3	0.5730	3	0.5513
Week	4	***< 0.0001***	4	***< 0.0001***
House	1	***< 0.0001***	1	***< 0.0001***
Segment x Week	12	0.9999	12	0.9981

Surprisingly, the expected spatial gradient between carpet segments was not observed due to movement patterns within the home and the sample collection frequency. Residents walked across the carpet in more than one direction. In three homes, the residents had to cross the carpet horizontally to get between rooms. This movement evenly distributed the mass laterally within a segment so that there was no statistical difference in the mass loading collected in different boxes, which is a desired result. Residents also were instructed to enter and exit the home by walking across the carpet. The longitudinal movement in two directions evenly distributed the particulate matter vertically. As a result of these factors, weekly sample collection was too infrequent to discern the spatial gradient expected. Future tests should limit longitudinal movement to one direction, preferably entry into the residence. In addition, more frequent sample collection is required.

The spatial-temporal statistical analysis was conducted again considering only the significant variable to identify statistically significant contrasts in mass loading on the carpet between weeks. The Tukey-Kramer least square means test identified differences between weeks. The full dataset produced contrasts that were significant for the differences between Week 0 and the remaining four weeks (Table 3-9). The only other significant contrasts were between Weeks 1–3 and Weeks 1–4. The reduced dataset produced contrasts that were significant for the differences between Week 0 and the other weeks. In addition, there was at least a 95% confidence of difference between Week 1–3, Week 1–4, Week 2–3, and Week 2–4. The reduced datasets better show the temporal differences without the bias of House 1, which was affected by the rainstorm.

These results help determine the sample collection frequency that should be implemented in future tests. The rapid soiling of the carpet during Week 1 indicates two to three sample sets should be collected during the first week.

Table 3-9. Results from the Tukey-Kramer tests identifying differences in mass loading per week. Statistically significant differences (95% confidence) listed in italics.

Residential tracking test comparison between weeks. Rain event (H1, Week 2) included.

	Week 0	Week 1	Week 2	Week 3	Week 4
Week 0		*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Week 1			0.4415	0.0036	0.0004
Week 2				0.9957	0.9921
Week 3					1.000
Week 4					

Residential tracking test comparison between weeks. Rain event (H1, Week 2) removed.

	Week 0	Week 1	Week 2	Week 3	Week 4
Week 0		*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Week 1			0.0809	*0.0451*	*0.0360*
Week 2				*0.0003*	*< 0.0001*
Week 3					0.4769
Week 4					

Although a PM tracking rate per carpet segment could not be calculated, rates for the entire carpet were calculated for each house (Table 3-10). The average PM gain in the carpet per week varied between 2.7 and 24.1 µg per in^2-week. The mass gain (or loss) per week probably is dependent on the number of traverses across the carpet by the occupants. Although not recorded directly, the number of occupants (Appendix B) is a possible surrogate variable that is directly related to the loading via the "house" variable (Table 3-8). Recording the number and direction of traverses would increase the sensitivity of the tracking results and provide more insight into the tracking mechanism.

Table 3-10. PM tracking rate per week at each house sampled. Weeks 1–2 were combined into one value per house.

House		Week 1–2 Avg	Week 3	Week 4	Avg ± Std Dev
T1	Mass Change (µg/in2- week)	8.04	8.20	-6.11	3.38 ± 8.22
	Cumulative Mass (µg/in^2)	8.04	16.24	10.13	
T2	Mass Change (µg/in^2- week)	25.03	39.95	7.24	24.07 ± 16.38
	Cumulative Mass (µg/in^2)	25.03	64.98	72.21	
T3	Mass Change (µg/in^2- week)	12.98	2.19	-1.50	4.56 ± 7.53
	Cumulative Mass (µg/in^2)	12.98	15.17	13.67	
T4	Mass Change (µg/in^2- week)	4.65	1.39	1.93	2.66 ± 1.75
	Cumulative Mass (µg/in^2)	4.65	6.04	7.97	

3.3 Laboratory Tracking Experiments

Laboratory tracking experiments examined the amount of particulate matter transferred from the shoe to carpet and vice versa. The fluorescent particles Tinopal and Uranine were selected for these experiments. General results from these experiments are presented in Tables 3-11 and 3-12.

Table 3-11. Uranine concentrations available for collection on the shoe, loaded onto the shoe, and transferred to the carpet during each step.

Test #	Available (µg/in²)	Shoe Loading (µg/in²)	Mass Transferred From Shoe to Carpet (µg/in²)					
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
1	2,973 ± 629	863	116 ± 56	34 ± 15	47 ± 16	36 ± 16	23 ± 10	38 ± 15
2	853 ± 110	726	557 ± 173	16 ± 9	12 ± 13	8 ± 1	3 ± 1	3 ± 3
3	462 ± 134	308	240 ± 178	2 ± 2	0.04 ± 0	0.04 ± 0	0.04 ± 0	0.7 ± 1
4	3,465 ± 233	457	158 ± 110	39 ± 17	47 ± 6	13 ± 10	13 ± 0.6	14 ± 4
5	15,983 ± 868	32,533	21,395 ± 3,157	385 ± 84	129 ± 23	41 ± 10	50 ± 33	93 ± 58
6	7,962 ± 4,197	7,491	7813 ± 8,118	205 ± 149	37 ± 27	25 ± 10	9 ± 1	8 ± 5
7	14,269 ± 2,944	5,873	4,274 ± 1,313	593 ± 267	483 ± 376	220 ± 83	152 ± 45	127 ± 56
8	14,731 ± 1,588	7,829	6,233 ± 737	582 ± 290	458 ± 355	164 ± 66	106 ± 64	106 ± 37

Table 3-12. Tinopal concentrations available for collection on the shoe, loaded onto the shoe, and transferred to the carpet during each step. Mass transferred from carpet to shoe during Step 1.

Test #	Available (µg/in²)	Transferred from Carpet to Shoe (µg/in²)	Mass Transferred From Shoe to Carpet (µg/in²)				
			Step 2	Step 3	Step 4	Step 5	Step 6
1	7,039 ± 790	42	0.0	0.0	0.0	0.0	0.0
2	11,234 ± 2,947	59	84 ± 20	130 ± 32	298 ± 176	42 ± 36	38 ± 5
3	5,227 ± 1,302	155	0.0	0.0	0.0	0.0	0.0
4	13,333 ± 4,145	166	12 ± 22	13 ± 22	0.0	0.0	10 ± 18
5	110,951 ± 2,362	1,226	285 ± 155	100 ± 49	48 ± 10	49 ± 15	92 ± 78
6	49,581 ± 23,268	699	224 ± 29	68 ± 15	152 ± 53	133 ± 27	78 ± 11
7	64,126 ± 3,192	820	47 ± 5	74 ± 36	48 ± 3	48 ± 14	39 ± 7
8	59,197 ± 21,604	0	0.0	0.0	0.0	0.0	0.0

3.3.1 Uranine Results

The variability in the mass loaded onto the shoes required normalization to allow comparison of the data between tests. The mass transferred from the shoe to the carpet (Steps 1–6) was normalized by the mass loading on the shoe (Step 0) to yield the mass fraction deposited per step. This conversion also allowed easy calculation of the fraction remaining on the shoe and cumulative fraction deposited on the carpet. The fraction deposited per step was not normally distributed. A "log" transformation of the data satisfied the normality parametric tests. The results from the spatial-temporal autoregressive analysis of the transformed database are shown in Table 3-13. The Tukey-Kramer least square means tests identified that the Step 1 mass fraction transferred was statistically significant different from the remaining steps at the 95% confidence level. The mass fractions transferred during Steps 2–6 were not statistically different.

Table 3-13. Results from the spatial-temporal autoregressive analysis of the Uranine data. Statistically significant variables (95% confidence) listed in italics.

Variable	Degrees of Freedom	p-value
Carpet Style	1	0.1598
Carpet Age	1	0.1311
Load	1	0.0827
Step #	5	*< 0.0001*
Load * Step	5	0.9685

Mass load onto the shoe was almost statistically significant at the 95% confidence level. The similarity in the fraction deposited during Steps 2–6 independent of mass loading was the primary cause. Tighter control over the mass loaded onto the shoe also may increase the probability of the parameter becoming statistically significant.

The relationship between step number and mass fraction remaining on the shoe load and the cumulative fraction transferred for the low mass loading tests is shown in Figure 3-2. A similar graph for high mass loading tests is shown in Figure 3-3. The figures confirm between 40% (low loading) and 80% (high loading) of the mass is transferred to the carpet on Step 1. Regardless of mass loading, only 10% of the mass on the shoe is transferred during subsequent steps. The mean (± std dev) mass fraction transferred per step for Steps 2–5 was 0.03 (± 0.02).

Figure 3-2. Transfer of Uranine from shoe to carpet per step during low loading tests. Mass fractions are averages of four tests. Fraction remaining on shoe after each step and cumulative fraction transferred per step are shown.

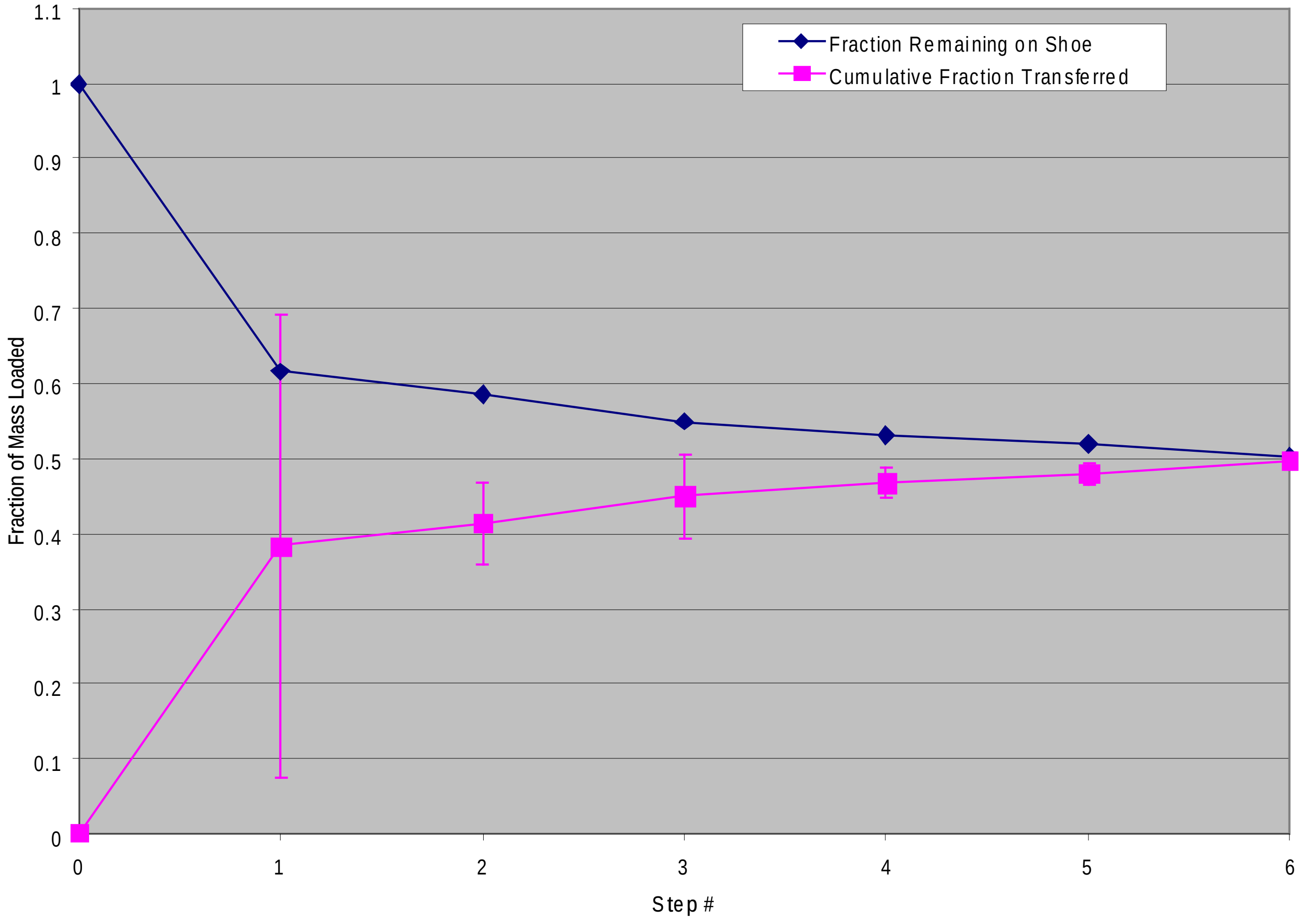
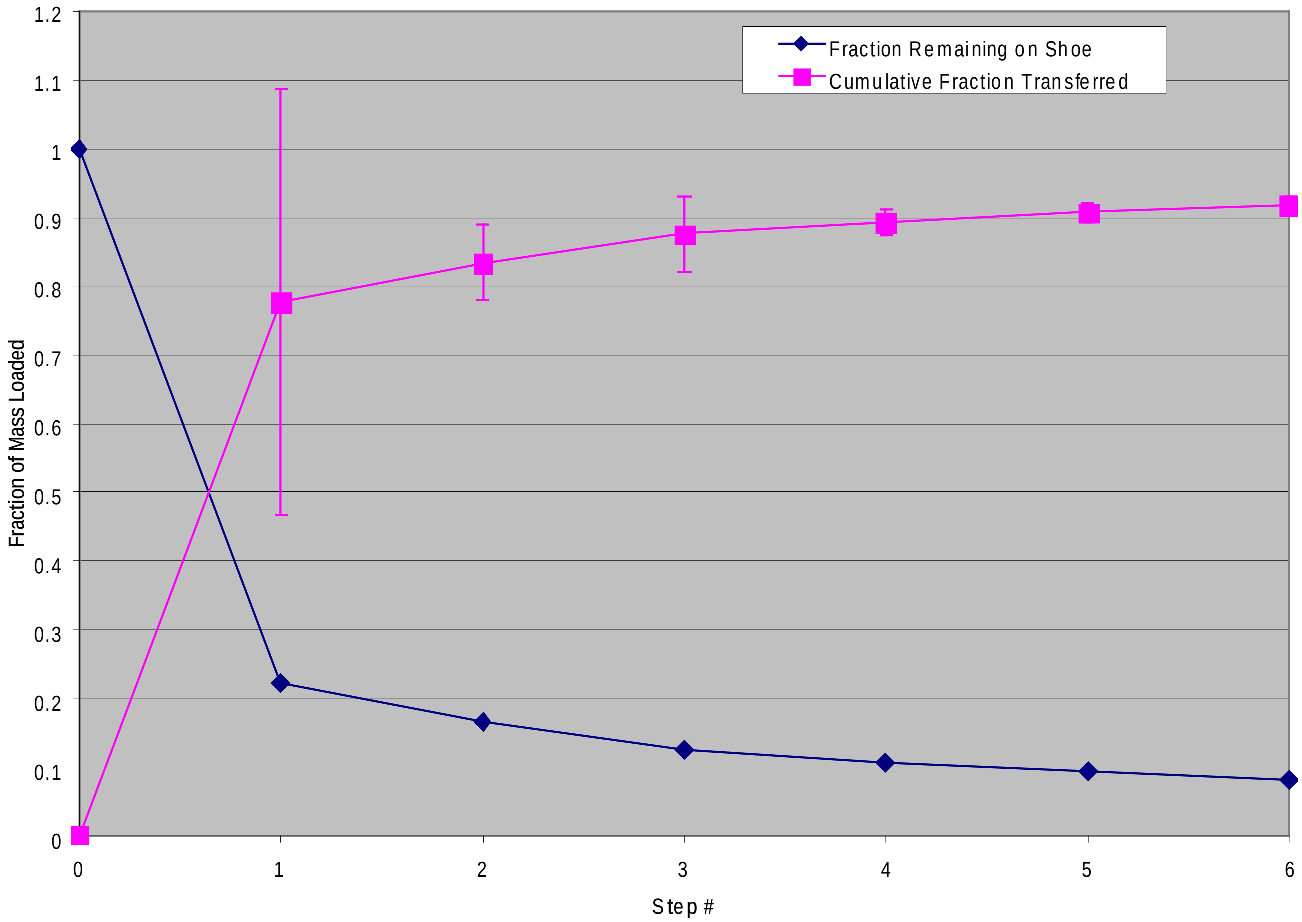


Figure 3-3. Transfer of Uranine from shoe to carpet per step during high loading tests. Mass fractions are averages of four tests. Fraction remaining on shoe after each step and cumulative fraction transferred per step are shown.



3.3.2 Tinopal Results

Tinopal loaded onto carpet determined the amount transferred from the carpet to the shoe during the first step. Subsequent steps determined the amount transferred from the shoe back into the carpet. Tinopal shoe-to-carpet transfer data, when combined with the Uranine data, would double the amount of data and increase the confidence in the statistical analysis.

The quantity of Tinopal loaded onto the carpet, the mass transferred to the shoe during the first step, and the fraction transferred data are presented in Table 3-14. The quantity of Tinopal from the carpet to the shoe during the first step was 1.1%. For unknown reasons, the quantity of Tinopal transferred to the shoe was a very small percentage of the total loaded onto the carpet. Because of the small quantity on the shoe, the shoe-to-carpet transfer data on subsequent steps for Tests 1, 2, 3, 4, and 8 did not follow the trend expected from the Uranine results. Thus, the results were inconclusive and additional statistical analysis was not possible.

Table 3-14. Total mass and mass fraction of Tinopal loaded onto carpet that was transferred to the shoe during Step 1.

Test #	Mass on Carpet (μg/in^2)	Mass on Shoe (μg/in^2)	% Transferred
1	7,039 ± 790	42.1	0.6
2	11,234 ± 2,947	58.6	0.5
3	5,227 ± 1,302	154.9	2.8
4	13,333 ± 4,145	166.4	1.2
5	110,951 ± 2,362	1,226.1	1.1
6	49,581 ± 23,268	699.1	1.4
7	64,126 ± 3,192	819.6	1.3
8	59,197 ± 21,604	0.0	0.0
		Mean Transferred	**1.1 ± 0.8**

4.0
Quality Assurance

Quality assurance and quality control measures for the project were outlined in the QAPP entitled "Resuspension of Particulate Matter on Flooring - Quality Assurance Project Plan for Basic Research Projects," EPA Order No. 4C-R179-NALX, EPA/NHSRC under Contract No. QT-OH-04-00315 RTI Project No. 09188). Tables 4-1 and 4-2 summarize the QA/QC measures for the project. The QA/QC results for each metric are presented below.

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

Metric	Precision	Accuracy	Completeness	IDL	MDL	MQL
Mass	± 20%	± 5%	± 95%	2 $\mu g/m^3$	1 $\mu g/m^3$	3 $\mu g/m^3$
APS	± 5%	a± 15%	± 95%	0.5 μm	NA	NA
Climet	± 10%	a± 20%	± 95%	0.5 μm	NA	NA
Fluorometry	± 5%	± 10	± 95%	0.3 μg	0.1 μg	0.3 μg
T	± 5%	± 5%	± 95%	1°C	NA	NA
RH	± 5%	± 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
APS	Precision: Collocated instruments once/week Zero: HEPA filter installed on inlet daily Background: Collected prior to each test
Climet	Precision: Collocated instruments once/week Zero: HEPA filter installed on inlet daily Background: Collected prior to each test
Mass	Precision: Collocated instruments once/week Field Blanks: 5% of filters collected Laboratory Blanks: 5% of filters collected Background: Collected prior to each test
Fluorometer	Precision: < 5% error compared against known standard Zero: Measured daily with clean, deionized water Background: At least 1 sample per experiment per surface

4.1 Gravimetric Mass

Gravimetric mass measurements determined the mass available for resuspension via the microvacuum and the mass resuspended via the URG samplers. The microvacuum and the URG samplers collected the mass on a filter that was analyzed gravimetrically.

The number of microvacuum and URG samples attempted and successfully collected is outlined in Table 4-3. The cumulative completeness percentage (99.2%) exceeded the data quality objective.

Precision and accuracy of the gravimetric method were other quality assurance criteria (Table 4-4). Precision in the gravimetric analysis was assessed by collecting collocated URG samples once per week. Precision was calculated as the % relative standard deviation (%RSD). Accuracy was assessed every gravimetric analysis 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.

Table 4-3. Metric sample completeness statistics.

Metric	URG Sampler	Microvacuum	Cumulative
Valid Samples	55	205	260
Planned Samples	56	206	262
% Completed	98.2	99.5	99.2

Table 4-4. Gravimetric analysis precision and accuracy statistics.

Precision		Accuracy	
Number Sample Pairs	8	Number Measurements	31
Mean %RSD	10.9%	Mean	99.6 μg
		% Difference	0.4%

A series of filter blanks assessed quality control in the field and laboratory (Table 4-5). The mean masses collected on the filter blanks for each metric were used as correction factors for the experimental samples. Field blanks typically had much higher variation in the mass gain/loss due to processing of the samples in the field where many potential sources of contamination existed. The percentage of blanks collected (10.8%) exceeded the planned percentage (10%).

Table 4-5. Filter blank statistics.

URG Field Blanks		Microvacuum Field Blanks		Laboratory Blanks	
Number	Mass (μg)	Number	Mass (μg)	Number	Mass (μg)
4	-0.1 ± 7.1	15	1.3 ± 7.0	9	0.1 ± 0.6

4.2 Climet Optical Particle Counters

Climet units measured resuspended particle number concentration throughout the test area. The QA/QC results for this metric are summarized below.

The number of Climet samples attempted and successfully collected is outlined in Table 4-6. The cumulative completeness percentage (95%) met the data quality objective. The primary reason for invalid samples was forgetting to start the instrument data collection.

Table 4-6. Climet sample completeness statistics.

Metric	Background	Test	Cumulative
Valid Samples	112	116	228
Planned Samples	120	120	240
% Completed	93.3	96.7	95.0

Precision (Table 4-7) and accuracy of the Climet measurements were other quality assurance criteria. Precision was assessed by collecting collocated Climet samples once per week, corresponding to the weeks a series of resuspension tests were conducted in a house. The correction factor was applied to all data because of known differences between units. Precision was calculated as the %RSD against the reference instrument (Climet #958304). Precision data quality objectives were met for all Climets. Accuracy was supposed to be determined via the manufacturer's calibration certificate for each instrument. However, the calibration certificates for these instruments had expired. The manufacturer also no longer supports these instruments and calibration would have exceeded the available resources for this project (~$1,000 per instrument for calibration). Instead, the Climets were collocated with the APS (reference), and Pearson correlation coefficients were calculated (Table 4-8). The APS was selected as a reference because it has a current calibration certificate. A correlation coefficient >0.8 satisfied the data quality objective.

The quality control assessment in the field was to make sure the Climets measured a concentration of 0 particles per cm^3 in the field. A HEPA filter was installed on the inlet to each unit once per house, for a total of 8 samples. All Climets always measured 0 particles per cm^3 when the HEPA filter was installed.

Table 4-7. Climet particle number concentration precision statistics. Climet #958304 was the reference instrument for application of correction factors.

Climet S/N	Number Comparisons	Correction Factor > 0.5 µm	Correction Factor > 5 µm	Mean %RSD (> 0.5 µm)	Mean %RSD (> 5 µm)
923954	8	1.3	1.4	7.3%	8.5%
958301	8	1.9	1.9	10.2%	10.8%
958302	8	1.4	2.3	7.7%	10.1%
958303	8	0.8	2.0	5.1%	9.7%
958304	8	1	1	Reference	Reference
958305	8	1.2	1.3	8.3%	9.5%

Table 4-8. Climet particle number concentration accuracy statistics. Accuracy determined by Pearson correlation coefficients between the APS and the Climet unit selected.

Climet S/N	Number Data Points	Pearson Correlation Coefficient > 0.5 µm	Pearson Correlation Coefficient > 5 µm
923954	120	0.88	0.86
958301	120	0.94	0.92
958302	120	0.85	0.82
958303	120	0.91	0.87
958304	120	0.96	0.92
958305	120	0.90	0.86

4.3 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 4-9. The cumulative completeness percentage (100%) exceeded the data quality objective.

Table 4-9. Aerodynamic Particle Sizer sample completeness statistics.

Metric	Background	Test	Cumulative
Valid Samples	28	28	56
Planned Samples	28	28	56
% Completed	100%	100%	100%

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 certificate was still valid. The APS was calibrated on December 15, 2004. The APS also agreed with the particle number concentrations measured by the Climet optical particle counters.

The quality control assessment in the field was to make sure the APS measured a concentration of 0 particles per cm3 in the field. A HEPA filter was installed on the inlet to the APS once per house, for a total of 8 samples. The APS always measured 0 particles per cm3 when the HEPA filter was installed.

4.4 Temperature and 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. The QA/QC results for this metric are summarized in Table 4-10. All data quality objectives were achieved.

Table 4-10. QA/QC results for the HOBO H8 temperature and relative humidity data.

Completeness		Accuracy	
	#		%
Valid Samples	28	Temperature	98.8
Planned Samples	28	RH	97.1
% Completed	100%		

4.5 MetOnes

All MetOne data were invalid and not used in any statistical analysis. MetOne optical particle counters did not exhibit the vertical concentration gradient demonstrated by the gravimetric and Climet optical particle counter data (Table 4-11). The corrections for differences in counting efficiency were included in the MetOne data analysis, although the correction factors were small (Table 4-12). The inability of the MetOnes to reach an equilibrium concentration during the six-second sampling interval combined with the rapidly changing resuspended PM concentration increased the signal-to-noise ratio in the data. Visual observation of the display screen during operation showed the measured concentration fluctuated greatly during sample collection. As a result, larger concentration differences between the two heights were required for the MetOnes to detect a height-dependent concentration gradient.

Table 4-11. MetOne concentrations at 18 and 36 inches. All data corrected for background and differences between units.

House/Test		#/cm^3	
		18 inches	36 inches
House 1	Test 1	1.77	1.48
	Test 2	1.34	1.37
	Test 3	1.99	1.50
	Test 4	no data	0.15
House 3	Test 1	0.36	0.30
	Test 2	0.18	0.19
	Test 3	0.25	0.22
	Test 4	0.16	0.21
House 4	Test 1	0.54	0.49
	Test 2	0.27	0.27
	Test 3	0.42	0.64
	Test 4	0.21	0.19
House 7	Test 1	0.34	0.72
	Test 2	0.32	1.18
	Test 3	0.03	0.18
	Test 4	-0.16	0.27

Table 4-12. MetOne concentration correction factors.

	Unit 1 : Unit 2	
	1-5 μm	> 5 μm
House 1	1.03	0.77
House 3	1.01	0.80
House 4	1.18	1.23
House 7	0.83	1.20
Means	1.01 ± 0.14	1.00 ± 0.25

4.6 Fluorometry

Fluorometer measurements quantified the mass of fluorescent material in each sample collected. A total of 768 measurements were collected, 384 of each type (Table 4-13). More than 99% of the samples collected were valid, although 8% of the Tinopal fluorescence readings were below the instrument detection limit when some fluorescence was expected. Invalid samples were caused by accidental spilling of the wash fluid.

Table 4-13. Fluorometry sample completeness statistics.

Metric	Uranine	Tinopal	Cumulative
Valid Samples	381	380	761
Planned Samples	384	384	768
% Completed	99.2	99.0	99.1

The precision in the fluorometry measurements was assessed by collecting duplicate readings for each sample. The nondestructive nature of the analysis allowed repeat fluorescence measurements if initial precision criteria (> 95%) were not achieved for a sample. If a sample was reanalyzed, a new aliquot of the sample was pipetted into a well-plate. The mean precision across all samples was 97.8%.

The accuracy of the fluorometry measurements corresponded to the calibration curve generated for each pair of tests (Table 4-14). From the calibration curve regression statistics, the accuracy in the measured mass concentrations was > 99% for all tests.

Table 4-14. Fluorometer calibration curve statistics for each pair of tests.

Test #	Uranine		Tinopal	
	Slope	R2	Slope	R2
1 & 4	0.0014	0.998	0.0020	0.993
2 & 3	0.0014	0.997	0.0019	0.996
5 & 6	0.0013	0.997	0.0018	0.998
7 & 8	0.0015	0.998	0.0019	0.997

Quality control during the experiments was assessed by collecting blank samples during each test (Table 4-15). Sample fluorometric masses collected from each source were corrected for the background mass. On average, the fluorometric mass found in background samples was less than 1% of the sample fluorometric mass.

Table 4-15. Fluorescent tracer mass found in quality control samples.

Background Source	Uranine (μg)	Tinopal (μg)
Blank 0.01 N NaOH	0.0 ± 0.3	0.0 ± 0.7
Shoe	0.4 ± 0.8	0.0 ± 0.0
Carpet – Step #1	0.5 ± 1.5	1.3 ± 3.2
Carpet – Steps #2-6	1.0 ± 1.8	0.0 ± 0.0
Cookie Sheet	0.0 ± 0.0	0.0 ± 0.0

5.0 Conclusions

Resuspension Experiments

1) Older carpet with poor maintenance released more PM mass during resuspension experiments than new, well-maintained carpet. Similarly, the mass available for resuspension varied between houses, with the old and poorly maintained carpet having greater quantities available. These findings agree with previously reported laboratory findings.
2) Vacuuming decreased the amount of PM mass resuspended by approximately 44% (independent of the mass available for resuspension) for most carpets. Only new, frequently vacuumed carpet did not show this decrease. A normal, residential vacuum could be an effective remediation measure. However, the quantity of mass removed must be balanced against the amount deposited onto the carpet by tracking or other mechanisms.
3) Resuspended PM concentrations did decrease as height above the floor decreased. PM concentrations 36 in above the floor were about 1.8 times lower than those 18 in above the floor. Vacuuming the carpet did not affect this ratio, indicating that vacuuming removed all particle sizes with uniform efficiency.
4) Emission factors varied between 0.006 (new, clean carpet) and 0.023 (old, recently vacuumed carpet). The emission factors fall within the range found during laboratory experiments.
5) As expected, emission factors varied with carpet age and carpet age–fiber length interaction. Rodes and Thornburg (2004) and Thornburg and Rodes (2004a, 2004b) showed carpet age affected emission factors because of variations in particle adhesion and loading characteristics. The hypothesized change in adhesion forces with age would cause the fiber length to become important after a period of time. Rodes (1998) showed emission factors vary with carpet fiber length.
6) Emission factors measured after vacuuming the carpet were 4 times greater than those prior to vacuuming. Although vacuuming reduced the total mass resuspended by a factor of 2.5, vacuuming also reduced the PM mass available for resuspension by a factor of 10. The net result is an increase in the measured emission factors. The unintuitive nature of this finding suggests carpet age, cleaning frequency, and other characteristics must be known when applying emission factors to exposure models.
7) Spatial-temporal analysis of the resuspension data suggests significant PM mass translocation occurs at distances of approximately 8 ft. Development of statistical or physical models to predict the amount of translocation and the salient characteristics (e.g., room size) was beyond the scope of this research. Simple ratios of the data indicate 10% to 50% of the resuspended PM migrates at least 8 feet (at a height of 36 in) from the source. However, the data are available for more thorough analysis.

Residential Tracking Experiments

1) A method and sample collection equipment were developed to collect microvacuum samples within homes to determine the PM movement rate due to tracking.
2) Rain or other events that change the moisture and adhesion properties of the PM can greatly influence the tracking rate.
3) The cumulative mass tracked into buildings varied between homes and between weeks. As expected, the cumulative mass accumulated in the carpet increased steadily during the four weeks and more mass was collected in homes with more occupants.
4) Tracking rates varied between 2.7 and 24.1 μg per in^2-week. The rate probably is highly dependent on the number of traverses across the carpet, currently identified by the number of residence occupants.

Laboratory Tracking Experiments

1) Experimental procedures were developed to evenly load a surface with a known quantity of fluorescent particles, collect samples from a variety of surfaces, extract and analyze the samples to determine the quantity of fluorescent mass, and reduce the data to determine the amount of mass per unit surface area. These procedures will be useful for conducting future tracking experiments to expand the preliminary findings reported here.
2) Data quality objectives were achieved for these experiments.
3) The amount of PM transferred was associated with the step number. More than 40% of the mass was transferred on the first step. The remaining 10% was transferred during the subsequent five steps in approximate 2% increments.

4) Uranine particle mass load on the shoe surface, carpet age, and carpet style did not influence the PM transfer from the shoe to the carpet. Uranine mass load was statistically significant at the 90% confidence level. It is possible additional testing, to increase the degrees of freedom, will prove PM load is a significant variable.
5) On average, 1.1% of the mass is transferred from the carpet to the shoe during a step. The fraction transferred was independent of the experimental conditions. Additional research is needed to understand the carpet-to-shoe transfer process. The small quantity transferred prohibited confirmation of the Uranine findings because there were not sufficient data for statistical analysis.

6.0
References

Farfel, M.R., Orlova, A.O., Lees, P.S.J., Bowen, C., Elias, R., Ashley, P.J., and Chisolm, J.J. "Comparison of Two Floor Mat Lead Dust Collection Methods and Their Application in Pre-1950 and New Urban Houses." *Environ. Sci. & Technol.,* 35:2078–2083 (2001).

Ferro, A.R., Kopperud, R.J., and Hildemann, L.M. "Source Strengths for Indoor Human Activities That Resuspend Particulate Matter." *Environ. Sci. & Technol.,* 38:1759–1764 (2004).

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

Rodes, C.E. 1998. "Experimental Methodologies and Preliminary Mass Transfer Factor Data for Estimation of Dermal Exposures to Particles From Surfaces." Final Report, RTI Project 6980, U.S. EPA Contract 68-D5-0040 WA019 and WA 023.

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.

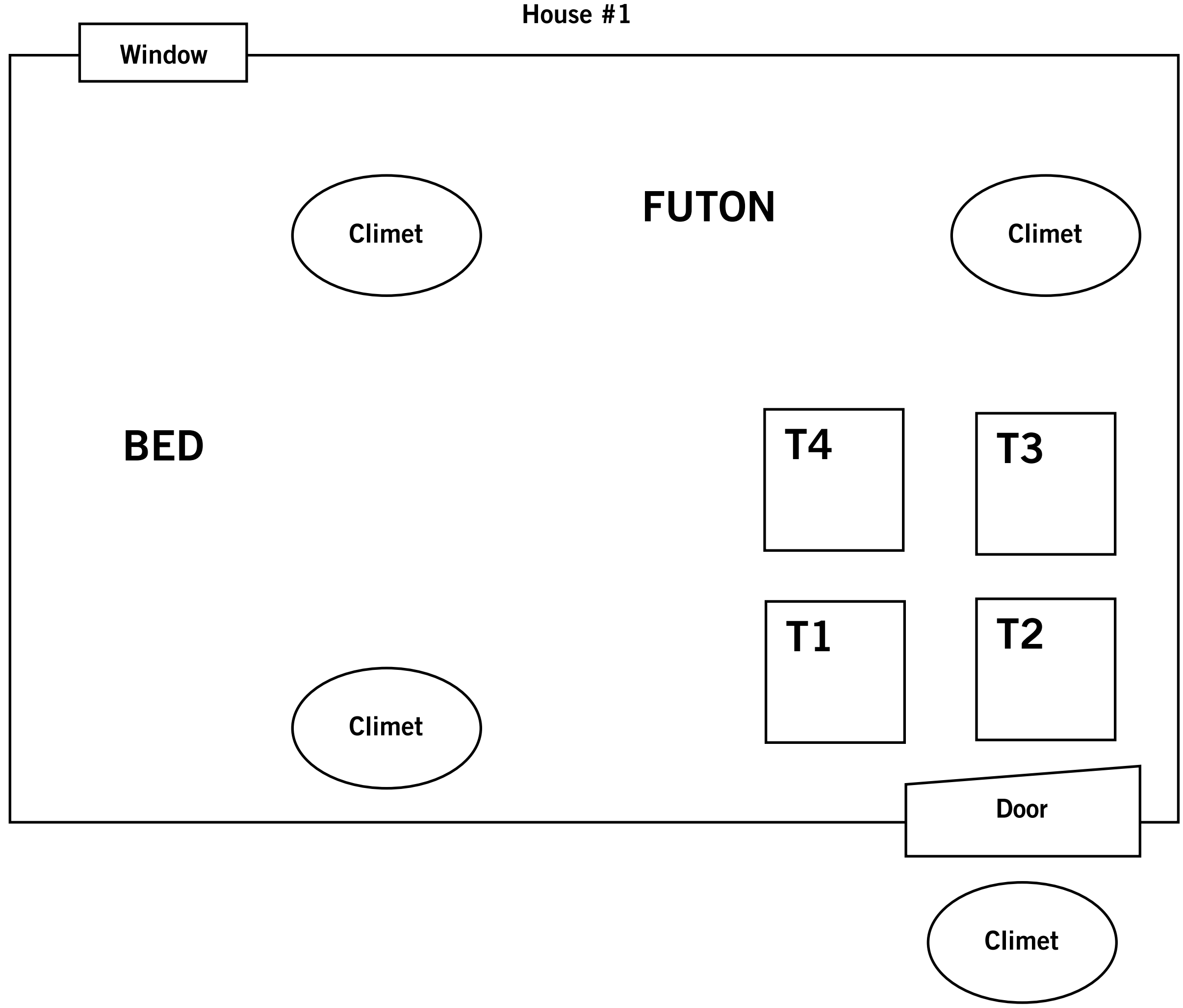
Thornburg, J., and Rodes, C.E. 2004a. "Resuspension of Fibers From Indoor Surfaces Due to Human Activity." Final Report, RTI Project 08924. U.S. EPA Contract 3C-R321-NANX.

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.

APPENDIX A
Characteristics of Houses Participating in Resuspension Tests

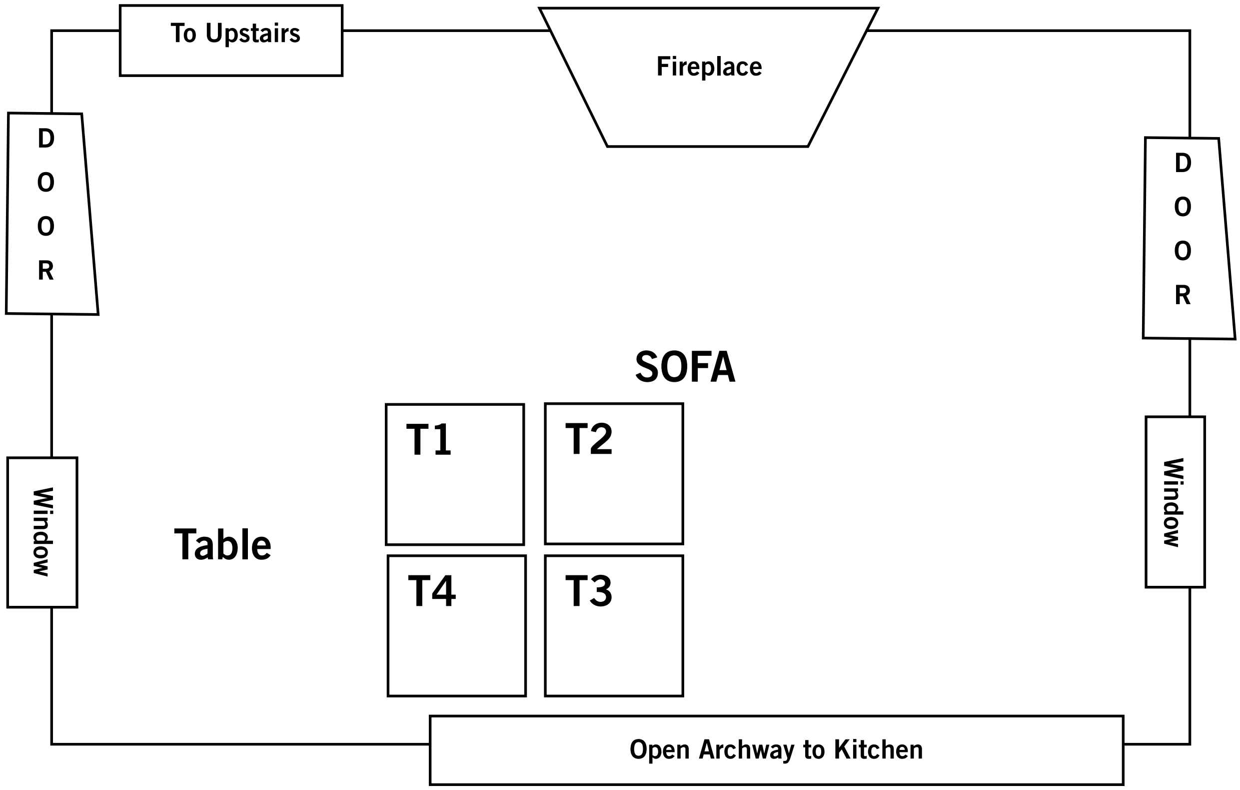
House ID	H1		
Room Description	Bedroom, 10.5 ft x 14 ft		
# Occupants			
Adults	2		
Kids	0		
Pets	3 cats	Outside?	yes
Carpet Characteristics			
Type	medium pile		
Pile height	15 mm		
Age	3.5–3.75 years		
Matted?	no		
Cleaning History			
Vacuum frequency?	~every 2 weeks		
Deodorizer?	on occasion		
Steam cleaned/shampoo?	never		
Interior Survey			
Water damage?	no		
Flaking paint?	bonus room (other side of house)		
Dusty surfaces?	no		
Clutter?	no, minimal furniture		
Exterior Survey			
Primary entrance?	front door and garage door		
Exterior paint condition?	good		
Front porch? Size?	concrete; 6 ft x 20 ft, slightly dirty		
Back deck? Size?	yes; large deck		
Concrete drive? Entrance?	gravel drive		
Dirt/grass yard?	natural front, grass lawn left and backyard		

House #1


Window
FUTON
Climet
Climet
BED
T4
T3
T1
T2
Climet
Door
Climet

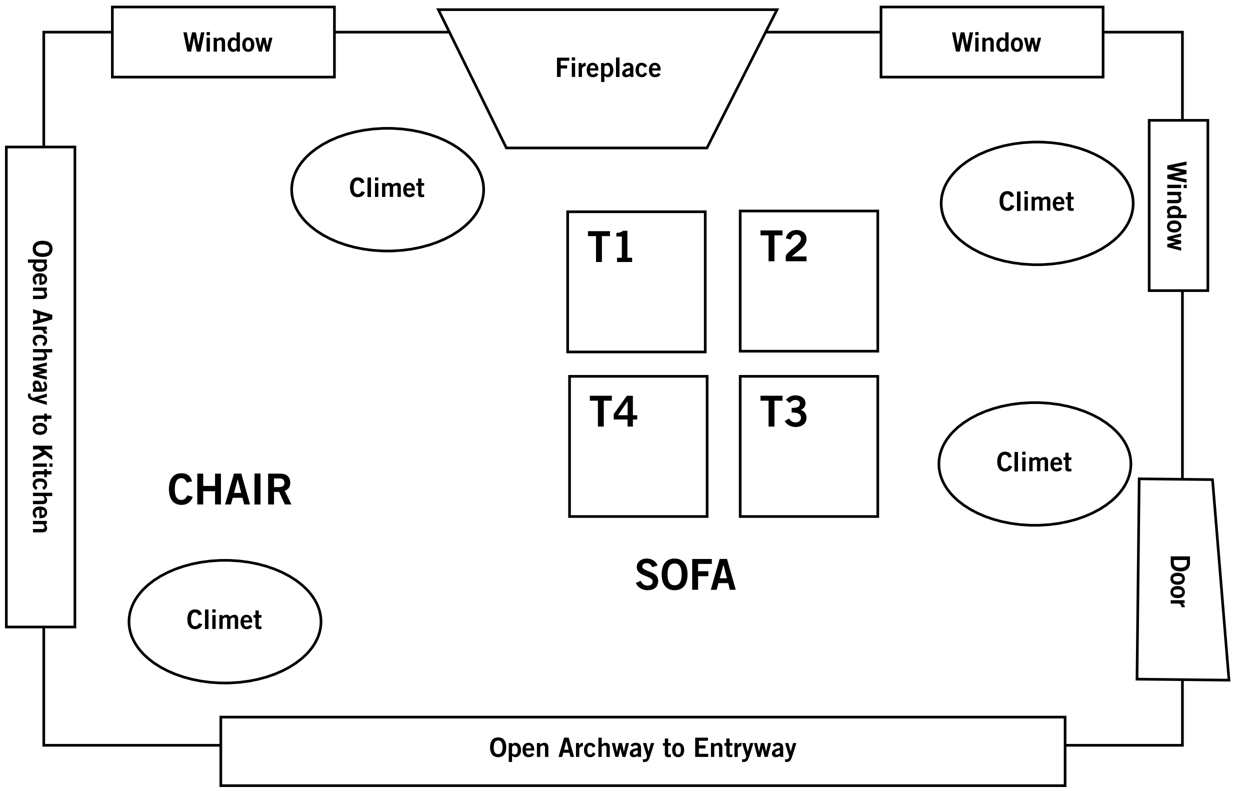
House ID	H2		
Room Description	Family Room		
# Occupants			
Adults	2		
Kids	1		
Pets	1 dog, 2 cats	Outside?	no
Carpet Characteristics			
Type	medium pile, cut loop		
Pile height	15 mm		
Age	3 years		
Matted?	somewhat; heavy foot traffic areas.		
Cleaning History			
Vacuum frequency?	twice per week		
Deodorizer?	yes		
Steam cleaned/shampoo?	no		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	no		
Clutter?	kids' toys		
Exterior Survey			
Primary entrance?	garage and front door		
Exterior paint condition?	good		
Front porch? Size?	yes; 6 ft x 6 ft, concrete		
Back deck? Size?	wood; 12 ft x 12 ft		
Concrete drive? Entrance?	yes; drive and walkway		
Dirt/grass yard?	grass in front and backyards		

House #2


To Upstairs
Fireplace
DOOR
DOOR
SOFA
T1
T2
T4
T3
Table
Window
Window
Open Archway to Kitchen

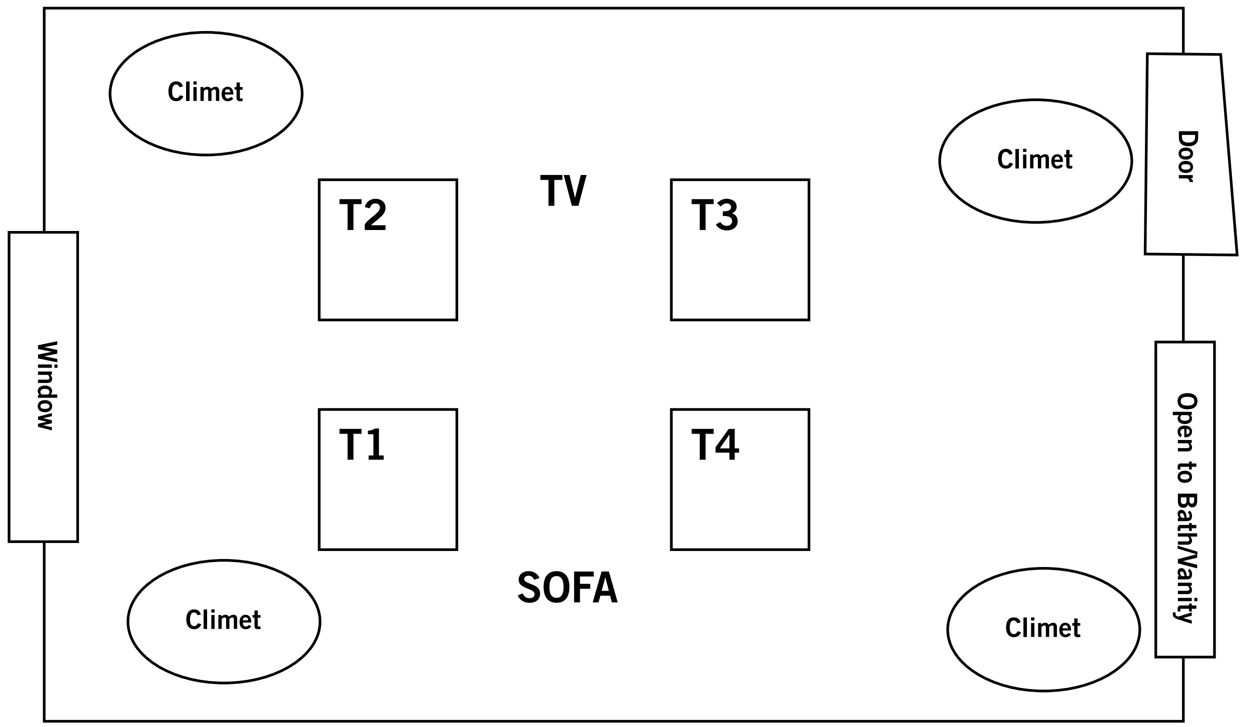
House ID	H3		
Room Description	Family Room		
# Occupants			
Adults	2		
Kids	2		
Pets	1 dog, 1 cat	Outside?	yes, both
Carpet Characteristics			
Type	medium pile, cut loop		
Pile height	10 mm		
Age	6 years		
Matted?	somewhat; heavy foot traffic areas		
Cleaning History			
Vacuum frequency?	once per week		
Deodorizer?	no		
Steam cleaned/shampoo?	November, 2004		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	no, some dirt on floor/tables		
Clutter?	kids' toys		
Exterior Survey			
Primary entrance?	garage		
Exterior paint condition?	good		
Front porch? Size?	yes; 8 ft x 6 ft, concrete.		
Back deck? Size?	wood; 16 ft x 12 ft, access thru sun porch		
Concrete drive? Entrance?	yes; drive and walkway		
Dirt/grass yard?	grass in front and backyards.		

House #3


Window
Fireplace
Window
Climet
Climet
Window
T1
T2
Open Archway to Kitchen
T4
T3
Climet
CHAIR
Door
SOFA
Climet
Open Archway to Entryway

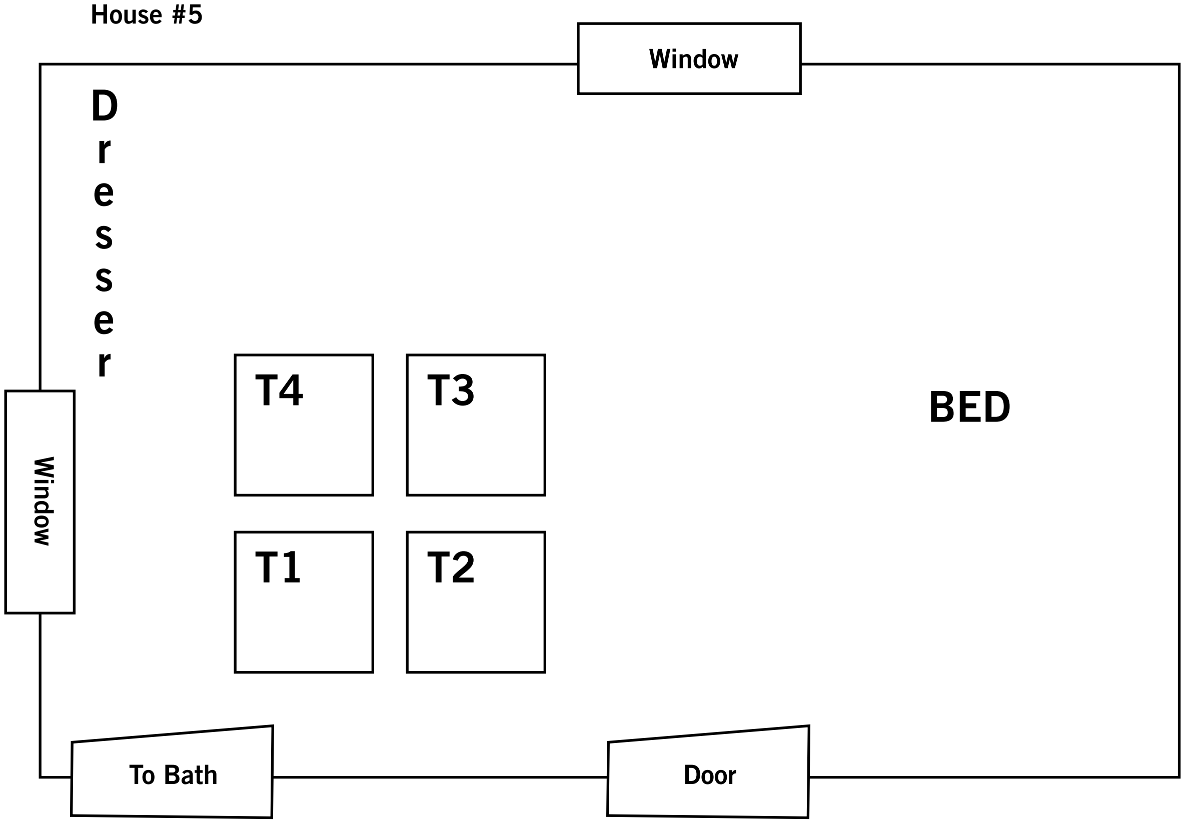
House ID	H4		
Room Description	Upstairs Bedroom		
# Occupants			
Adults	2		
Kids	0		
Pets	2 cats	Outside?	no
Carpet Characteristics			
Type	medium pile		
Pile height	10.5 mm		
Age	1.5 years		
Matted?	no		
Cleaning History			
Vacuum frequency?	once per week		
Deodorizer?	yes, with pet hair release		
Steam cleaned/shampoo?	no, but uses spot remover occ.		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	no		
Clutter?	no		
Exterior Survey			
Primary entrance?	through garage		
Exterior paint condition?	vinyl siding		
Front porch? Size?	no; stoop		
Back deck? Size?	yes; 8 ft x 8 ft		
Concrete drive? Entrance?	yes; into garage		
Dirt/grass yard?	yes, doesn’t walk through		

House #4


Climet
Climet
Door
TV
T2
T3
Window
Open to Bath/Vanity
T1
T4
SOFA
Climet
Climet

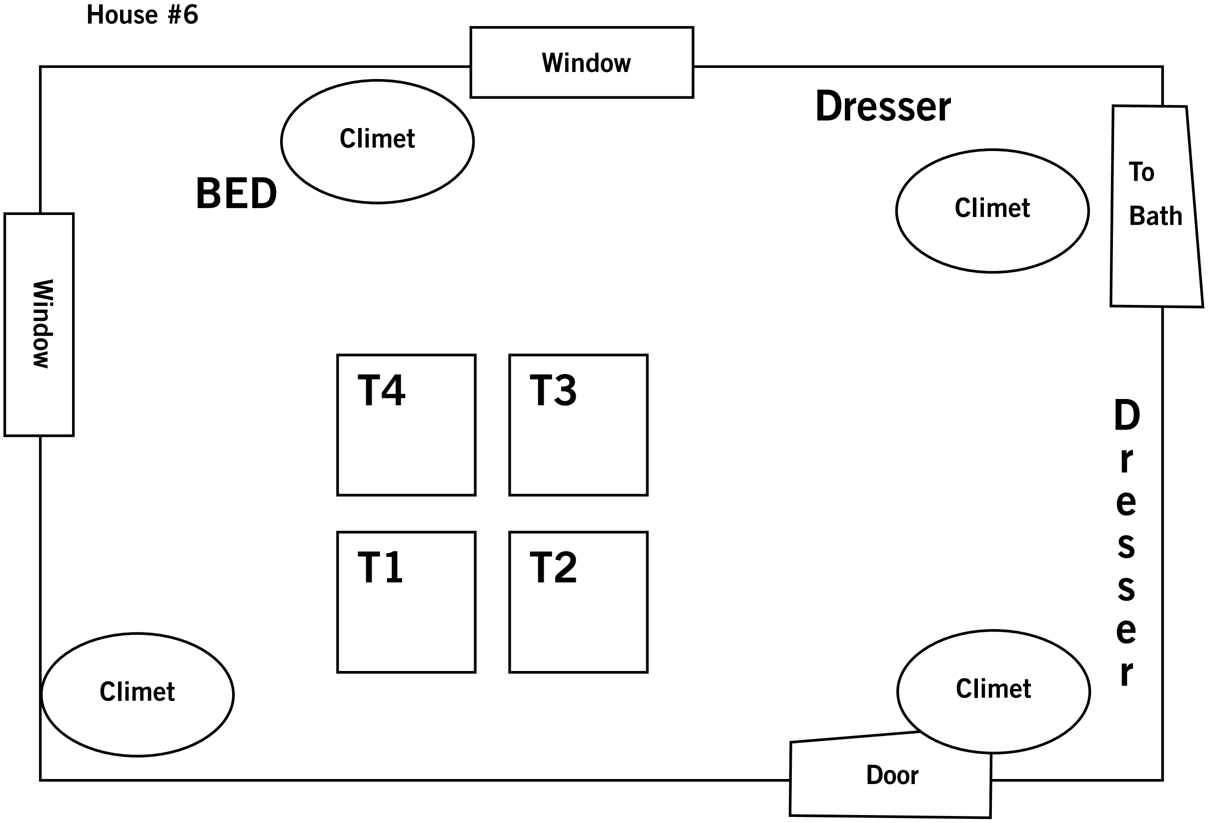
House ID	H5		
Room Description	Master Bedroom		
# Occupants			
Adults	2		
Kids	0		
Pets	1 dog, 2 cats	Outside?	yes
Carpet Characteristics			
Type	medium pile, cut loop		
Pile height	8 mm		
Age	> 10 years		
Matted?	yes		
Cleaning History			
Vacuum frequency?	weekly		
Deodorizer?	yes, monthly		
Steam cleaned/shampoo?	~ 4 years ago		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	some dust		
Clutter?	lots of furniture		
Exterior Survey			
Primary entrance?	kitchen door		
Exterior paint condition?	good		
Front porch? Size?	yes; wood, 8 ft x 20 ft		
Back deck? Size?	no		
Concrete drive? Entrance?	concrete drive and walk to porch		
Dirt/grass yard?	grass front and backyard		

House #5



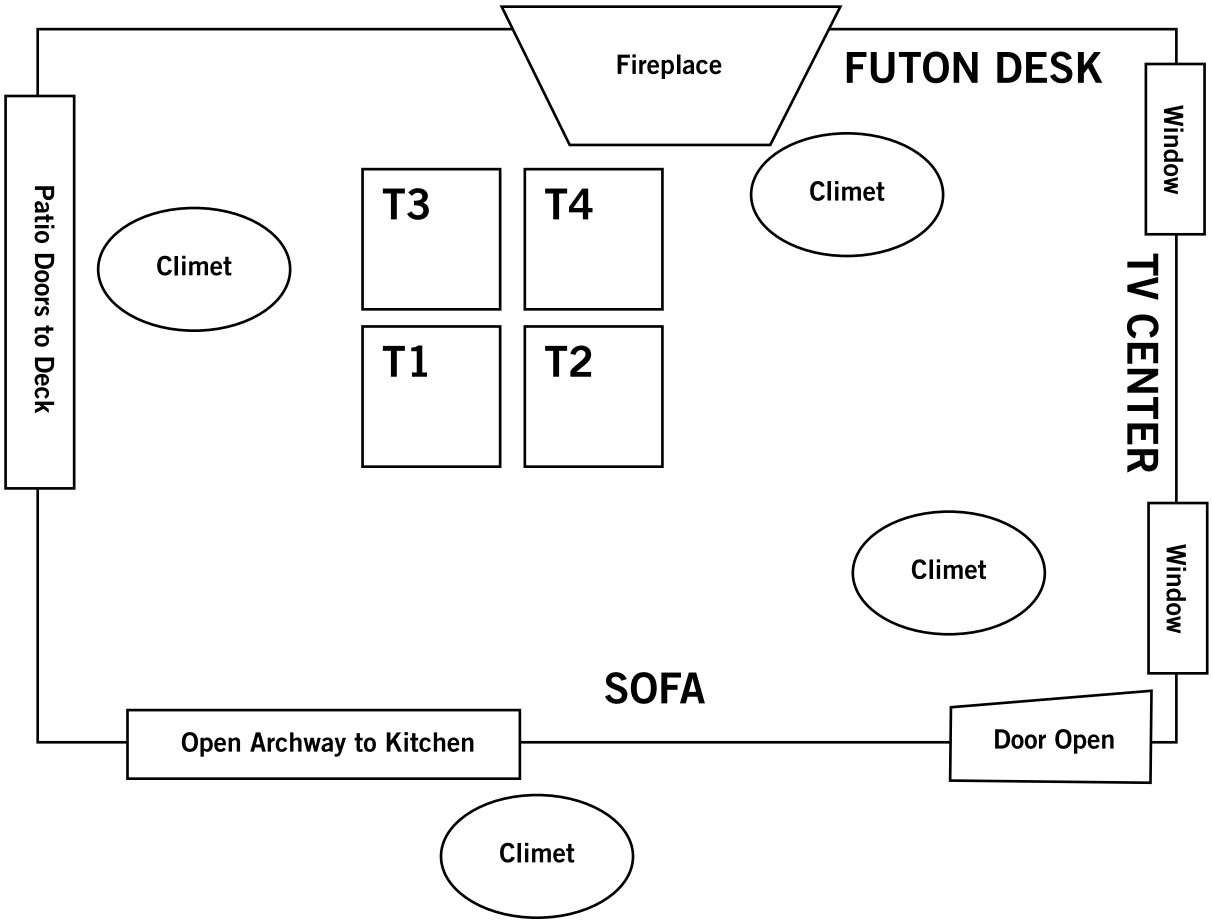
House ID	H6		
Room Description	Living Room		
# Occupants			
Adults	1		
Kids	0		
Pets	0	Outside?	no
Carpet Characteristics			
Type	medium pile, cut loop		
Pile height	5 mm		
Age	> 10 years		
Matted?	yes		
Cleaning History			
Vacuum frequency?	every 2 months		
Deodorizer?	no		
Steam cleaned/shampoo?	> 5 years		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	yes, not cleaned > 3 months		
Clutter?	no, minimal furniture		
Exterior Survey			
Primary entrance?	front door		
Exterior paint condition?	good		
Front porch? Size?	no		
Back deck? Size?	yes; 10 ft x 10 ft		
Concrete drive? Entrance?	concrete drive and walk to porch		
Dirt/grass yard?	dirt front yard, grass backyard		

House #6


Window
Climet
Dresser
BED
To
Bath
Climet
Window
T4
T3
D
r
e
s
s
e
r
T1
T2
Climet
Climet
Door

House ID	H7		
Room Description	Living Room		
# Occupants			
Adults	2		
Kids	0		
Pets	1 dog, 2 cats	Outside?	no
Carpet Characteristics			
Type	medium pile, cut loop		
Pile height	5 mm		
Age	8 years		
Matted?	somewhat		
Cleaning History			
Vacuum frequency?	every month		
Deodorizer?	yes		
Steam cleaned/shampoo?	> 2.5 years		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	yes, not cleaned in 2 months		
Clutter?	yes		
Exterior Survey			
Primary entrance?	front door		
Exterior paint condition?	good		
Front porch? Size?	yes; wood, 5 ft x 18.5 ft		
Back deck? Size?	yes; 10 ft x 13 ft		
Concrete drive? Entrance?	concrete drive and walk to porch		
Dirt/grass yard?	grass front and backyard		

House #7


Fireplace
FUTON DESK
Window
Patio Doors to Deck
Climet
T3
T4
Climet
T1
T2
TV CENTER
Climet
Window
SOFA
Open Archway to Kitchen
Door Open
Climet

APPENDIX B
Characteristics of Houses Participating in Walk-off Mat Tracking Tests

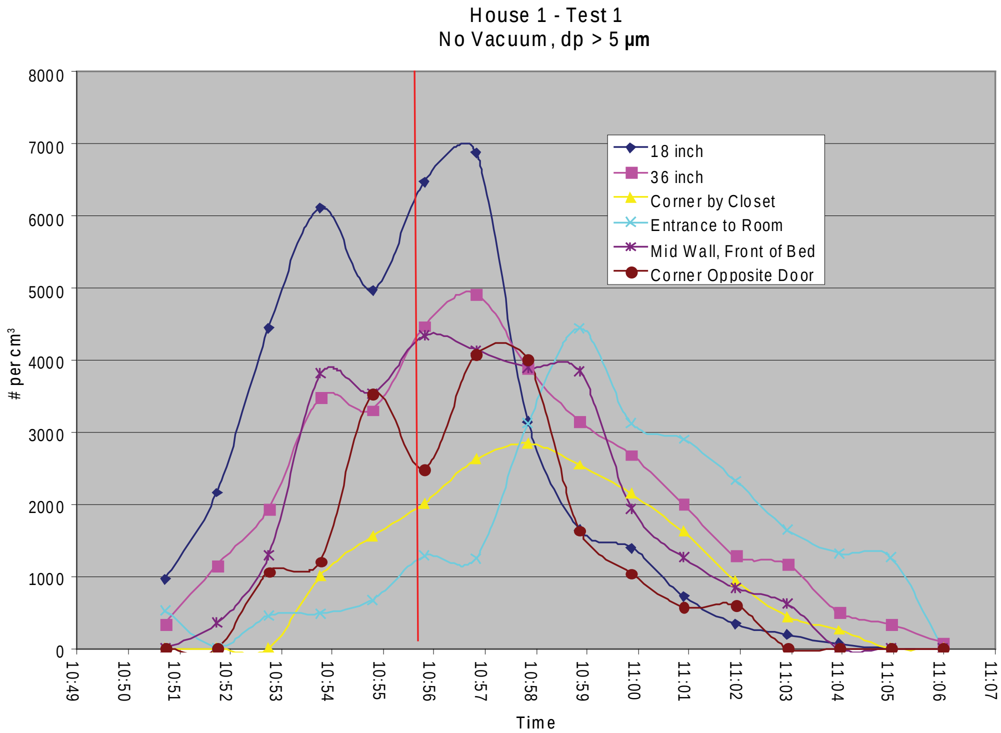
House ID	T1 (Same as H1)		
Room Description	Front Hall (at Door) 3.5 ft x 12 ft		
# Occupants			
Adults	2		
Kids	0		
Pets	3 cats	Outside?	yes
Carpet Characteristics			
Type	Mohawk Horizon		
Pile height	11.5 mm		
Age	new		
Matted?	no		
Cleaning History			
Vacuum frequency?	**DO NOT VACUUM**		
Deodorizer?	N/A		
Steam cleaned/shampoo?	N/A		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	no		
Clutter?	no		
Exterior Survey			
Primary entrance?	front door		
Exterior paint condition?	good		
Front porch? Size?	yes; small, concrete 6 ft x 20 ft		
Back deck? Size?	yes; large, off dining rm		
Concrete drive? Entrance?	no; gravel, leads to front steps		
Dirt/grass yard?	grass lawn on left and backyard, woods in remainder of yard		

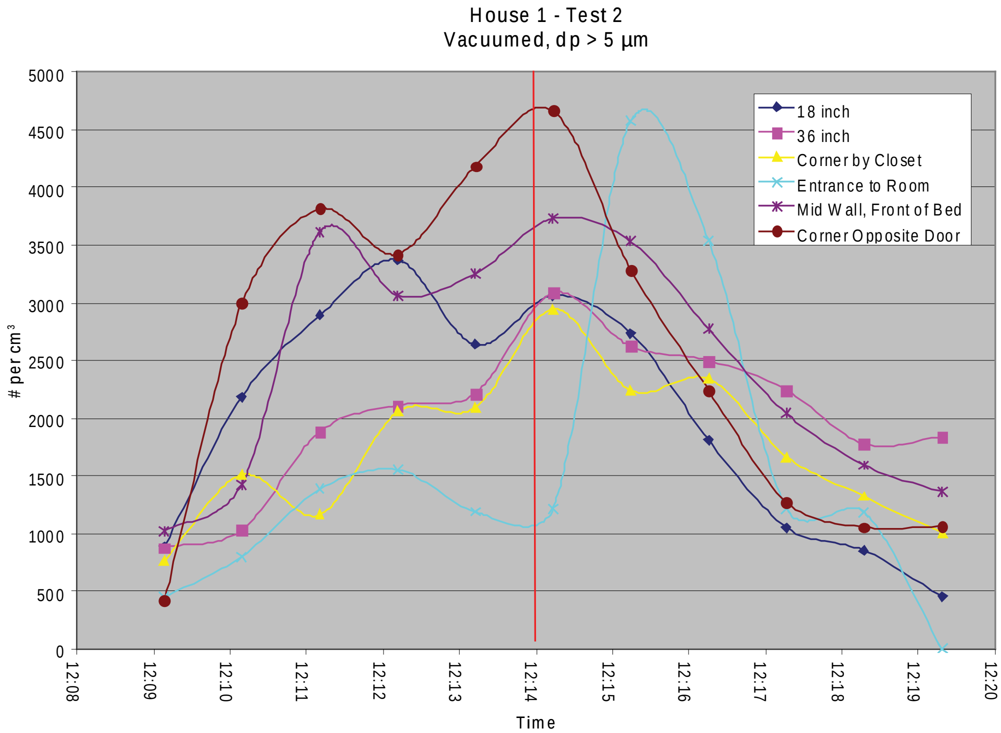
House ID	T2		
Room Description	Entry Hall, 3 ft x 12 ft		
# Occupants			
Adults	2		
Kids	1		
Pets	2 cats, 1 dog	Outside?	dog
Carpet Characteristics			
Type	Mohawk Horizon		
Pile height	11.5 mm		
Age	new		
Matted?	no		
Cleaning History			
Vacuum frequency?	**DO NOT VACUUM**		
Deodorizer?	N/A		
Steam cleaned/shampoo?	N/A		
Interior Survey			
Water damage?	no		
Flaking paint?	yes, outside		
Dusty surfaces?	no		
Clutter?	no		
Exterior Survey			
Primary entrance?	front door		
Exterior paint condition?	flaking on columns and porch ceiling		
Front porch? Size?	yes; 12 ft x 40 ft		
Back deck? Size?	N/A		
Concrete drive? Entrance?	no; gravel drive, concrete walkway		
Dirt/grass yard?	both; walk through lawn to porch		

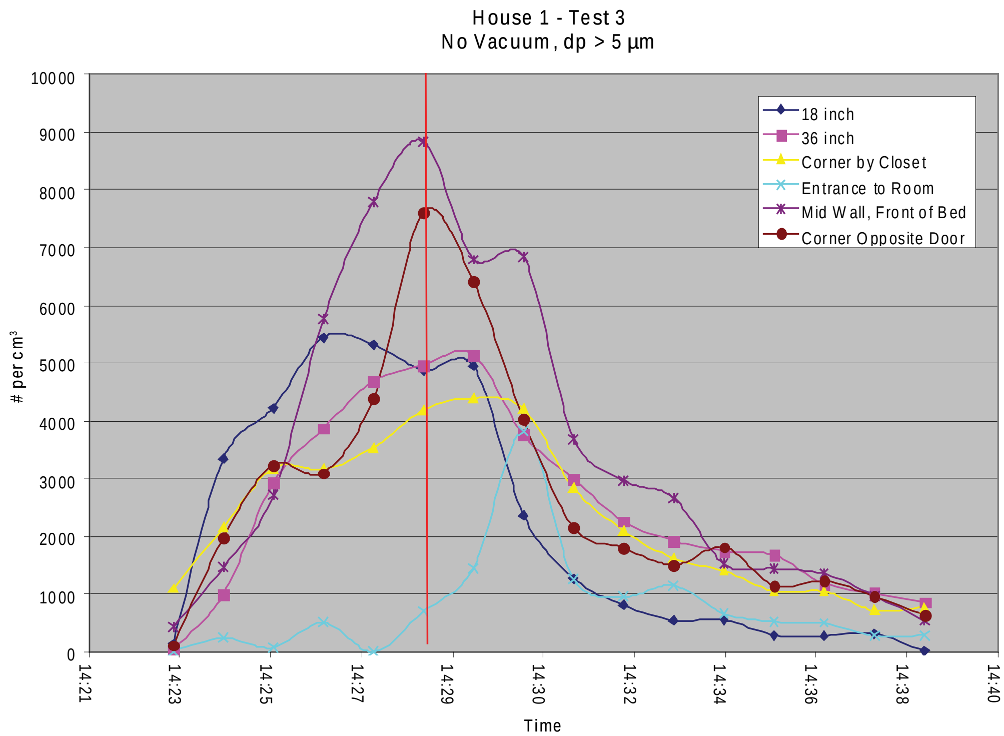
House ID	T3		
Room Description	Front Hall		
# Occupants			
Adults	2		
Kids	0		
Pets	2 cats	Outside?	no
Carpet Characteristics			
Type	Mohawk Horizon		
Pile height	11.5 mm		
Age	new		
Matted?	no		
Cleaning History			
Vacuum frequency?	**DO NOT VACUUM**		
Deodorizer?	N/A		
Steam cleaned/shampoo?	N/A		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	no		
Clutter?	no		
Exterior Survey			
Primary entrance?	back door		
Exterior paint condition?	good		
Front porch? Size?	10 ft x 30 ft		
Back deck? Size?	small porch/stoop		
Concrete drive? Entrance?	gravel drive		
Dirt/grass yard?	grass front, mulch backyard		

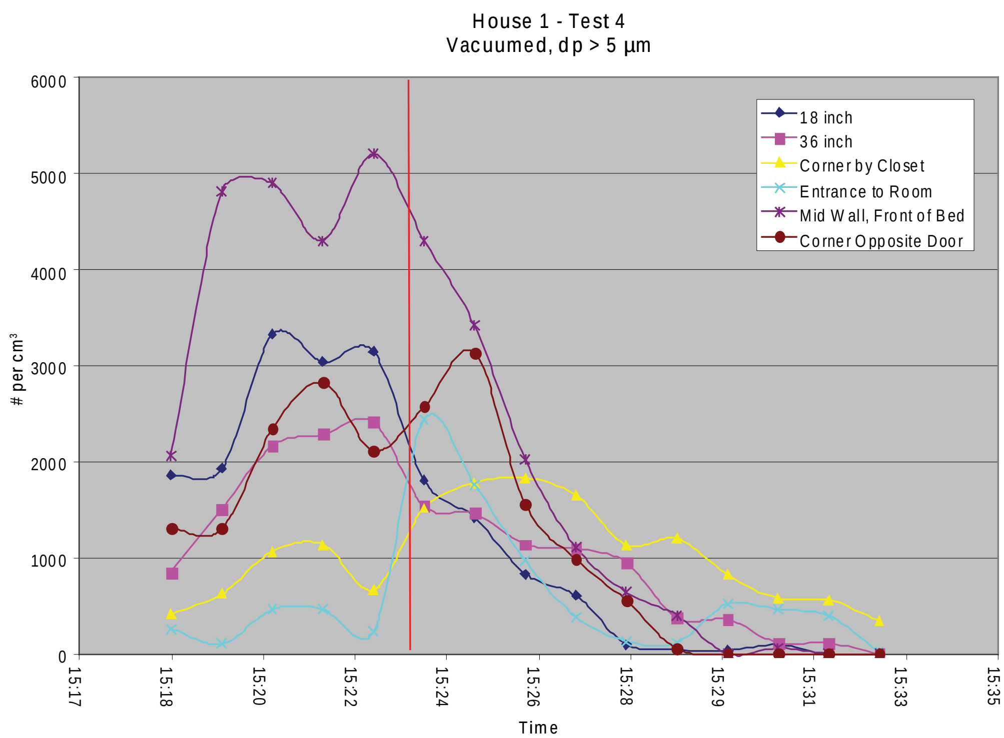
House ID	T4		
Room Description	Hallway		
# Occupants			
Adults	1		
Kids	1		
Pets	0	Outside?	
Carpet Characteristics			
Type	Mohawk Horizon		
Pile height	11.5 mm		
Age	new		
Matted?	no		
Cleaning History			
Vacuum frequency?	**DO NOT VACUUM**		
Deodorizer?	N/A		
Steam cleaned/shampoo?	N/A		
Interior Survey			
Water damage?	no		
Flaking paint?	no		
Dusty surfaces?	no		
Clutter?	no		
Exterior Survey			
Primary entrance?	front door		
Exterior paint condition?	vinyl siding - excellent condition		
Front porch? Size?	no		
Back deck? Size?	8 ft x 6 ft		
Concrete drive? Entrance?	sidewalk and breezeway		
Dirt/grass yard?	in back of unit		

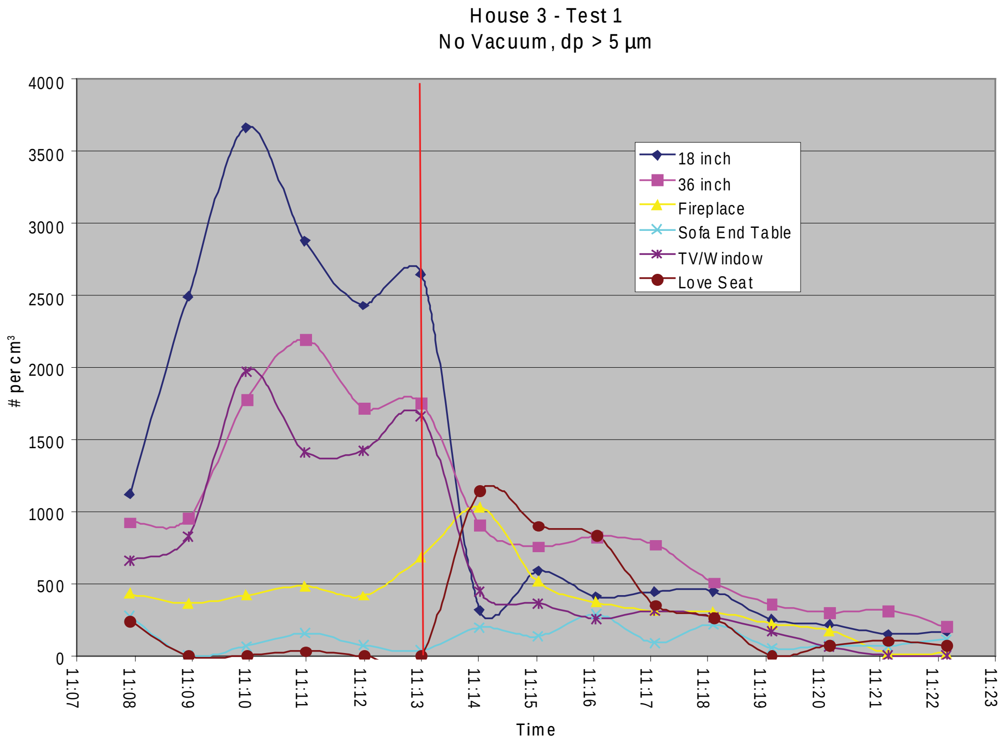
APPENDIX C
Climet Translocation Graphs

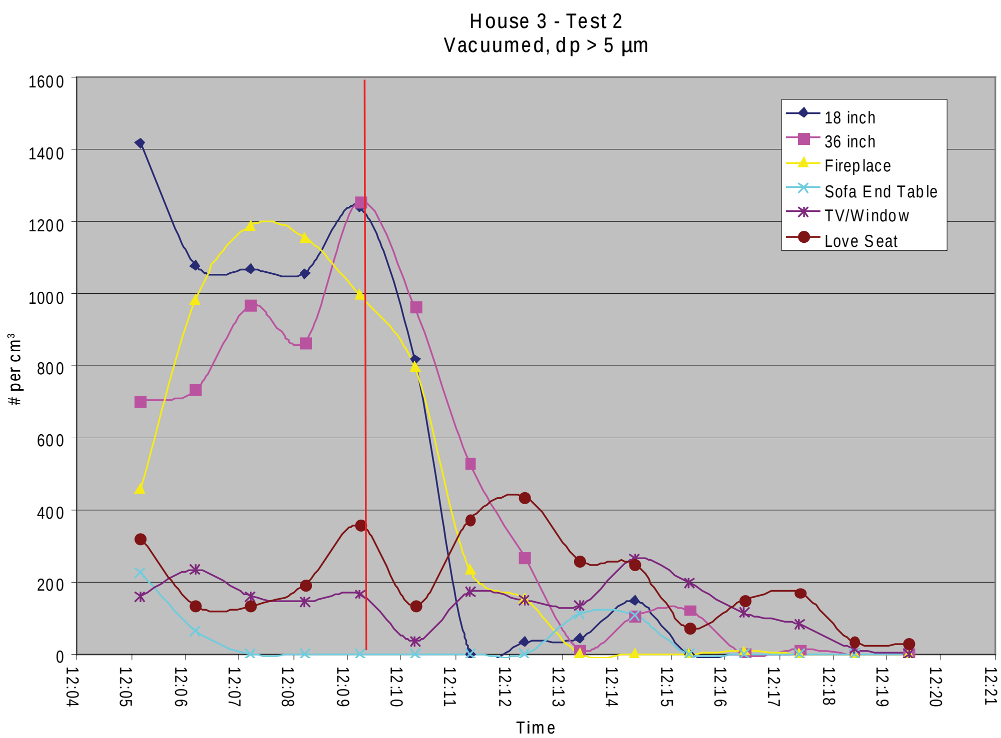


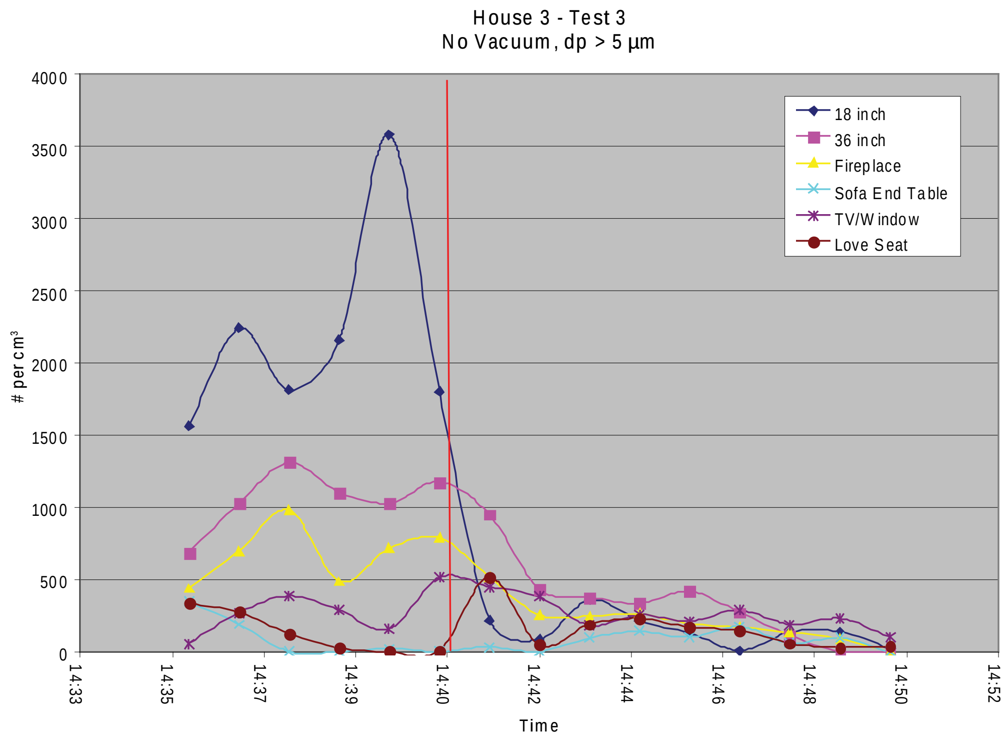


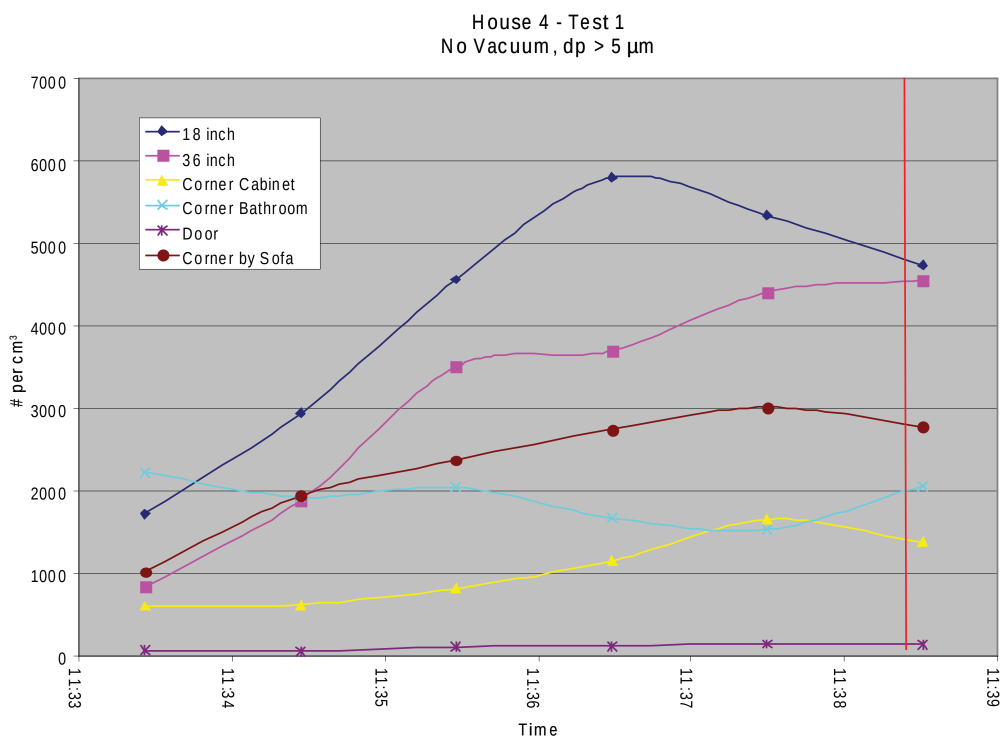

House 1 - Test 3
No Vacuum, dp > 5 µm
per cm³
Time
18 inch
36 inch
Corner by Closet
Entrance to Room
Mid Wall, Front of Bed
Corner Opposite Door
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
14:21
14:23
14:25
14:27
14:29
14:30
14:32
14:34
14:36
14:38
14:40

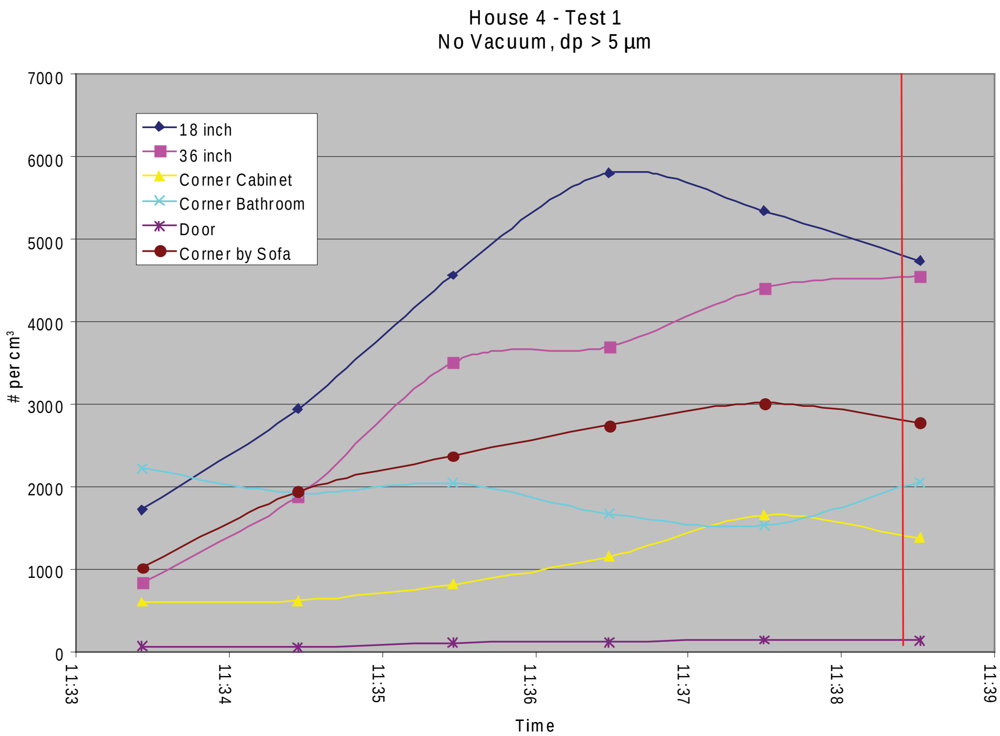

House 1 - Test 4
Vacuumed, dp > 5 µm
per cm³
Time
18 inch
36 inch
Corner by Closet
Entrance to Room
Mid Wall, Front of Bed
Corner Opposite Door
0
1000
2000
3000
4000
5000
6000
15:17
15:18
15:20
15:22
15:24
15:26
15:28
15:29
15:31
15:33
15:35


House 3 - Test 1
No Vacuum, dp > 5 µm
per cm³
4000
3500
3000
2500
2000
1500
1000
500
0
18 inch
36 inch
Fireplace
Sofa End Table
TV/Window
Love Seat
11:07
11:08
11:09
11:10
11:11
11:12
11:13
11:14
11:15
11:16
11:17
11:18
11:19
11:20
11:21
11:22
11:23
Time

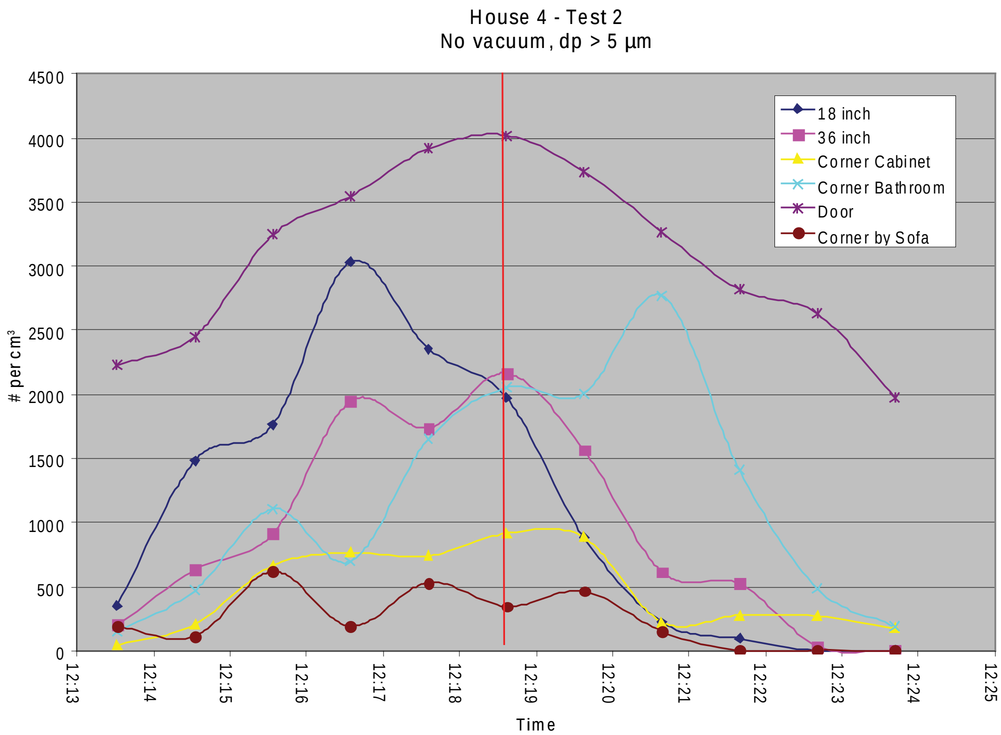

House 3 - Test 2
Vacuumed, dp > 5 µm
per cm³
1600
1400
1200
1000
800
600
400
200
0
18 inch
36 inch
Fireplace
Sofa End Table
TV/Window
Love Seat
12:04
12:05
12:06
12:07
12:08
12:09
12:10
12:11
12:12
12:13
12:14
12:15
12:16
12:17
12:18
12:19
12:20
12:21
Time


House 3 - Test 3
No Vacuum, dp > 5 µm
4000
3500
3000
2500
2000
1500
1000
500
0
per cm3
14:33
14:35
14:37
14:39
14:40
14:42
14:44
14:46
14:48
14:50
14:52
Time
18 inch
36 inch
Fireplace
Sofa End Table
TV/Window
Love Seat

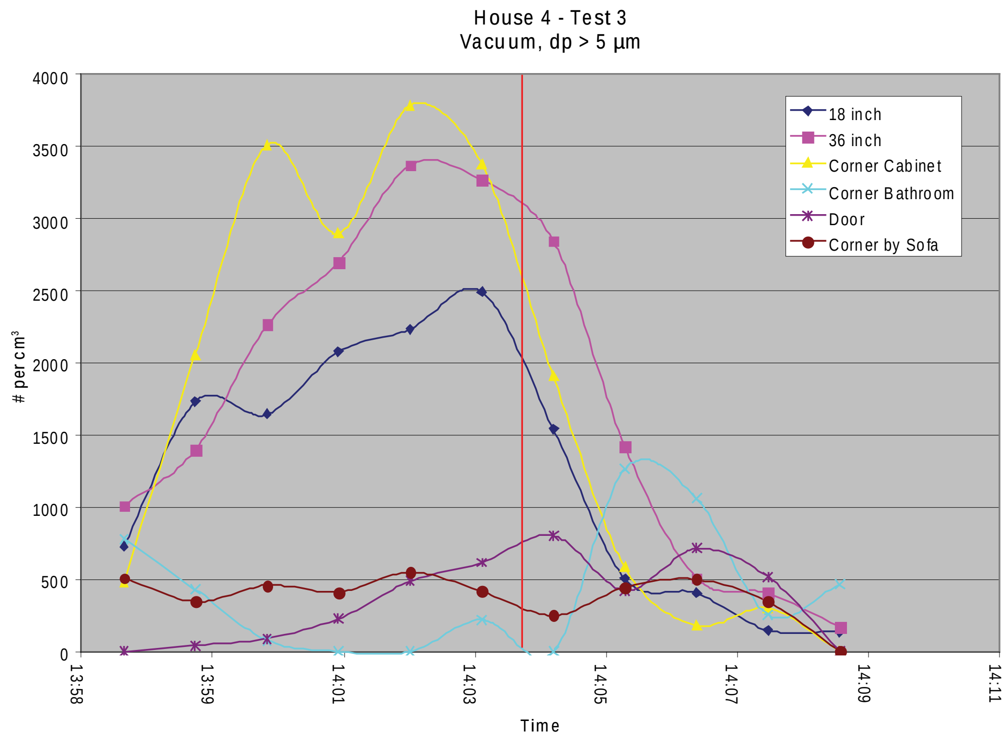

House 4 - Test 1
No Vacuum, dp > 5 µm
7000
6000
5000
4000
3000
2000
1000
0
per cm3
11:33
11:34
11:35
11:36
11:37
11:38
11:39
Time
18 inch
36 inch
Corner Cabinet
Corner Bathroom
Door
Corner by Sofa

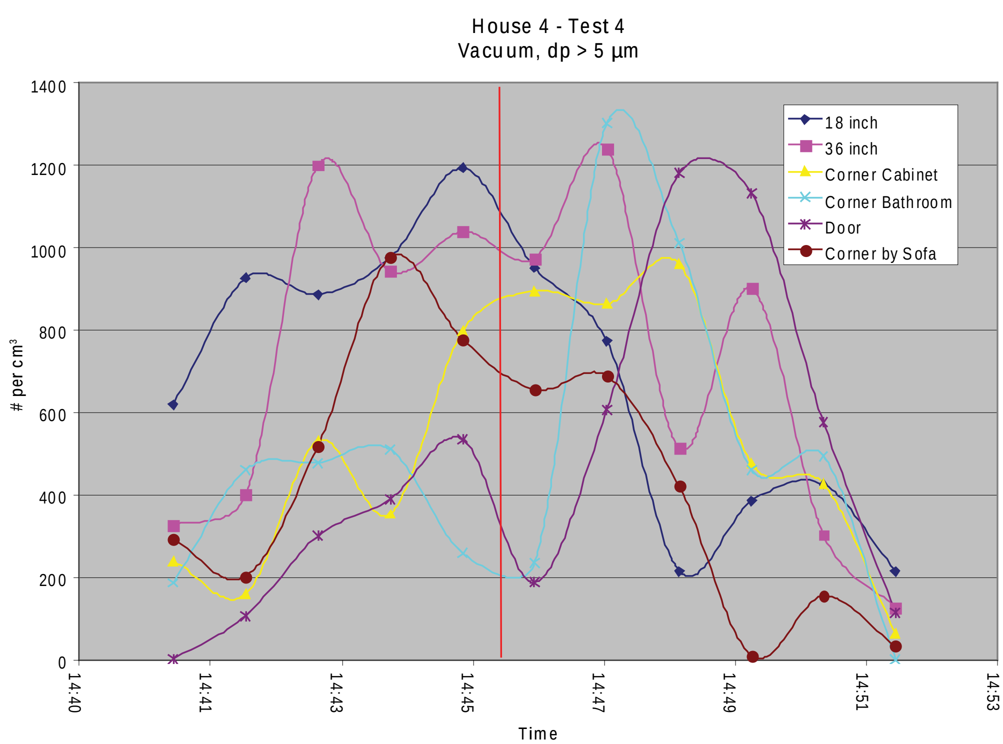


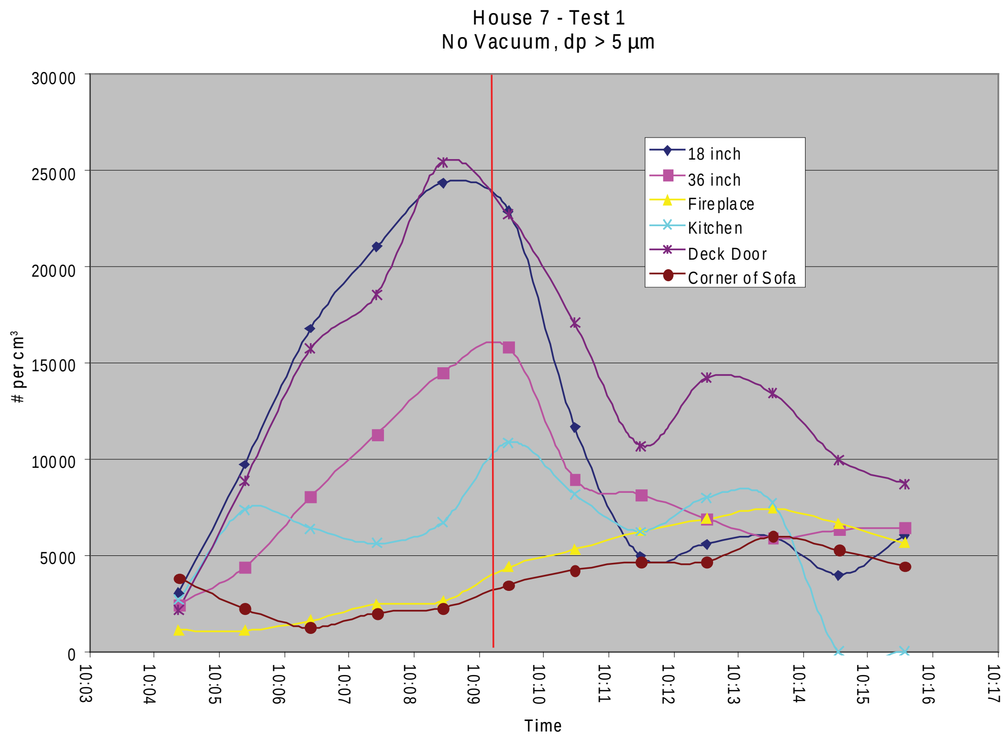
House 4 - Test 1
No Vacuum, dp > 5 µm
7000
6000
5000
4000
3000
2000
1000
0
per cm³
18 inch
36 inch
Corner Cabinet
Corner Bathroom
Door
Corner by Sofa
11:33
11:34
11:35
11:36
11:37
11:38
11:39
Time

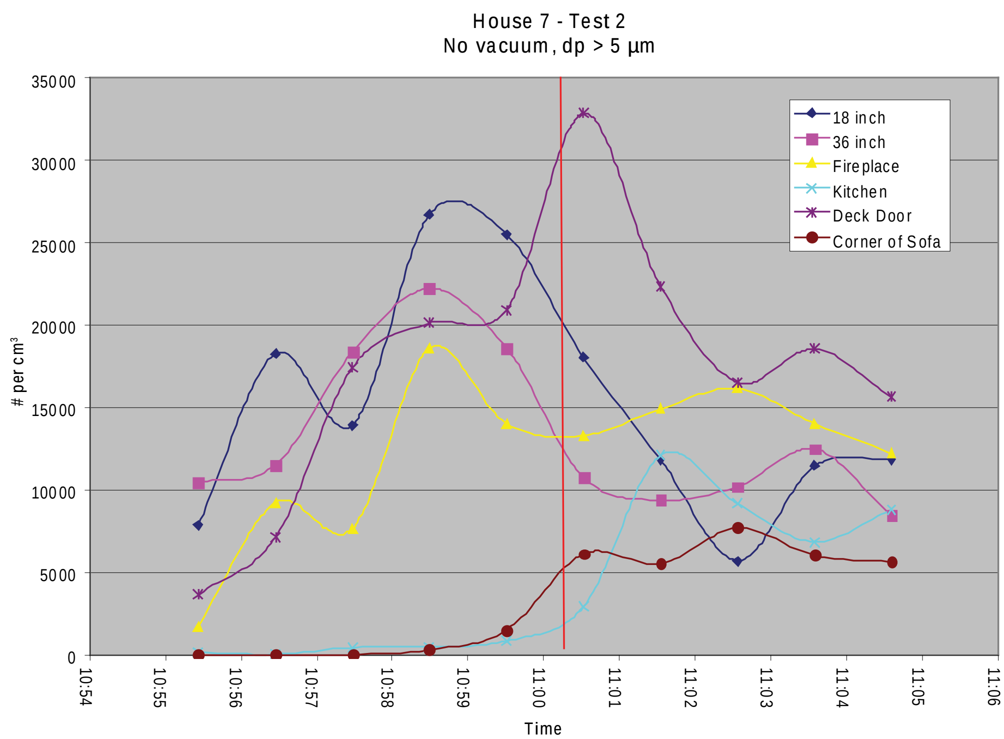


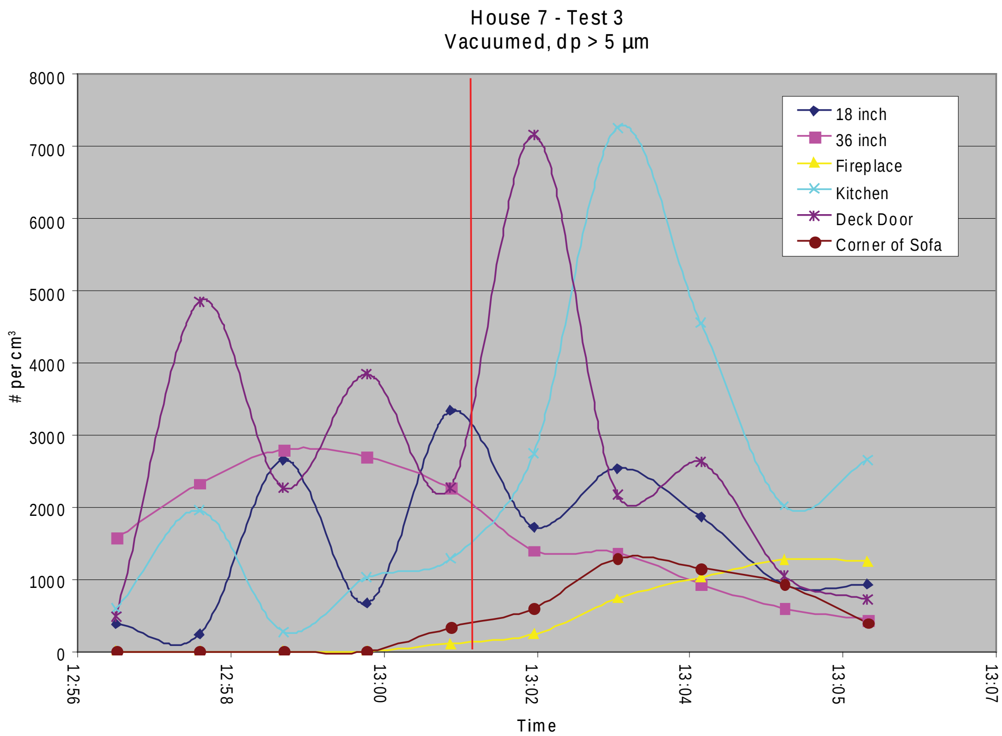
House 4 - Test 2
No vacuum, dp > 5 µm
4500
4000
3500
3000
2500
2000
1500
1000
500
0
per cm³
18 inch
36 inch
Corner Cabinet
Corner Bathroom
Door
Corner by Sofa
12:13
12:14
12:15
12:16
12:17
12:18
12:19
12:20
12:21
12:22
12:23
12:24
12:25
Time

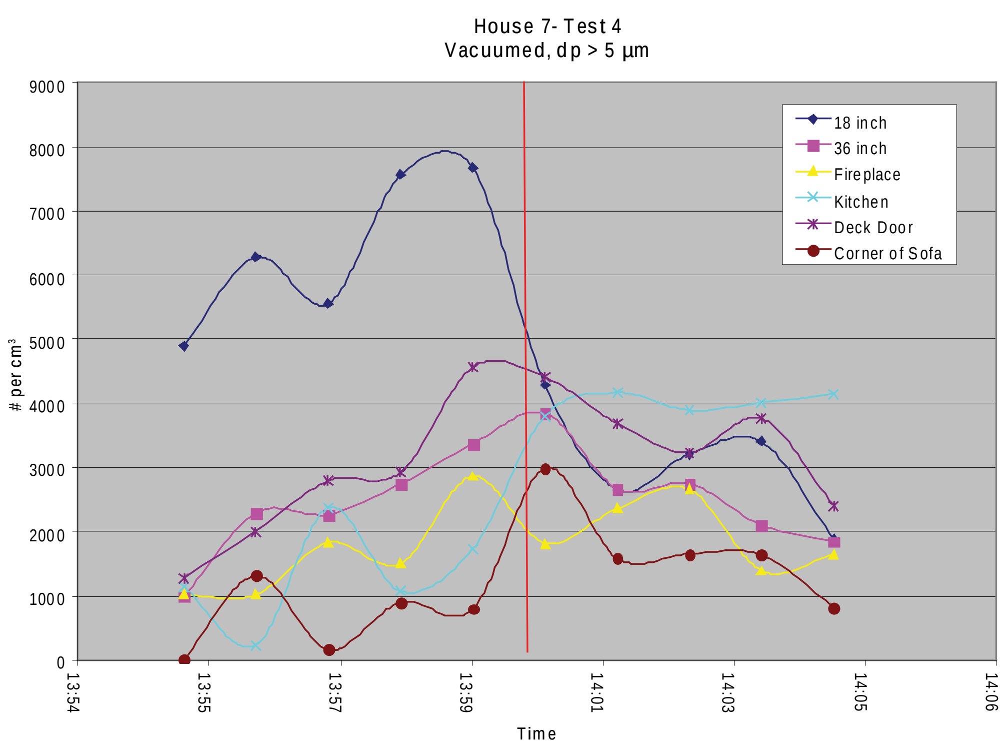

House 4 - Test 3
Vacuum, dp > 5 µm
4000
3500
3000
2500
2000
1500
1000
500
0
per cm³
13:58
13:59
14:01
14:03
14:05
14:07
14:09
14:11
Time
18 inch
36 inch
Corner Cabinet
Corner Bathroom
Door
Corner by Sofa


House 4 - Test 4
Vacuum, dp > 5 µm
1400
1200
1000
800
600
400
200
0
per cm³
14:40
14:41
14:43
14:45
14:47
14:49
14:51
14:53
Time
18 inch
36 inch
Corner Cabinet
Corner Bathroom
Door
Corner by Sofa


House 7 - Test 1
No Vacuum, dp > 5 µm
per cm³
Time
18 inch
36 inch
Fireplace
Kitchen
Deck Door
Corner of Sofa
30000
25000
20000
15000
10000
5000
0
10:03
10:04
10:05
10:06
10:07
10:08
10:09
10:10
10:11
10:12
10:13
10:14
10:15
10:16
10:17


House 7 - Test 2
No vacuum, dp > 5 µm
per cm³
Time
18 inch
36 inch
Fireplace
Kitchen
Deck Door
Corner of Sofa
35000
30000
25000
20000
15000
10000
5000
0
10:54
10:55
10:56
10:57
10:58
10:59
11:00
11:01
11:02
11:03
11:04
11:05
11:06


House 7 - Test 3
Vacuumed, dp > 5 µm
8000
7000
6000
5000
4000
3000
2000
1000
0
per cm3
12:56
12:58
13:00
13:02
13:04
13:05
13:07
Time
18 inch
36 inch
Fireplace
Kitchen
Deck Door
Corner of Sofa


House 7- Test 4
Vacuumed, dp > 5 µm
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
per cm3
13:54
13:55
13:57
13:59
14:01
14:03
14:05
14:06
Time
18 inch
36 inch
Fireplace
Kitchen
Deck Door
Corner of Sofa

APPENDIX D
Household Tracking Data

Note: Position indicates row number and location number specified in Figure 2-4. The first digit is the row number and the second digit is the location number. Week 0 corresponds to the background samples collected immediately after deployment of the carpet inside the house.

House T1

Week	Segment	Position	Mass (µg)
0	1	11	20.90
0	1	25	12.60
0	2	11	14.90
0	2	25	14.50
0	3	11	15.50
0	3	25	21.20
0	4	11	8.70
0	4	25	29.70
1	1	22	100.30
1	1	14	120.20
1	2	22	73.70
1	2	14	80.10
1	3	22	100.80
1	3	14	115.90
1	4	22	73.80
1	4	14	73.20
2	1	21	564.90
2	1	13	653.30
2	2	21	389.90
2	2	13	604.60
2	3	21	785.00
2	3	13	628.80
2	4	21	329.30
2	4	13	616.30
3	1	24	221.50
3	1	12	178.60
3	2	24	157.60
3	2	12	176.00
3	3	24	130.50
3	3	12	183.20
3	4	24	138.10
3	4	12	142.40
4	1	23	176.90
4	1	15	112.70
4	2	23	153.40
4	2	15	90.50
4	3	23	118.00
4	3	15	55.90
4	4	23	163.20
4	4	15	82.70

House T2

Week	Segment	Position	Mass (µg)
0	1	11	14.50
0	1	25	26.10
0	2	11	26.90
0	2	25	45.00
0	3	11	51.70
0	3	25	41.40
0	4	11	24.50
0	4	25	44.60
1	1	22	260.10
1	1	14	444.70
1	2	22	356.90
1	2	14	447.00
1	3	22	580.60
1	3	14	440.80
1	4	22	327.40
1	4	14	467.50
2	1	21	82.30
2	1	13	167.20
2	2	21	115.20
2	2	13	150.80
2	3	21	71.40
2	3	13	156.70
2	4	21	80.80
2	4	13	167.60
3	1	24	526.00
3	1	12	627.60
3	2	24	440.20
3	2	12	431.00
3	3	24	699.30
3	3	12	775.80
3	4	24	748.90
3	4	12	853.40
4	1	23	772.00
4	1	15	666.60
4	2	23	836.50
4	2	15	352.80
4	3	23	742.30
4	3	15	636.70
4	4	23	727.40
4	4	15	955.80

House T3

Week	Segment	Position	Mass (μg)
0	1	11	8.60
0	1	25	18.10
0	2	11	19.50
0	2	25	6.30
0	3	11	10.10
0	3	25	11.70
0	4	11	15.10
0	4	25	7.40
1	1	22	186.60
1	1	14	71.50
1	2	22	84.20
1	2	14	124.90
1	3	22	88.70
1	3	14	76.80
1	4	22	89.20
1	4	14	82.50
2	1	21	279.60
2	1	13	262.50
2	2	21	142.10
2	2	13	159.90
2	3	21	158.40
2	3	13	120.20
2	4	21	128.50
2	4	13	129.30
3	1	24	275.70
3	1	12	161.10
3	2	24	121.10
3	2	12	145.60
3	3	24	154.40
3	3	12	134.60
3	4	24	111.20
3	4	12	138.50
4	1	23	159.80
4	1	15	100.80
4	2	23	159.90
4	2	15	136.10
4	3	23	151.60
4	3	15	148.40
4	4	23	110.10
4	4	15	132.50

EPA/600/R-07/131 | November 2007 | www.epa.gov/ord

United States
Environmental Protection
Agency

PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT NO. G-35

Office of Research and Development
National Homeland Security Research Center
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300