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# House Dust Collection Efficiency of the High Volume Small Surface Sampler on Worn Carpets

Erik Svendsen,<sup>1</sup> Peter Thorne,<sup>2</sup> Patrick O'Shaughnessy,<sup>2</sup>  
Dale Zimmerman,<sup>3</sup> and Stephen Reynolds<sup>4</sup>

<sup>1</sup>University of South Carolina, Department of Epidemiology and Biostatistics, Columbia, South Carolina

<sup>2</sup>University of Iowa, Department of Occupational and Environmental Health, Iowa City, Iowa

<sup>3</sup>University of Iowa, Department of Statistics and Actuarial Science, Iowa City, Iowa

<sup>4</sup>Colorado State University, Department of Environmental and Radiological Health Sciences, Fort Collins, Colorado

*The High Volume Small Surface Sampler (HVS3) is a dust-sampling vacuum that allows for set airflow and back pressure during sampling, increasing precision. Total dust collection efficiency of the HVS3 has been evaluated only on new carpets—not worn carpets. We performed a factorial study to assess the impact of carpet wear, dust deposition level, carpet type, and relative humidity during sampling on HVS3 collection efficiency. House dust was aerosolized in a 1-m<sup>3</sup> exposure chamber and allowed to settle on test carpets and reference filters. Dust was embedded into the carpets and later extracted with the HVS3 under controlled environmental conditions according to established protocols. Overall collection efficiency was high, 88.3%. Collection efficiency was significantly higher at low relative humidity levels (30%) relative to high (75%) ( $p = < 0.0001$ ), though differentially between cut-pile and closed-loop carpets. Collection efficiency of carpets with high wear was significantly lower than those with midlevel wear ( $p = 0.01$ ). These results demonstrate that the design of the HVS3 partially corrects for differences in dust load and carpet type. However, collection efficiency of the HVS3 is affected by high levels of carpet wear and ambient humidity during sampling.*

**Keywords** carpet wear, dust, HVS3, vacuum sampler

Address correspondence to: Erik Svendsen, University of South Carolina, Department of Epidemiology and Biostatistics, 1600 Sumter St., Columbia, SC 29208; e-mail: svendsee@gwm.sc.edu.

## INTRODUCTION

Because carpets are dust reservoirs, carpet dust collected by vacuum samplers has been used as an indicator of long-term dust exposure in many field studies of various health outcomes.<sup>(1–4)</sup> However, true exposure could be very different from that implied from vacuum sample data, depending on the primary exposure route (inhalation

or dermal/ingestion) and duration of the exposure (acute, subchronic, or chronic).<sup>(3,4)</sup> Recent studies have validated the use of vacuum-collected carpet dust samples as indicators of subchronic (weeks-months) house dust allergen exposure<sup>(5)</sup> but not chronic (several years) exposure.<sup>(6)</sup> There is still a place for vacuum samples in field epidemiologic studies.

All household carpets are not alike.<sup>(7,8)</sup> There is tremendous variability in carpeting between homes<sup>(7–10)</sup> and in the types of samplers used in field studies to collect the dust from them.<sup>(1–4)</sup> Exposure measurement error associated with vacuum-based dust collection methods, due to the variability between carpets or the sampler performance itself, may misrepresent the true exposure and bias its association with observed health outcomes.<sup>(11)</sup> Data on the characterization of such biases could be incorporated into exposure assessments within future field studies, perhaps advancing our knowledge of the true health effects from exposure to residential dusts and their components.

Most house dust vacuum-based surface sampling methods are unable to control vacuum flow and pressure during operation. Surface type, humidity, dust load,<sup>(12)</sup> and carpet wear<sup>(13)</sup> can affect vacuum sampler performance, reducing comparability between samples and their utility for predicting health outcomes.<sup>(11)</sup> A vacuum sampling device was developed in 1990 to address vacuum performance concerns: the High Volume Small Surface Sampler (HVS3; CS3, Inc., Bend, Ore.). Although the sampling performance of the HVS3 has been characterized for lead dust,<sup>(14)</sup> pesticide residues,<sup>(15)</sup> total dust, and allergens (house dust mite and cat),<sup>(9,10,16)</sup> on new carpets, its dust sampling efficiency on carpets with a range of wear has not. The goal of this study was to evaluate the total dust collection efficiency of the HVS3 when sampling worn carpets under a variety of environmental conditions.

**TABLE I. Study Design**

3	Replicates
2	Carpet types: cut pile, closed loop
3	Wear levels: low, medium, high
2	Sampling environments: low humidity (30% RH), high humidity (75% RH)
2	Dust loading levels: 13.6 g/m <sup>2</sup> , 38.1 g/m <sup>2</sup>
72	Samples

## METHODS

### Experiments

To evaluate a vacuum sampler's collection efficiency, a known quantity of dust needs to be loaded onto a dust-free carpet that is then sampled with the device being evaluated. The collected mass is then compared with the loaded mass to get the collection efficiency (CE). We developed such an experiment to test house dust collection efficiency on (a) two types of carpets, (b) three wear levels, (c) in two sampling environments, (d) with two dust loads using a factorial design, as shown in Table I.

Cut-pile (CP) and closed-loop (CL) carpets of corresponding wear level were deposited simultaneously in each trial, one for subsequent high humidity (HH) and one for low humidity (LH) sampling conditions. Each deposition set (CP LH, CL LH, CP HH, and CL HH) was tested six ways: with 3 replicates of each, half at each dust loading concentration (3 ways with high, 3 ways with low dust loads) totaling 18 dust loading experiments.

### Test Dust and Carpets

Test dust was pooled from bulk household dust samples extracted using the HVS3 from home carpets. Bulk dust was sieved through a 100-mesh (150  $\mu\text{m}$ ) screen on a shaker using an established standard method.<sup>(17)</sup> Test dust was not adulterated with a compound to prevent agglomeration, such as fumed silica. Rather, agglomeration was reduced with the use of an in-line 20 mCi Ni<sup>63</sup> particle charge neutralizer. A 676-gram composite dust sample was collected and used for all carpet deposition trials. In order to retain as much dust as possible, dust was recovered from within the deposition chamber using the furniture attachment on the HVS3 after each experiment, resieved, and stored for additional experimental use. Test dust was stored at 4°C when not in use and allowed to equilibrate to room temperature for at least 45 min prior to use. Particle size distribution of the test dust was evaluated with an electronic particle counter (GRIMM Technologies, Inc., Douglasville, Ga.), placed in the center of the chamber during dust deposition experiments on initiation, at midway, and on completion of the study.

Two large worn carpets were procured from a local carpet installer (Randy's Carpets and Interiors, Coralville, Iowa) that represented the two types most often installed in homes (personal communication; Cary Mitchell, Carpet

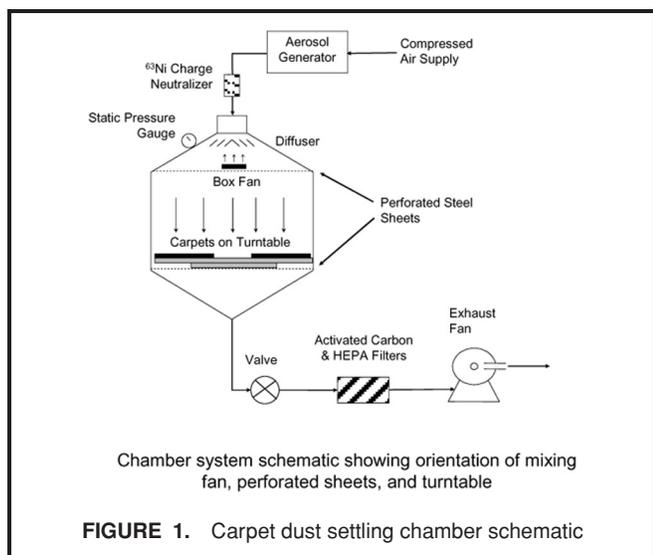
and Rug Institute, Dalton, Ga.) and corresponded well with established carpet wear reference scales (CRI Series A-1 and B-1, Carpet and Rug Institute). The carpets were similar to those recommended for vacuum performance testing:<sup>(18)</sup> one cut-pile (Saxony) and one closed-loop (Berber) carpet. The closed-loop carpet had a pile height of approximately  $\frac{1}{4}$  inch (0.6 cm), the cut pile approximately  $\frac{1}{2}$  inch (1.3 cm). No other carpet design characteristics were determined. Twenty 1-ft<sup>2</sup> (929 cm<sup>2</sup>) sections of each carpet were marked out for grading by a carpet wear grading panel. The panel consisted of three trained and experienced field staff who had routinely performed carpet wear testing. Carpet wear grading is commonly used both in quality assurance testing during carpet manufacture and in warranty claims assessments. Carpet wear is measured ordinarily, by decreasing wear from 1.0–5.0 in 0.5 unit intervals. We performed carpet grading according to the industry standard method (CRI Test Method 101, Carpet and Rug Institute), using a series of photographic reference scales exhibiting levels of wear specific to the carpet type (CRI Series A-1 and B-1, Carpet and Rug Institute). The method is rather easy to learn and apply to field studies. To limit a recall effect and maintain the independence of each reading, we had three graders read the carpet sections three times, with at least 1 week in between each series of grading.

Each carpet section was assigned a composite wear score. Carpets that were scored consistently (standard deviation <0.05) and that represented three different wear levels (low, medium, and high) were considered for inclusion in the study. Correlation statistics were used to select carpet pairs, one section to be sampled at high humidity and one at low. Six carpet pairs with highly correlated wear scores ( $R^2 > 0.90$ ) were selected, one pair at each wear level for each carpet type.

Selected test carpets were preconditioned prior to use according to an established method (ASTM F-608). Carpets were thoroughly cleaned with a brush agitating vacuum and then sampled with the HVS3 until there was no visible dust collected within the sample bottle. The selected carpet sections were then cut out and preconditioned again, as before. Carpet sections were reused in replicated experiments and reconditioned as above prior to each reuse.

### Dust Deposition Method

Dust was deposited onto preconditioned dust-free carpets within a 1-m<sup>3</sup> Rochester-style environmental chamber<sup>(19)</sup> operated with a very low flow rate (20 L/min) to best simulate natural dust settling onto a carpeted surface. The only flow into the chamber was via the aerosol generation system consisting of a compressed pure air source (20 psi, 20 L/min) that carried the test dust from a Wright Dust Feed (WDF) aerosol generator (0.33 rpm; BGI, Inc., Waltham, Mass.), through a 20 mCi Ni<sup>63</sup> charge neutralizer, and into the top of the chamber (Figure 1). To facilitate an even distribution of dust over the carpet surfaces, a plenum volume was developed with the addition of a perforated stainless steel sheet (1.6 mm diameter holes) directly above the main chamber volume. Mixing within the plenum was enhanced with a 4-inch (10-cm) in-line diffuser



at the top of the chamber and just below the aerosol injection point, and a 4" (10-cm) counter-flow fan mounted just above the perforated sheet. Four inch (10 cm) diameter plastic piping was used throughout with true union ball valves and O-ring connectors (Spears Manufacturing Co., Sylmar, Calif.) that allowed for rapid disassembly for cleaning. The true union ball valve in the chamber exhaust was adjusted to create a slight negative pressure ( $-0.13$  cm water) as provided by a downstream exhaust fan. Exit air was charcoal- and HEPA-filtered prior to discharge outside.

Chamber pressure was monitored with a Magnahelic water gauge (Dwyer, Michigan City, Ind.). Total chamber flow was monitored using a Durablock inclined manometer (Dwyer) attached to an orifice plate in the exhaust line. The low flow rate and large cross-sectional area of the chamber provided nearly quiescent conditions within the main chamber volume (downward velocity = 20 mm/min, equivalent to the settling velocity of a 3- $\mu$ m particle). Temperature and humidity during dust deposition were similar between all dust deposition experiments (mean temperature [ $^{\circ}$ C] = 22.1, CV = 2.5%; mean humidity [RH] = 52.1%, CV = 8.8%).

Particulate concentrations in the center of the main chamber volume were monitored for reproducibility using a direct-reading aerosol photometer (HAM; PPM, Inc., Knoxville, Tenn.) that was calibrated daily prior to use. Mean dust concentration within the chamber was high ( $\sim 20$  mg/m<sup>3</sup>) allowing for a 0.85 g/mm<sup>2</sup>/hour deposition rate. Dust particles settled onto four test carpets and five reference filters lying on a 0.9 m diameter rotating disc at the base of the chamber (Figure 2). The slotted stainless steel disc was attached to a low-speed turntable (Rotolite ST 350; Vue-More, Nutley, N.J.) and covered with a fine-mesh screen. The turntable speed was reduced to 0.67 rpm with a voltage regulator during experiments. Mean deposition load (ng/mm<sup>2</sup>) was determined by gravimetric analysis of the reference filters for each deposition experiment. Increasing deposition duration was used to increase carpet dust loading.

## Dust Embedding Method

Dust was embedded into the test carpets according to ASTM method F-608<sup>(20)</sup> to simulate foot traffic. This method used 30 passes of a 30-lb roller across the surface to press the dust deeply into the carpet. The angle and speed during each pass were consistent to enhance reproducibility. The test carpets were then transferred to cardboard boxes and stored at 4 $^{\circ}$ C.

## Sampling Environment

A 3.5 m  $\times$  3.5 m  $\times$  2.4 m (30 m<sup>3</sup>) environmental chamber was used for all carpet sampling. This stainless steel chamber has a supply air diffuser located in the center of the ceiling and an exhaust vent located in each corner. Incoming air was conditioned to desired temperature and humidity and cleaned of particulates and volatile gases with high-efficiency filters and carbon trays, respectively. The sampling chamber was maintained at 21 $^{\circ}$ C, and at either 30% or 75% relative humidity during carpet sampling, measured using an in-duct transmitting thermometer and hydrometer. All carpets were placed in the center of the sampling chamber for equilibration within loosely covered 1-ft<sup>2</sup> cardboard boxes for at least 12 hours prior to sampling.

## Dust Sampler

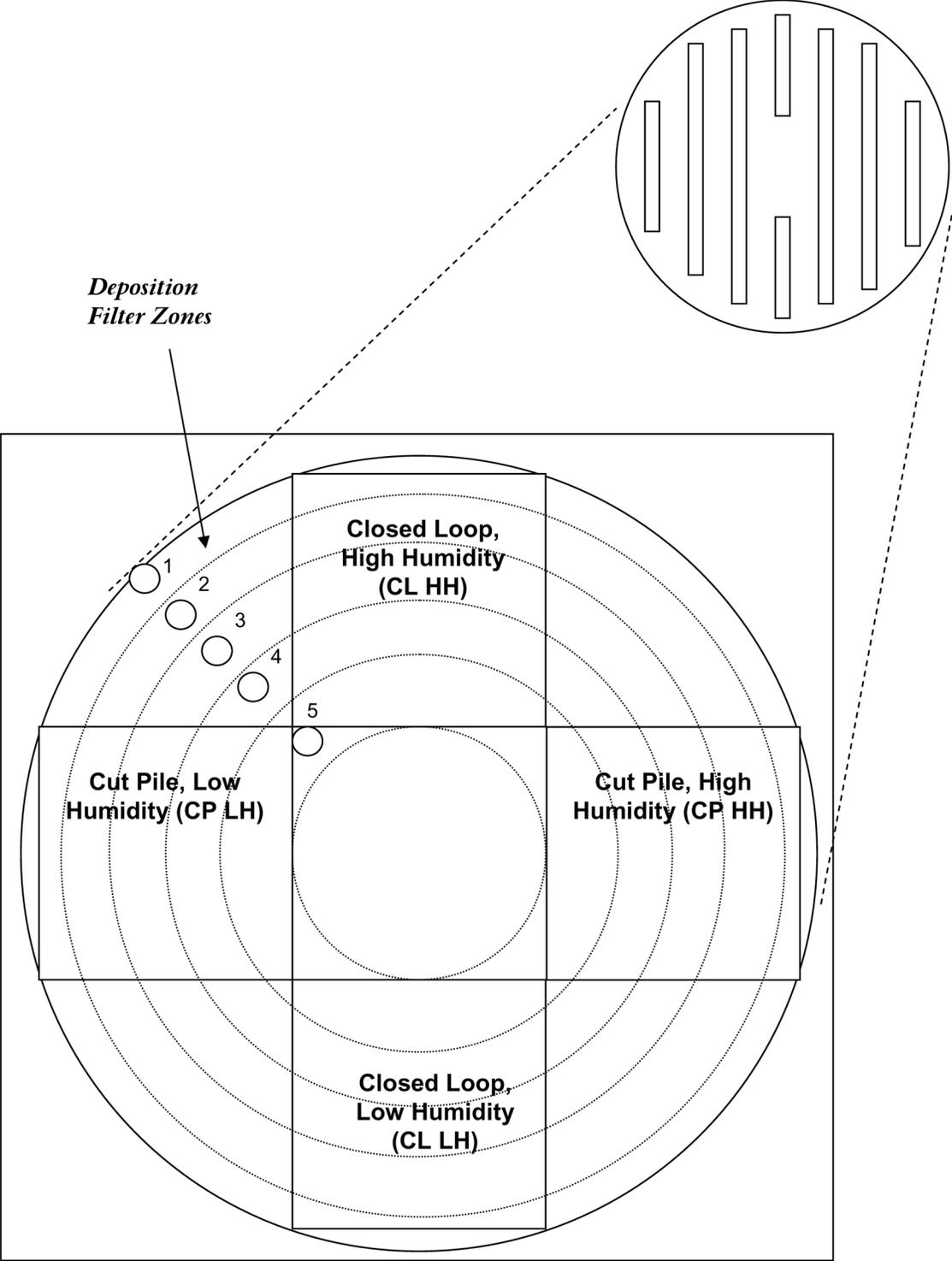
The HVS3 is a modified 10-amp vacuum cleaner that utilizes suction without agitation. The nozzle is set to level and perpendicular over the floor prior to sampling. A cyclone with a threaded coupling at the base allows for sample collection directly into sample bottles. Back-pressure and airflow are set and monitored according to the carpet type. More detailed information on the dust sampler is found elsewhere.<sup>(21)</sup>

## Sampling Method

The HVS3 sampling method was consistent with the standard HVS3 sampling protocol<sup>(20,21)</sup> with the following exceptions: (a) the surface area sampled was 1 ft<sup>2</sup> (929 cm<sup>2</sup>) rather than 1 m<sup>2</sup>, (b) the sampling rate was decreased to 15 cm/sec for increased precision, (c) samples were collected into 250 mL wide mouth Nalgene polypropylene bottles, and (d) bottles were sterilized in an autoclave and allowed to air dry prior to use.

A support carpet, similar to the one recommended in the standard method,<sup>(20)</sup> was fabricated. We placed a cut-pile carpet, with pile height similar to the test carpets, onto carpet-backing foam mounted on a 1.9 cm thick 1.22 m  $\times$  1.22 m square plywood board. A 929 cm<sup>2</sup> piece was cut out of the support carpet center to allow for test carpet attachment. To minimize dust migration from the foam backing into the test carpets, a 0.3 cm thick plastic sheet was placed over the foam backing. The support carpet and foam backing were securely attached to the board and fully reconditioned with the HVS3 prior to each use. A single test carpet was placed in the center cutout section of the support carpet. Using a staple gun, the

*Slotted Support Disc atop the turntable and beneath carpets*



**FIGURE 2.** Carpet deposition experimental design (top view not to scale)

test carpet was secured by stapling its four corners in place. Following sampling, staples were easily extracted using a large flathead screwdriver and pliers. The HVS3 cyclone housing was cleaned with electrostatic wipes (Swiffer; Procter and Gamble, Cincinnati, Ohio) after reconditioning the support carpet and between carpet types. Solvent cleaning methods were not considered due to length of drying time needed and safety concerns with the use of volatile solvents in an enclosed space.

### Gravimetric Analysis

Samples of recovered dust were sieved through a 100-mesh (150- $\mu\text{m}$ ) sieve according to an established protocol<sup>(17)</sup> and transferred into preweighed 2-mL microtubes for storage and potential allergen analysis. Weighing was performed in a temperature and humidity controlled weighing room at approximately 20°C and 50% relative humidity. All dust samples were allowed to equilibrate for at least 24 hours prior to weighing. Microtubes and reference filters were analyzed with dynamic weighing on a Mettler MT5 microbalance (Mettler Instrument Corp., Hightstown, N.J.) that was calibrated prior to use. Staticmaster ionizing units (NRD, Inc., Grand Island, N.Y.) were used to reduce static prior to filter analysis.

### Statistical Analyses

All statistical analyses were done using SAS/STAT v8.0 (SAS Institute). The following descriptive statistics were determined: mean deposition load (ng/mm<sup>2</sup>), its standard deviation, and coefficient of variation (CV). Collection efficiency was calculated by dividing the collected surface load by the mean deposition surface load. An analysis of variance (ANOVA) was used to determine the statistical significance of main effects of the four design factors on collection efficiency and to investigate the importance of two-factor interactions. Correlation statistics and paired t-tests were used to evaluate the mean measured level of carpet wear for individual carpet pairs. Analysis of covariance (ANCOVA) was used to evaluate the effects of concomitant variables, such as experimental dust deposition group, technician, duration of dust deposition, temperature, and relative humidity during dust deposition, chamber equilibration time prior to sampling, dust deposition rate, number of times dust generation was temporarily stopped for reloading, and date dust deposited. Regression diagnostics were used to evaluate model fit.

## RESULTS

There was good agreement in carpet wear scores. Between- and within-grader agreement were consistent each week that carpets were graded ( $R^2 = 0.91\text{--}0.96$  inter-rater,  $0.87\text{--}0.96$  intra-rater). The carpets that were chosen for the study were representative of the three levels of wear and each pair was strongly correlated (mean Pearson  $R^2 > 0.95$ ).

The deposition and sampling experiments were performed reproducibly. The mean deposition variability between

**TABLE II. Four-Way ANOVA of the Effect of Study Design Parameters on Total Dust Collection Efficiency**

	DF	SS	F	p
Model	6	8870	5.63	<0.0001
Error	65	17067		
Corrected total	71	25937		

	R-Square	CV (%)	Mean CE
	0.34	18.3	88.32

Source	DF	Type III SS	F Value	Pr > F
Deposition Level	1	850	3.24	0.077
Carpet wear: <sup>A</sup> Low	1	502	1.91	0.172
Carpet wear: <sup>A</sup> High	1	1823	6.94	0.011
Sampling %RH	1	4859	18.50	<.0001
Carpet type	1	173	0.66	0.420
Product of carpet type and %RH	1	1164	4.43	0.039

<sup>A</sup>Medium is the referent.

locations on the turntable was considered reasonable, CV = 18%. However, the mass median aerodynamic diameter (MMAD) of the test dust increased during the course of the experiments (beginning: MMAD = 5.6  $\mu\text{m}$ , GSD = 2.4; end: MMAD = 16.2  $\mu\text{m}$ , GSD = 3.3). Overall variability in humidity during environmental equilibration was reasonable, CV = 10%.

Results from a four-factor ANOVA showed that sampling humidity and high carpet wear were significantly associated with dust collection efficiency after accounting for the other design parameters (Table II). The effect of sampling humidity differed significantly by carpet type. Collection efficiency was greater in closed-loop than in cut-pile carpets (102% vs. 91%) at low sampling humidity and lower (78% vs. 83%) at high sampling humidity. An ANCOVA model was constructed that included other possible covariates, such as chamber equilibration time prior to sampling, dust deposition rate, number of times dust generation was temporarily stopped for reloading, and date dust deposited. The resulting best model explained over 70% of the variability in collection efficiency but did not appreciably change the magnitude of the associations of the design variables (data not shown). Including concomitant variables in the ANCOVA model did not modify the effects of the design parameters other than reducing the variability in the parameter estimates and increasing overall study precision (CV = 12.9%).

The mean collection efficiency for each design parameter was calculated and is reported in Table III. Overall mean collection efficiency was reasonably high (88.3%). Collection efficiency of carpets with midrange wear was significantly

**TABLE III. Mean Percentage Collection Efficiency by Study Design Parameters**

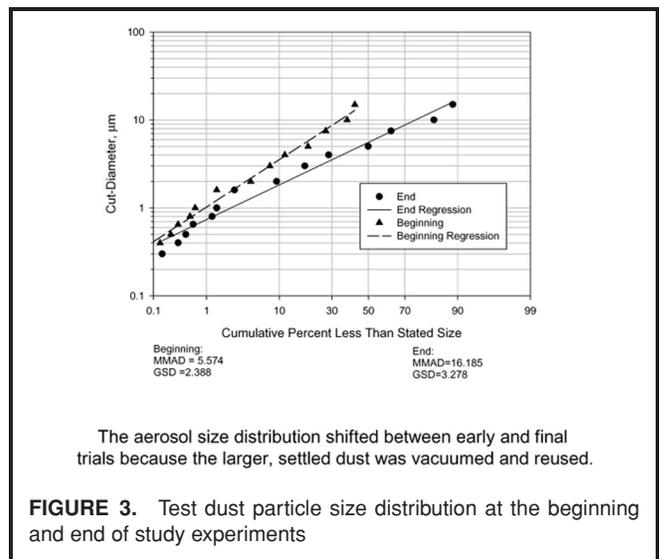
Design Parameter	Level	Mean	CV (%)
Carpet wear	Low	88.1	21
	Medium	94.6	21
	High	82.3	21
Carpet type	Closed loop	89.9	26
	Cut pile	86.8	16
Deposition level	Low	84.9	27
	High	91.8	16
Sampling humidity level	Low	96.5	17
	High	80.1	23

higher than the overall mean (94.6% vs. 88.3%, respectively,  $p < 0.05$ ) and carpets with high wear (82.3% vs. 94.6%,  $p < 0.05$ ). Carpet type and deposition load did not significantly affect collection efficiency. However, collection efficiency exhibited differential results between low and high humidity levels ( $p = 0.0001$ ).

## DISCUSSION

There were several strengths to this study. The test dust that was used in these experiments was actual household dust collected with the HVS3, not a surrogate dust as used in other studies<sup>(14)</sup> or house dust extracted by other methods.<sup>(9,10,13)</sup> Therefore, our results are more generalizable to field studies using the HVS3. The panel of carpet graders graded the test carpets consistently. Dust aerosols were generated evenly under near quiescent conditions simulating natural dust settling for both low and high deposition levels. Our dust deposition reproducibility (CV 18%) compared well with other carpet dust deposition methods.<sup>(12,22–24)</sup> Manual application of dust,<sup>(12)</sup> a perforated PVC rolling column,<sup>(22)</sup> and aerosols<sup>(23,24)</sup> have been used in carpet dust sampling research.

Our collection efficiency was higher and our variance lower than those reported by Wang et al.,<sup>(12)</sup> who did not use a cyclonic dust sampling method, and was comparable with the HVS3 results reported by Farfel et al.<sup>(14)</sup> on new carpets. Our observed high collection efficiencies could be partially explained by the use of an aerosol deposition method that evenly distributed the dust over the carpet surface rather than using a manual or roller method. Good overall study repeatability was demonstrated (CV = 18.3%). Carpet pairs had dust deposited on them simultaneously by design and then were sampled at different humidity levels. This design eliminated the possibility of differential deposition bias between samples of analogous test carpets sampled at different experimental humidity levels. We assessed carpets with a wide range of wear, all originating from the same cut-pile or closed-loop parent carpets, unlike the only other study of wear effects on vacuum sampler dust collection efficiency, which used well-characterized new carpets that were systematically worn



(equivalent to wear from a four-person home after 4–5 years) following soiling.<sup>(13)</sup>

There were some weaknesses in this study. Because our test carpets were the same except for their type, we could not test the effects of any other carpet design factors, unlike previous studies.<sup>(9,10)</sup> However, carpet dust exposure assessment using vacuum samplers would never include comprehensive assessment of all possible carpet design parameters because their assessment is destructive and infeasible in field settings. Lacking a standardized method for wearing carpet, we used residential worn carpet samples reproducibly graded for wear.

We were forced to reuse the carpet dust throughout the course of the experiments, which may have contributed to the particle size distribution increase that we observed in our test dust (Figure 3). To test whether this drift had any role on the collection efficiency of the HVS3, we included a variable within the ANCOVA for the date dust deposited. The date when the dust deposition experiment was performed was not associated with collection efficiency ( $p > 0.1$ ), so we concluded that the particle size drift that we found in our test dust did not significantly affect our study results. However, these findings are limited to house dusts with similar particle size distributions (Figure 3).

Another limitation was that we were unable to achieve extremely low humidity levels ( $\leq 20\%$  relative humidity) in our sampling environmental chamber as was done by others.<sup>(12)</sup> This was preliminary work limited to only three replicates. The use of larger replicate sizes may have better elucidated the modest deposition level effect. The main effects that we modeled explained only about one-third of the variability in dust collection efficiency ( $R^2 = 0.34$ , Table II). Additional work is needed to identify other carpet characteristics that may influence dust collection efficiency, yet are observable in a field setting.

We found that high carpet wear significantly reduced collection efficiency. This effect could be attributed to either the dust loading or sampling step. First, extensively worn carpets

are often matted, with the carpet tufts compacted. Such a carpet could easily retain dust within it during sampling, but because such carpets are matted it may have been difficult to thoroughly embed the dust into the carpets. Therefore, dust could have been pushed off the carpet instead of being pushed into the carpet during the embedding process. However, we find this unlikely because no such dust loss was noted during the embedding procedure. Carpets with medium wear actually had the highest collection efficiency, though not significantly different than those with low wear. Though this could be explained by chance, it could be due to true differences. New carpets lose fibers during vacuuming independent of any wear, due simply to the presence of loose fibers remaining from the manufacturing process. Perhaps the medium wear carpets were less dense due to fiber loss, allowing for better collection efficiency than in the carpets with low wear. Further study is needed to explain the differences in collection efficiency between different wear levels.

Humidity level during sampling was significantly associated with collection efficiency. There was a significant interaction between carpet type and sampling humidity levels. The effect of humidity during sampling on collection efficiency appears to be independent of the vacuum sampler, though differential between carpet types. Wang et al.<sup>(12)</sup> found that collection efficiency was lower at high humidity (85%) than at modest humidity (60%). Dust is hygroscopic, absorbing moisture and allowing the dust to adhere more strongly to carpet fibers under extremely high humidity levels. Likewise, under extremely low humidity (20%)<sup>(12)</sup> static allows for increased adherence of very small particles to carpet fibers. Our results show that under moderately low humidity (30%) there appears to be less static and moisture adhesion, allowing for greater collection efficiency than at high humidity (75%). Wang et al.<sup>(12)</sup> reported that closed-loop carpets were less affected by sampling humidity compared with shag carpets. We found that closed-loop carpets were more affected by humidity than cut pile. Closed-loop carpets appear to be more susceptible to the effect of humidity during sampling than do cut-pile carpets, though less than shag carpets. Further study with a wider range of humidity levels and carpet types is needed to completely ascertain the effect of sampling humidity on sampler collection efficiency.

Carpet type was not significantly associated with collection efficiency, unlike the findings reported by Wang et al.<sup>(12)</sup> This was likely due to the use of the HVS3 in our study, which, by design, adjusts for differences in carpet types (cut pile or closed loop) since backpressure and flow are set according to the appropriate carpet type prior to sampling. The HVS3 is cyclonic and is not susceptible to performance loss due to increasing dust load.<sup>(21)</sup> However, we found that collection efficiency was lower at low deposition levels compared with high, though not significantly. This is in contrast to the finding of Wang et al. and was attributed to the reduction in sampler performance during sampling at high dust loads. Because irretrievable dust loss due to the embedding procedure, loss in transport to the sampling chamber, and other handling losses

were consistent, the proportional loss due to handling was less for the samples loaded the most and greatest for those loaded the least. Perhaps this could explain the slight difference in dust collection efficiency between dust loading levels. More study is needed with a wider range of dust deposition levels and carpet types to demonstrate the veracity of this finding.

## CONCLUSIONS

This study has demonstrated factors that influence total dust sample collection efficiency with the HVS3. Superior design of the HVS3 compensates for the effect of carpet type and dust deposition level on collection efficiency. However, high levels of carpet wear significantly reduced dust collection efficiency. High humidity during sampling (75% vs. 30%) significantly reduced dust collection efficiency, though differentially between carpet types with closed-loop carpets more affected by humidity. Additional studies of HVS3 dust collection efficiency are needed with broader ranges of carpet wear, sampling humidity, and dust deposition level and with a greater variety of carpet types.

## RECOMMENDATIONS

These results demonstrate that the recording of humidity and carpet wear level data during exposure assessments using the HVS3 may enhance exposure estimates in field studies.

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