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During mortar removal with a right angle grinder, a building renovation process known as "tuck pointing," worker exposures to respirable crystalline silica can be as high as 5 mg/m^3, 100 times the recommended exposure limit developed by the National Institute for Occupational Safety and Health. To reduce the risk of silicosis among these workers, a vacuum cleaner can be used to exhaust 80 ft^3/min (2.26 m^3/min) from a hood mounted on the grinder. Field trials examined the ability of vacuum cleaners to maintain adequate exhaust ventilation rates and measure exposure outcomes when using this engineering control. These field trials involved task-based exposure measurement of respirable dust and crystalline silica exposures during mortar removal. These measurements were compared with published exposure data. Vacuum cleaner airflows were obtained by measuring and digitally logging vacuum cleaner static pressure at the inlet to the vacuum cleaner motor. Static pressures were converted to airflows based on experimentally determined fan curves. In two cases, video exposure monitoring was conducted to study the relationship between worker activities and dust exposure. Worker activities were video taped concurrent with aerosol photometer measurement of dust exposure and vacuum cleaner static pressure as a measure of airflow. During these field trials, respirable crystalline silica exposures for 22 samples had a geometric mean of 0.06 mg/m^3 and a range of less than 0.01 to 0.86 mg/m^3. For three other studies, respirable crystalline silica exposures during mortar removal have a geometric means of 1.1 to 0.35. Although this field study documented noticeably less exposure to crystalline silica, video exposure monitoring found that the local exhaust ventilation provided incomplete dust control due to low exhaust flow rates, certain work practices, and missing mortar. Vacuum cleaner airflow decrease had a range of 3 to 0.4 ft^3/min (0.08 to 0.01 m^3/sec^2) over a range of vacuum cleaners, hose diameters, and hose lengths. To control worker exposure to respirable crystalline silica, local exhaust ventilation needs to be incorporated into a comprehensive silica control program that includes respiratory protection, worker training, and local exhaust ventilation.

Keywords dust control, grinder, mortar removal, respirable crystalline silica, respirable dust, ventilation

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INTRODUCTION

To prevent water damage, exterior building renovation often requires the removal of deteriorated mortar between bricks or blocks and the subsequent replacement with new mortar. This process is termed "tuck pointing." Construction workers use hand-held, right angle grinders equipped with a 4.5-inch grinding wheel rotating at 10,000–12,000 rotations per minute (rpm) to pulverize the deteriorated mortar, which contains crystalline silica. While operating the right angle grinder, the worker applies pressure to the grinding wheel to maintain a cut depth of 0.39–0.79 inch (1–2 cm). The cut mortar dust moves tangentially away from the grinding wheel as the wheel exits the cut. The momentum of the mortar debris and the motion of the grinding wheel induces airflow that disperses dust throughout the work place.(1)

More than 35,000 nonresidential construction workers in the United States are exposed to more than twice the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) for crystalline silica.(2) Approximately 8500 of members of the Brick and Allied Craft workers union are involved directly in tuck pointing as part of the building restoration business.(3)

Mortar removal is known to cause excessive exposure to respirable crystalline silica. Shields(4) documented excessive respirable crystalline silica exposures during tuck pointing. Of the 37 exposure measurements taken over nearly a full shift, 38% of the samples exceeded 1 mg/m^3, and 19% of the exposures exceeded 5 mg/m^3 of respirable crystalline silica. These exposures are 20 to 100 times the NIOSH recommended exposure limit of 0.05 mg/m^3 as a time-weighted average for up to a 10-hour day during a 40-hr week.(5)

In a compilation of worker exposure to respirable dust and crystalline silica, a data set of 101 exposure measurements for respirable crystalline silica exposures during mortar removal was assembled from Occupational Safety and Health Administration (OSHA) compliance files, academic researchers, and private sources.(6) The geometric mean exposure was 0.60 mg/m^3 with a geometric standard deviation of 5.5. For

FIGURE 1. Photo of grinder hood from Industrial Contractors Supply.

this data, 10% of the exposures are expected to exceed 5.4 mg/m^3.[7] This suggests that control measures need to provide at least a factor of 100 reduction in respirable dust and respirable crystalline silica emissions so that most exposures are below the NIOSH recommended exposure limit.

Clearly, mortar removal causes excessive exposure to respirable crystalline silica that must be controlled. In Flynn and Susi's[8] literature review, local exhaust ventilation (LEV) is reportedly used to capture silica laden aerosol during tuck point grinding. A ventilated hood, as shown in Figure 1, is mounted on the grinder and a hose connects the exhaust take-off of the hood to a vacuum cleaner. A grinder's exhaust hood captures the dust that is directed into the exhaust take-off.[9] The vacuum cleaner exhausts air from the hood and separates the debris and respirable crystalline silica from the air.

The American Conference of Governmental Industrial Hygienists (ACGIH®) manual, *Industrial Ventilation*, contains specifications for the design of ventilation systems used for grinding operations.[10] In the manual's Figures VS-40-01 to VS40-03, an exhaust flow rate of 25–60 ft^3/min/inch of wheel diameter (0.22 to 0.66 m^3/min/cm) is recommended. As a practical matter, ventilation rates of 70 ft^3/min (2 m^3/min) provided an order of magnitude reduction in exposure when a 4 inch (10 cm) diameter grinding wheel was used for mortar removal during tuck pointing.[11] Because this airflow is only 15.6 ft^3/min/inch (0.17 m^3/min/cm) of blade diameter, the airflow may be too low to adequately control the airborne dust created by mortar removal. For such operations, the DustControl Company (Norsborg, Sweden), a manufacturer of commercial vacuum cleaners, recommends exhaust flow rates of 106 ft^3/min (3 m^3/min) based on proprietary data.[12]

An experimental study and computational fluid dynamic (CFD) analysis of the tuck point grinding process using LEV has provided some insight as to how the ventilation rates affects the capture of the dust generated by mortar removal.[4,13] The underlying physical model for the computational model considered the momentum of the particles as they exited the cut. The momentum of a stream of particles is known to induce airflow that will have a direction tangentially to the motion of the grinding wheel as it exits the cut.[1] The results of this simulation study utilizing CFD and a controlled laboratory experiment indicate exhaust ventilation rate and distance between the exhaust take-off and the mortar surface affect mortar dust capture by an LEV.

Figures 2A and 2B schematically illustrate the key findings from the CFD analysis. When the gap between the exhaust

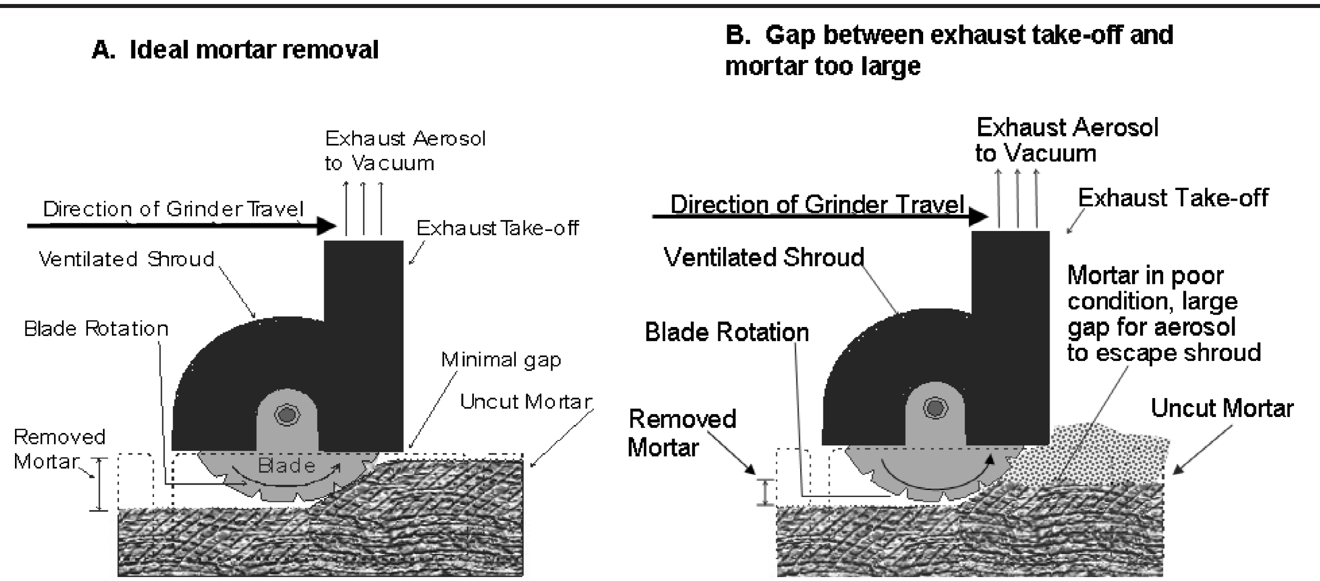

FIGURE 2. Ventilated shroud about a grinding blade: (A) Minimal gap between shroud and uncut mortar allow for good capture of pulverized mortar coming off blade. (B) Large gap between shroud and uncut mortar permits aerosol containing pulverized mortar to escape.

take-off and the uncut mortar is eliminated, a flow rate of 8 ft^3/min (0.23 m^3/min) is required to exhaust the grinder. Because mortar is typically recessed from the bricks, a gap will exist between the bottom of the exhaust take-off and the mortar. When this gap is sufficiently small and the airflow is sufficiently large, the dust and debris is captured as shown in Figure 2A. When this gap is too large and/or the exhaust volume is too small, the dust and debris flows between the bottom of the exhaust take-off and uncut mortar as shown in Figure 2B. For a gap of 0.5 inches (1.2 cm) and an airflow of 85 ft^3/min (2.4 m^3/min), the CFD analysis indicated complete particle capture. Experimentally, airflows larger than 80 ft^3/min (2.26 m^3/min) did not provide further reduction in the observed emission rate. At 80 ft^3/min, the observed respirable aerosol emission rate during laboratory studies was reduced by a factor of over 100 as compared with grinding with a hood at a zero ventilation rate. Thus, there was close agreement between the experimental and computational results. Because uncontrolled mortar removal can cause respirable crystalline silica exposures that exceed the NIOSH REL by a factor of 100, a minimum airflow of 80–85 ft^3/min (2.26–2.40 m^3/min) must be maintained, and the grinder hood needs to be positioned as shown in Figure 2A so that the capture of respirable dust is optimized.

This article reports the findings of field trials conducted to evaluate the exposure outcomes and functionality of using LEV to control the dust and debris generated by using right angle grinders to remove mortar. Specifically, the field trials were conducted to evaluate the dust exposures that occur when LEV is used to reduce worker dust exposures during mortar removal. In addition, airflows were continuously measured during some sampling sessions to evaluate whether vacuum cleaners maintained a steady state airflow.

METHODS

These field trials were conducted at three sites. Vacuum cleaners were chosen for use in the field studies based on their availability and their published specifications that indicate they provide the required flow rates and filtration efficiency (at least 99% efficient). A list of the vacuum cleaners used during these field trials is shown in Table I, and this table provides a list of available specifications for the vacuum cleaner. The Dust Director exhaust hood (Industrial Contractor Supply, N. Huntingdon, Pa.), shown in Figure 1, was used at all of the sites. The three study sites had been using this control measure before the authors arrived to collect data. If the subjects were not familiar with grinding with an engineering control (the local exhaust ventilation), they were instructed in the proper use and encouraged to grind as long as they felt necessary to become proficient with the modified grinder.

The three study sites were unique and there were important differences that may affect the dust exposure at each site. The following text briefly describes the different study sites:

A. At Site A in Iowa, two–three workers were removing mortar from the side of a school building and retaining wall. The ShopVac (Shop-Vac Corporation, Williamsport, Pa.) and Dust Director vacuum cleaners were used interchangeably at this site. The mortar at this site had deteriorated and some of the mortar was missing. The workers worked independently of each other and there were no obvious extraneous dust sources. The workers were generally at ground level.
B. At Site B in Minnesota, DustControl vacuum cleaners were used by three workers. This work was done on swing stages that were suspended from the roof. Two workers were on a swing stage along with the two vacuum cleaners. These workers were within 20 feet (6 m) of each other and are potentially exposed to each others' dust.
C. At Site C in Minnesota, the AltoWap vacuum cleaner (Hadsund, Denmark) was used by a crew of 2–4 workers who worked as a team to remove and repair mortar on the side of a brick building that was a power plant. The building was surrounded by scaffolding and the workers were next to each other. The scaffolding was enclosed by other parts of the building structure and by a plastic wrap. Thus, natural ventilation at this site was reduced as compared with the other sites during this study.
D. At Site D in Iowa, a single worker was removing mortar from the external walls of stadium at ground level. He used a Bosch vacuum cleaner (Mt. Prospect, Ill.) with an electrically powered rapper that is intended to knock accumulated debris off the final filter. At this site, exposure monitoring was not conducted as the budget for exposure monitoring had been expended.

During the current study (with ventilation), individual names were not recorded to protect human subject confidentiality.

Respirable Dust and Respirable Crystalline Silica Measurements

Respirable dust and respirable crystalline silica concentrations were measured on the worker, on the vacuum cleaner near the exhaust, and away from the operation. Personal samples were taken to evaluate whether the NIOSH REL for respirable silica was exceeded while the controls were in place. On the vacuum cleaner, the sample was located near the air discharge from the vacuum to evaluate whether vacuum cleaners can be a noticeable emission source. Because the cyclones will sample the respirable dust in air that has a velocity of 250 to 500 cm/sec at the discharge from the empty vacuum cleaner, estimated aspiration efficiencies for particles larger than 4 μm is estimated to be under 65% based on equations developed by Hangal and Willeke and summarized by Brockman.[14] Thus, this measurement may understate the magnitude of the respirable dust emissions. Ambient samples collected 3–6 m away from the grinding operation were collected to characterize the background respirable dust and respirable crystalline silica concentrations. The concentration measurements were task based and were made during the mortar removal aspects of the job. These tasks included mortar

TABLE I. Description of Vacuum Cleaners

Manufacturer	Model	Current (amperes)	Maximum Hose Diameter (inches)	Filtration	Description of Filter Cleaning
Alto Wap (Hadsund, Denmark)	SQ23	15	2	Bag and one-panel filters with total area of 1 m^2. Filter efficiency specifications were not available.	Manual beater bar for final filter.
Bosch (Mt. Prospect, Ill)	3931	11.1	2	Bag and Filter with a surface area of 0.8 m^2. The advertised filter efficiency is 99.93% of particles at 3.0 μm and larger.	Electric motor used to vibrate final filter when vacuum cleaner motor is off.
DustControl (Norsborg, Sweden)	2700	10	2	Filter and, sometimes used with cyclone. This vacuum cleaner has a tangential inlet. The filter area is 1.5 m^2. The advertised filtration efficiency is "better than 99.9%."	Cover inlet to vacuum cleaner and release vacuum removing plastic cover from a vent hole. This causes the final filter to flex and drop material into a plastic bag.
Shop Vac (Shop-Vac Corp., Williamsport, Pa.)	QUL650	12	2	Bag and final filter with area of 0.4 m^2. Final filter efficiency is 99.97% at 0.3 μm.	Manually shake vacuum cleaner, turn vacuum cleaner on and off.
Dust Director (Industrial Contractor Supply, N. Huntingdon, Pa.)		9.5	2	Bag and filter with area of 0.4 m^2. Final filter efficiency is 99.97% at 0.3 μm.	Manually shake vacuum cleaner, turn vacuum cleaner on and off.

removal with ventilated grinder, vacuum cleaner maintenance, positioning of the vacuum cleaner, and the moving swing stages or suspended scaffolding. Samplers were paused for lunch breaks. This mortar removal was performed only for part of a shift.

To measure respirable dust and respirable crystalline silica concentrations, a battery-operated pump moved 4.2 L/min through a cyclone and a preweighed 37 mm diameter, 5 μm pore-size low-ash polyvinyl chloride filter. The filter was supported by a backup pad in a three-piece filter cassette sealed with a cellulose shrink band. The top of the filter cassette was removed and the open cassette was mounted on a GK2.69 cyclone (BGI, Waltham, Mass.). This cyclone is used by the United Kingdom's Health and Safety Executive to measure respirable dust and crystalline silica exposure.(15) The mass of material collected on the filters was determined as described by NIOSH method 600.(16) Subsequently, the filters were analyzed for crystalline silica by X-ray diffraction in accordance with NIOSH method 7500.(16) The limit of quantitation is 0.01 mg for both quartz and cristobalite on filters.

Respirable Dust and Respirable Crystalline Silica Concentration-Data Analysis

At these study sites, workers had been using grinder hoods and vacuum cleaners to capture and control the respirable dust generated by mortar removal. Because the authors did not want to elevate worker exposure to respirable crystalline silica, the workers were not asked to conduct mortar removal without ventilation. To assess the effect of ventilation on worker exposures, current study data was compared with published data on respirable dust and crystalline silica exposures during mortar removal. Three data sets were used for this comparison:

1. The data published by Flanagan et al.[6] was compiled from private, research, and regulatory sources. For dust exposures during mortar removal, this data set included 101 and 97 exposure measurements for respirable crystalline silica and respirable dust, respectively. These exposure measurements were made between 1992 and 2002. These results involved short-term, presumably task-based sampling, and long-term sampling (greater than 6 hours). For 83% of the exposure measurements, including numerous other tasks besides mortar removal, information about the presence or absence of control measures was missing.[6]
2. Nij et al.[17,18] reported on a study of silica exposures and control measured in the Dutch construction industry. They reported 10 exposure measurements for mortar removal. Again, the use of control measures was not reported for the exposure measurements. As part of this study, questionnaires were sent to construction workers. Among 17 workers who responded to this questionnaire and who performed mortar removal, only 3 workers reported using local exhaust ventilation to control worker dust exposure.
3. The respirable dust and respirable crystalline silica concentrations measured on the worker were compared with OSHA compliance measurements in the Chicago, Illinois, area.[4] This compliance data set was assembled before control measures were implemented. These workers may also be engaged in site preparation, pointing (process of adding wet mortar to the joint as opposed to grinding dry mortar), and other tasks that are likely to result in little or no personal exposure to respirable silica for the time workers are performing nongrinding tasks. These measurements were assembled and reviewed by Charles Shields of OSHA Region 5. These exposure measurements and documentation for these measurements have been published elsewhere.[4]

Before statistical analysis, the logarithms of the respirable dust concentrations and respirable crystalline silica concentrations were computed. The concentrations below the limit of quantitation were replaced with a concentration estimated as the limit of detection divided by 2.[18] The Smith-Sauterthwaite t-test for unequal variances was used to evaluate whether the respirable crystalline silica and respirable dust concentrations differed significantly between the data collected during this field trial and the comparison data sources mentioned above.[19]

At Site A, the Dust Director and Shop Vac vacuum cleaners were used interchangeably. Both vacuum cleaners had a similar design and both employed identical high-efficiency filter media and bags. At the other two work sites, all the workers used the same make and model of vacuum cleaner. A one-way analysis of variance was performed for each study site to evaluate whether sampling location affected the geometric mean for respirable dust concentration. This analysis was performed on the natural logarithms of the respirable dust concentrations. Then, Tukey's multiple comparison test was used to evaluate concentration differences between geometric means. This test was conducted at an overall confidence level of 95%.[19] This analysis was not conducted on the respirable crystalline silica concentrations because the respirable crystalline silica concentration at the ambient sampling location was frequently below the limit of detection.

Airflow Measurement

During some of the task-based exposure measurements, vacuum cleaner static pressure was measured and logged to obtain the time dependence of the airflow rate during the grinding tasks. The fan curve, the relationship between airflow and static pressure that was experimentally determined, was used to convert the static pressure measurements to airflow. The pressure transducer (Smart Reader Plus 4, SPR-004-5G; ACR Systems, Surrey, British Columbia, Canada) is a digital barometer that recorded absolute pressure to the nearest 0.2 inches of water (0.05 kPa). The pressure transducer incorporated a 12-bit data logger with 32 kilobytes of memory. The pressure transducer measured absolute pressure in the space between the final filter and the inlet to the vacuum cleaner motor.

Pressure measurements were made by positioning a tube from a pressure transducer into the space between the final filter and the inlet to the vacuum cleaner motor or, if space permitted, by placing the pressure transducer directly in the space between the inlet to the motor and the final filter. Any resultant holes were sealed with a silicone caulk. The vacuum cleaner static pressure was computed as the difference between atmospheric pressure and the pressure between the last filter and the inlet to the vacuum cleaner motor. The pressure measured, when the vacuum cleaner was off, was the atmospheric pressure. The pressure was logged every 8 sec.

Prior to conducting the field trials, the fan curve, the relationship between flow rate and vacuum cleaner static pressure, was established experimentally. Figure 3 shows a schematic of the laboratory apparatus used to determine the relationship between static pressure and flow rate. Static pressure just after the final filter and before the fan was measured with a U-tube manometer (Dwyer Instruments, Michigan City, IN). When the

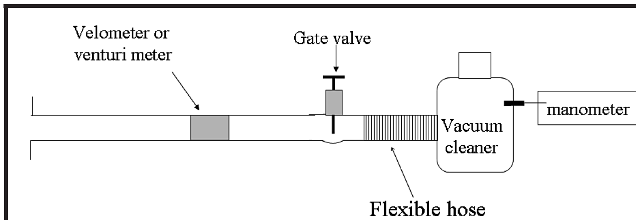

FIGURE 3. Apparatus for determining vacuum cleaner fan curve. Note that the vacuum cleaner static pressure is measured between the final filter and the vacuum cleaner motor inlet.

vacuum cleaner was on, flow rate was manipulated by adjusting the gate valve shown in Figure 3.

Static pressure measurements and the airflow rates were recorded at zero flow (gate valve closed) and maximum flow (gate valve fully open) and at least eight flow rates in between the minimum and maximum flow rate. Flow rates were measured with a venturi meter (model 2 HVT-FV; Primary Flow Signal, Tulsa, Okla.). The formulas relating the pressure differential produced in the venturi meter and airflow are well described in fluid mechanics text books and a standard published by the American Society of Mechanical Engineers (ASME).[20,21] Over the range of flow rates tested, 20–200 ft^3/min (0.56 to 5.6 m^3/min), the uncertainty in the flow rate measurement was less than 2%.[22]

Airflow Measurements–Data Analysis

The fan curves were obtained by using the regression analysis tools available with an Excel 2003 spreadsheet. Airflow (Q) was modeled as a linear function of vacuum cleaner static pressure (ΔP):

$$Q = m(\Delta P) + b \quad \textbf{(1)}$$

where Q = the airflow (cfm); ΔP = the static pressure at the vacuum cleaner inlet (inches of water); m, b = regression coefficients for slope and intercept. The intercept (b) was the airflow at zero static pressure.

For the field trials, Eq. 1 was used to estimate airflow from the measured vacuum cleaner static pressure. As the vacuum cleaners collected debris, a prefilter cake inevitably formed on the vacuum cleaner's filters and this accumulation of dust reduced airflow through the vacuum cleaner. Several times during a sampling session, workers would stop grinding and take actions to dislodge this debris from the vacuum cleaner filter. This caused the flow rate to temporarily increase to a new initial value.

To characterize the flow rate loss, the initial flow rates and the final flow rates were tabulated. Then, the difference between the starting airflow after dislodging debris and the final flow before dislodging debris was divided by the elapsed time. This is termed flow rate loss (ft^3/min^2). The Minimum Unbiased Estimate of the Arithmetic Mean was computed for flow rate loss, the initial flow rates, and the final flow rates. Land's Exact Estimate of the Arithmetic Mean Confidence Limits was computed for the flow rate loss.[7] A one-way analysis of variance (Proc GLM, version 9.1, SAS Institute) was conducted to evaluate whether flow rate loss varied between the different vacuum cleaners studied and operating conditions. The normality of the residuals from this analysis was evaluated using the Shapiro-Wilk statistic (Proc Univariate, version 9.1, SAS Institute, Cary, N.C.).

Video Exposure Monitoring

Video exposure monitoring (VEM) was used to evaluate how work activities affect exposure.[23] This limited data collection involved one worker each at Sites A and C. An aerosol photometer (Casella Windust Pro, Bedford, U.K.) measured the worker's real-time dust exposure for a 30–60 minute period during routine mortar removal. The sampling probe for the aerosol photometer was located in the workers' breathing zone. Concurrently, a data logging pressure transducer recorded vacuum cleaner static pressure, whereas workplace activities were recorded using a digital video camera. Start times were synchronized prior to beginning VEM. The dust exposure and flow rate were graphically and numerically overlaid onto the videotape using VEM software developed by NIOSH.[23] This information was used to prepare annotated plots that indicated

TABLE II. Personal Exposures

Data, Source	n	Geometric Mean (mg/m^3)	Geometric Standard Deviation	Range (mg/m^3)	P for t-test for Difference Between Reported Data and Data from this Study
Respirable dust					
Shields compliance data[4]	37	12.3	4.1	0.25–349.10	$P < 0.0001$
Flanagan et al.[6]	97	6.1	3.9	Not reported	$P < 0.0001$
Nij et al.[18]	10	2.4	2.7	0.55–8.0	0.014
The present study (with ventilation)	22	1.0	2.1	0.31–4.50	
Respirable crystalline silica					
Shields compliance data[4]	37	1.14	6.5	0.01–76.10	$P < 0.0001$
Flanagan et al.[6]	101	0.60	5.5	Not reported	$P < 0.0001$
Nij et al.[18]	10	0.35	2.8	0.089–1.6	0.0003
The present study (with ventilation)	22	0.06	3.2	<0.01–0.86	

TABLE III. Geometric Mean Respirable Dust Concentrations at the Different Sampling Locations and Grouping Code from Tukey's Multiple Comparison Test

Sampling Location	Dust Director/Shop Vac Geometric Mean (mg/m^3)	Dust Director/Shop Vac Geometric Std. Dev.	Dust Director/Shop Vac Grouping Code[A]	Dust Control 2700 Geometric Mean (mg/m^3)	Dust Control 2700 Geometric Std. Dev.	Dust Control 2700 Grouping Code	Alto Wap Geometric Mean (mg/m^3)	Alto Wap Geometric Std. Dev.	Alto Wap Grouping Code
Personal	0.96	2.70	a	0.94	2.59	a	1.09	1.69	A
Vacuum cleaner exhaust	0.2	8.15	a	0.44	3.08	a	0.09	4.37	B
Ambient	0.02	1.90	b	0.06	3.97	b	0.13	2.70	B
Probability > F		0.0006			0.007			<0.0001	
Number at each study site		6			5			11	

[A]Locations with different grouping codes are significantly different at an overall level of confidence of 95%.

increased dust exposures and activities that contributed to exposures.

RESULTS

Respirable Dust and Respirable Crystalline Silica Exposures

As documented in Table II, personal exposures (time-weighted averages) to respirable dust and silica for workers using LEV during the present study were significantly less than was reported for the three comparison data sets from the literature. The silica exposures measured during the current study (with ventilation) had a geometric mean of 0.06 mg/m^3 for 22 personal exposure measurements at the three study sites. In contrast, the geometric means for the three studies listed in Table II were between 0.35 and 1.14 mg/m^3. The exposures from the three comparison studies were approximately 5 to 20 times greater than the mean exposure for workers using a grinder with LEV in the current study. As tabulated in Table II, these differences are all significant.

Table III summarizes the personal and area sampling respirable dust concentrations by study site and vacuum cleaner. As documented earlier, different vacuum cleaners were used at different sites. The analysis of variance showed that sampling location (personal, vacuum cleaner exhaust, and ambient) significantly affected the respirable dust concentration. Based on Tukey's multiple comparison test, the personal respirable dust concentrations were significantly higher than the ambient respirable dust concentration. For the Dust Control 2700 and Shop Vac/Dust Director vacuum cleaners, the respirable dust concentration measured near the vacuum cleaner exhaust was significantly higher than the ambient concentration. This result suggests that vacuum cleaners may be an emission source. However, fugitive dust from the grinding operations may also be contributing to the increased respirable dust concentration in the vacuum cleaner exhaust. Controlled laboratory testing is needed to the overall performance of these vacuum cleaners to collect airborne dust.

Video Exposure Monitoring

In Figures 4 and 5, aerosol photometer and airflow measurements are plotted as a function time and the plots are annotated to note work tasks that appeared to elevate exposure. At Site C, where the data in Figure 4 was collected, the wall was in relatively good condition with little mortar missing. In this figure, many of the momentary spikes in exposure were the result of vertical plunge-cuts. During these cuts, the gap between the exhaust take-off and the mortar appeared to exceed 0.5 inch (1–2 cm) allowing dust to escape capture. The large aerosol peaks at approximately 9:07–9:09 involved deteriorated and missing mortar as well as a damaged brick. As a result, the gap between the mortar and the exhaust take-off was too large, allowing dust and debris to escape capture. At this location, much of the mortar in the joint was absent, and

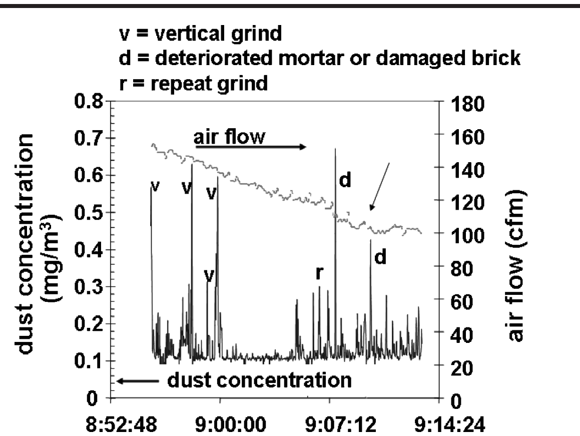

FIGURE 4. Annotated plot showing flow rate and dust exposure at a site where the mortar was largely in tact.

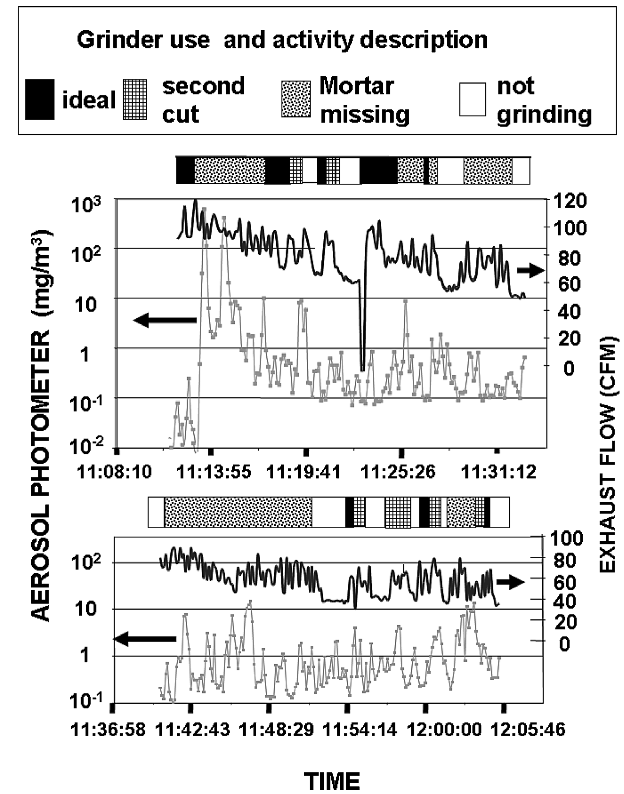

FIGURE 5. Annotated plot of flow rate, aerosol exposure, and task descriptor during mortar grinding. The site was not ideal because there was much missing mortar.

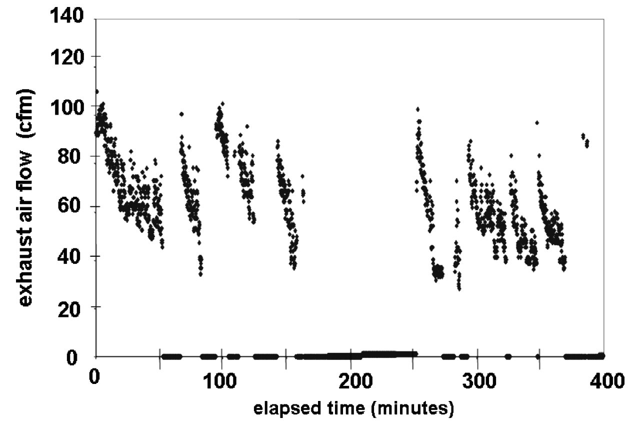

FIGURE 6. Exhaust air flow through Dust Director vacuum operated with 12 ft of 1.5-inch diameter corrugated hose

the distance appeared to exceed 0.5 inch (1–2 cm) between the grinder and the mortar. Vacuum cleaner airflow rates were above 100 ft^3/min (2.8 m^3/min) during the data collection on this trial.

Compared with Figure 4 the exposure peaks in Figure 5 are much larger. During this trial at Site A, the overall condition of the brick wall and mortar was poor. Because much of the mortar was missing, the gap between the exhaust take-off and the mortar unavoidably exceeded 0.5 inch (1–2 cm), allowing dusty air to flow between the exhaust take-off and missing mortar. In addition, the vacuum cleaner airflow rates decreased from 120 to 40 ft^3/min (3.4 to 1.1 m^3/min) over a 50-min time period.

Airflow

The regression results in Table IV show a consistent linear relationship between vacuum cleaner static pressures and flow rates since the values of R^2 are greater 0.98. This is consistent with other literature on vacuum cleaners.[12] In Table IV, the intercept is the airflow at zero static pressure loss. The Shop Vac and Dust Director had the greatest maximum flow rate for any of the tested vacuums and the greatest loss of volumetric flow for each unit increase in static pressure. In contrast, the DustControl vacuum cleaner had the smallest intercept (airflow at zero static pressure) and the smallest slope.

Figures 6 through 9 show temporal plots of exhaust ventilation rates for the vacuum cleaners used in conjunction with a ventilated hood during tuck point grinding, and Table V describes the flow rate losses for the different combinations of hose and vacuum cleaner observed in this study. In applying these results to other situations, one must realize that the mass loading per unit time and the dust size distribution of the captured dust may have differed between sites and even

TABLE IV. Regression Results for Equation Relating Static Pressure to Vacuum Cleaner Airflow

Vacuum Cleaner	R^2	n	Standard Error of Estimate (ft^3/min)	Slope (ft^3/min/inch of water)	Intercept (ft^3/min)
ShopVac	0.989	22	6.57	–5.17	261
Alto Wap two-blowers	0.987	12	7.38	–3.58	257
Dust Director	0.997	12	1.64	–4.39	222
Bosch	0.985	17	3.85	–1.6	120
DustControl	0.999	11	0.64	–1.33	120

Notes: The model is: Airflow = intercept + slope × (vacuum cleaner static pressure). R^2 – fraction of variability explained by model. n – number measurements. Standard error of estimate—standard deviation about regression line. Conversion factors to metric units are given in Appendix A.

TABLE V. Summary Statistics Describing Average Flow Rate Decrease per Minute of Grinding

Vacuum Cleaner	Hose Diameter (inches)	Average Flow Rate Loss MVUE (ft^3/min/min of grinding)	Geometric Standard Deviation	n	95% Confidence Limits on Mean: Lower	95% Confidence Limits on Mean: Upper	Grouping Code from Scheffe's Test[A,B]
Shop Vac QUL650	2	3	1.81	6	2.04	6.65	A
Dust Director 9.5	1.5	2.01	1.47	9	1.62	2.68	A,B
Bosch 3931	2	1.17	1.72	5	0.78	2.8	A,B
Dust Director 9.5	2	1.16	1.48	9	0.94	1.57	B,C
Alto Wap SQ23	2	0.97	2.32	6	0.58	4.08	B,C
DustControl 2700	1.5	0.66	1.27	4	0.52	0.95	B,C
DustControl 2700 (with/cyclonic preseparator)	2	0.41	1.39	5	0.33	0.62	C

[A]The combination of vacuum cleaner and hose diameter significantly affected geometric mean slope P < .0001; the residuals were normally distributed.
[B]Geometric means with different grouping codes were significantly different.

between different sessions at the same site. However, the data clearly show that the ventilation rate decreases as the vacuum filter loads with captured debris and dust. Captured debris and dust form a cake on the filter causing a decrease in flow rate until the worker acted to knock the dust cake off the filter(s). After the prefilter cake had been dislodged as described in Table I, the airflow through the vacuum cleaner increased and then the airflow decreases as shown in Figures 6–9.

Figure 6 shows the exhaust ventilation rate for the Dust Director vacuum during routine grinding operations. As the vacuum loads with pulverized mortar (debris and dust), flow rate decreased rapidly. The vacuum system was operating well below the 80–85 ft^3/min (2.26–2.4 m^3/min) flow rate that is recommended for mortar capture.[(4)] In Figure 7, the DustControl vacuum cleaner operated with ventilation rates near or above 85 ft^3/min for approximately half the time during data collection. In contrast, the Shop Vac vacuum cleaner described in Figure 8 experienced a rapid decrease in exhaust ventilation rates as the filter loaded with pulverized mortar while grinding. Figure 9 describes exhaust ventilation rates during capture of pulverized mortar for the AltoWap vacuum cleaner. This vacuum system was able to maintain an airflow rate that was larger than 85 ft^3/min during most of its operation.

In Table V, the airflow rate losses per minute during mortar removal differed significantly ($P < 0.0001$) among the different combinations of hoses and vacuum cleaners for which flow rate monitoring was performed. The deviations from the assumption of normality were not significant ($P = 0.5$). The average flow rate decreases were between 3 and 0.4 ft^3/min (0.01 m^3/min^2) of grinding. The Shop Vac vacuum cleaner had the greatest slope in Table IV, –5.17 ft^3/min/inch of water (-6×10^{-4} m^3/min/pascal), the greatest flow rate loss in Table V, 3 ft^3/min/minute (0.08 m^3/sec^2) of grinding, and the largest intercept in Table IV, 261 ft^3/min (7.4 m^3/min). In contrast,

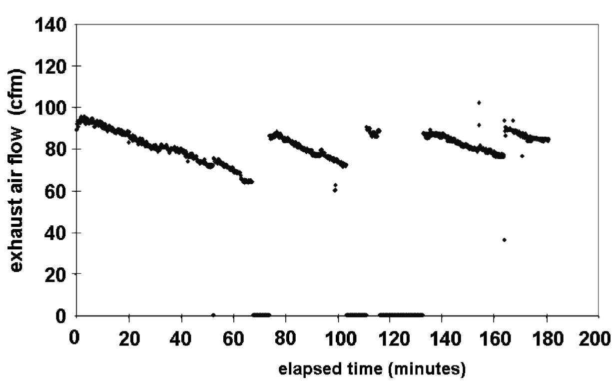

FIGURE 7. Exhaust air flow through Dust Control vacuum operated with 16 ft of 2-inch diameter corrugated hose. This vacuum cleaner was used with a cyclonic preseparator.

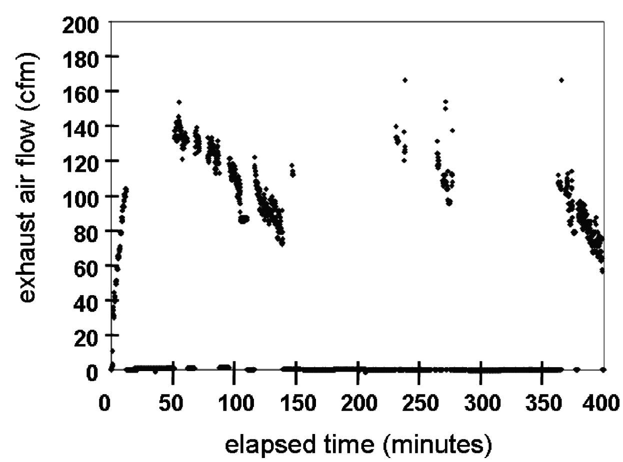

FIGURE 8. Exhaust air flow through Shop Vac vacuum operated with 16 ft of 2-inch diameter corrugated hose.

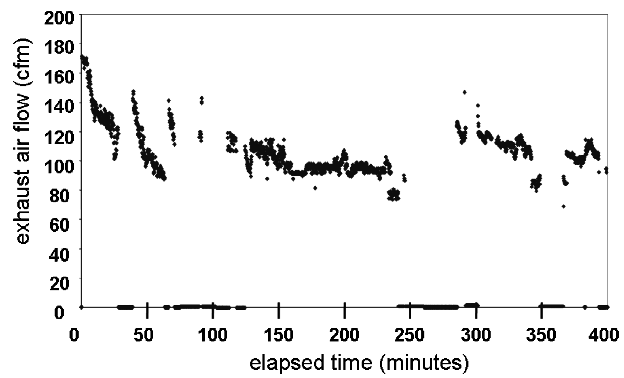

FIGURE 9. Exhaust air flow through Alto Wap vacuum operated with 12 ft of 2-inch diameter corrugated hose.

the DustControl vacuum cleaner had the smallest slope in Table IV, −1.4 cfm/inch of water (-1.6×10^{-4} m^3/min/pascal) the smallest flow rate decrease in Table V, 0.4 ft^3/min/minute (0.01 m^3/min^2) of grinding, and the smallest intercept in Table IV, 120 ft^3/min (3.4 m^3/min).

Table VI documents the average initial and final flow rates used to compute flow rate loss. During routine mortar removal, final flow rates were below 50 ft^3/min (1.4 m^3/min) for a number of vacuum cleaners. Clearly, the ability of vacuum cleaners to maintain 80 ft^3/min (2.26 m^3/min) is problematical and vacuum cleaner airflow maintenance is an important practical issue. However, the reader must cautiously interpret the flow rate data in Tables V and VI and in Figures 6–9, as vacuum cleaner flow rates are determined by the mass of material collected, the mass of material on the filter faces, the frequency of actions taken to dislodge accumulated debris from filters and, perhaps, other environmental conditions.

DISCUSSION

In this study, the use of LEV during tuck point grinding resulted in personal dust exposures that were about 5–20 times less than those found at other studies where tuck point grinding was conducted.[4,16,18] Without the use of ventilation, respiratory protection with an assigned protection factor of 50 is not enough to adequately protect a worker who is tuck point grinding without the benefit of a ventilated grinder. During the current study with ventilation, only a single exposure was greater than 10 times the NIOSH REL of 0.05 mg/m^3. Thus, a worker using a tuck point grinder with LEV will generally have adequate exposure reduction from a respirator with an assigned protection factor of 10. However, further exposure monitoring or exposure assessment is needed at each site to determine the correct level of respiratory protection as exposures will probably vary with worksite conditions such as wind and the extent to which the job site is enclosed.

Vacuum cleaners will probably continue to be an important control option for respirable dust exposures in construction for dust exposure sources, such as mortar removal, concrete grinding, hole drilling, and brick cutting where water application is impractical. Measuring actual airflow is an important issue during field research. As shown in Figures 6–9, the measured flow rates show periodic flow rate fluctuations caused by debris accumulating on filter faces and the debris being periodically dislodged from the face of filters. Thus airflow rate measurements need to adhere to the Nyquist[24] sampling criterion that was developed for communications engineering and digital signal processing. This criterion specifies a sampling frequency that is at least twice the frequency of phenomena under study so that the measured average flow rate is not biased.

To understand and document cyclical flow rate fluctuations caused by debris accumulating on filter faces and actions taken to dislodge the accumulated debris, airflows need to be measured digitally at frequencies much greater than the frequency of these flow rate fluctuations to document the magnitude and period of the flow rate fluctuations. The procedures reported in this article are one option for measuring airflows as a time series. If one could avoid the plugging and fouling of static pressure ports, hood static pressure could also be measured and logged to obtain airflow as a time series. Hood static pressure

TABLE VI. Average Initial and Final Flow Rates

Vacuum Cleaner	Hose Diameter (inches)	Average Initial Flow (ft^3/min)	Geometric Std. Dev.	Average Final Flow Rate (ft^3/min)	Geometric Std. Dev.	n^A
Alto Wap SQ23	2	128.95	1.20	103.11	1.11	6
Bosch 3931	2	79.28	1.08	52.85	1.05	5
Dust Director 9.5	1.5	84.78	1.11	46.48	1.29	9
Dust Director 9.5	2	88.68	1.21	50.14	1.47	9
Dust Control 2700	1.50	70.95	1.23	48.38	1.43	4
Dust Control Model 2700 (with cyclonic preseparator)	2	90.21	1.04	76.99	1.14	5
Shop Vac QUL650	2	104.79	1.21	54.66	1.36	6

^{A}As number of unique grinds.

may also be affected by the mass flow rate of debris and the mass flow rate of air. In this study, the mass flow rate of air was generally between 4.4 and 1.5 kg/min. It is conceivable that instantaneous debris removal rates could be as high as 0.25 to 0.5 kg/min. At relatively low flow rates, the debris removal rate will noticeably affect the hood static pressure as pressure loss in a pneumatic conveying system is computed as a function of the mass flow rates of the solid phase (the debris) and gas phase (the air).[25] Measuring airflow based on vacuum cleaner static pressure avoids this complication.

Based on the study results, which identified several factors that affect the level of dust control provided by LEV during tuck point grinding, the following recommendations are provided regarding the implementation of this engineering control.

Vacuum cleaner hose diameter. Vacuum cleaner hose diameters should be 2 inch (5 cm) inside diameter vs. 1.5 inch (3.8 cm) diameter. Pressure loss through ventilation ducts is inversely proportional to the fourth power of duct diameter.[26] For the same flow rate, reducing the duct diameter from 2 to 1.5 inches (5 to 3.8 cm) increases the pressure loss by a factor of 3.2. As described in Appendix B, the estimated pressure loss for 12 feet (3.6 m) of hose from 2 to 1.5 inches (5 to 3.8 cm), causes an additional pressure loss of 10 inches of water (2.4 kPa). As shown in Table IV, the slopes of the vacuum cleaner fan curves ranged between -5.2 and -1.4 ft^3/min/inch of pressure loss (-0.6 to -0.14 m^3/min/kPa). Thus, an additional pressure loss of 10 inches of water (2.4 kPa) reduces initial vacuum cleaner airflows by 50 to 14 ft^3/min (1.4 to 0.4 m^3/min) depending on the slope of the vacuum cleaner's fan curve. Using a larger diameter hose can help maintain adequate airflow.

Flow rate maintenance. Workers need to monitor vacuum cleaner airflows. As the vacuum cleaner collects dust and debris, the pressure loss across the vacuum cleaner filters will increase and the flow rates will decrease as shown in Table V and Figures 6–9. This will reduce the capture efficiency of the hood.

In addition, as flow rates fall below 76 ft^3/min (2.1 m^3/min) in a 2-inch (5-cm) hose, the air velocity in the hose will be less than the 3500 ft/min (1067 m/min) specified to prevent debris from accumulating in ventilated ducts and plugging the ducts.[10] Accumulated material in a hose would probably further decrease the flow rate provided by the vacuum cleaner. During the field trials, the workers periodically stopped grinding to dislodge material from the vacuum cleaner filters and to change filter bags.

As presented in Table V, average flow rate decreases can be as high as 3 ft^3/min (0.09 $m^{3/}min^2$) suggesting that workers may need to dislodge prefilter cakes as frequently as every 5 min when the initial flow rate is only 95 ft^3/min. Perhaps cyclones and other preseparators, with a modest pressure loss, can be used to keep debris off the filters. When the flow rate becomes too low for effective dust capture and the transport of debris through the vacuum cleaner hose, workers need to dislodge accumulated debris from the vacuum cleaner's filters per the manufacturers' recommendations, and the workers may need to remove accumulated debris from the hose.

Vacuum cleaners used for mortar removal should have a pressure gauge to monitor static pressure in the space between the final filter and the inlet to the vacuum cleaner motor. The DustControl vacuum cleaners have a pressure gauge. The manufacturer of the vacuum dust collector can color code part of the pressure gauge green for acceptable airflows and red for unacceptable flow rates. This will provide a clear indication as to when debris accumulation in the vacuum cleaner needs to be addressed and whether the desired flow rate is being maintained.

Work practices and worker training. The worker will need to understand that the use of this control approach is sensitive to work practices as listed below:

1. The distance between the exhaust take-off and the uncut mortar must be minimized as described in Figure 2A.
2. The grinding wheel needs to be moved against its natural rotation so the debris is directed in the exhaust take-off.
3. The worker must periodically stop grinding and take action to maintain airflow. They must dislodge accumulated debris from final filters, change vacuum cleaner bags, and, perhaps remove accumulated debris from hoses.

Due to production requirements, compliance with these work practices will be incomplete. Worker training needs to include a realistic assessment as to the capability and limitations of this control approach. This dust control approach will be used on masonry walls where the distance between the mortar and the exhaust take-off will inevitably be too large and mortar dust escapes, increasing the worker's crystalline silica exposure, Consequently, the workers need to understand that both ventilation and respiratory protection are needed to adequately control the worker's exposure to respirable crystalline silica and respirable dust.

Vacuum cleaners. Vacuum cleaners used to exhaust air from the grinding hoods used in mortar removal need to be chosen for their ability to maintain an adequate airflow and their ability to remove respirable crystalline silica from the air. Figures 6–9 show that maintaining airflow is a major problem since none of the vacuum cleaners maintained airflows greater than the 80–85 ft^3/min (2.26–2.4 m^3/min), which was recommended based on laboratory and computational studies. Furthermore, this flow rate is also needed to maintain adequate transport of debris to the vacuum cleaner.

The DustControl 2700 vacuum cleaner was used with a cyclonic preseparator, and Figure 7 shows that this vacuum cleaner kept the airflow above 85 ft^3/min (2.4 m^3/min) for periods as long as 30 min. This cyclonic preseparator has a pressure loss of 6 inches of water (1.5 kPa) at 85 ft^3/min (2.4 m^3/min).[12] Based on the slope of the fan curve listed in Table IV, the cyclone reduces the initial airflow by about 9 ft^3/min (0.25 m^3/min). However, the cyclone limits the amount of debris that accumulates on the vacuum cleaner's filter and it may allow the vacuum cleaner to maintain airflows for a longer time period. Perhaps inertial separators such as cyclones can be incorporated into vacuum cleaners so that the amount of debris that accumulates on the vacuum cleaner's filters is minimized.

CONCLUSIONS

The use of LEV during tuck point grinding resulted in personal dust exposure levels that were about 5–20 times less than those found in other studies where tuck point grinding was conducted without any engineering controls. However, the observed workers' geometric mean exposures still exceeded the NIOSH REL of 0.05 mg/m^3 for respirable crystalline silica. The exposure reduction provided by this control approach was limited by the inability of the vacuum cleaners to maintain an airflow of 80–85 ft^3/min (2.26–2.4 m^3/min) and the size of the gap between mortar and the bottom of the exhaust take-off. As a control measure, grinders with LEV should be used as component in a comprehensive program for the control of exposure to respirable crystalline silica. Such a program will need to address equipment selection, equipment maintenance, worker training, work practices that facilitate optimal dust capture, and respiratory protection.

Further research on the ability of ventilated grinding hoods to control this dust exposure source is needed. The gap between the exhaust take-off and the uncut mortar appeared to elevate aerosol photometer response. The extent to which the ventilation rate needed to capture the dust varies with the size of this gap is unknown. Clearly, work on developing vacuum cleaners that can better maintain airflows as debris is collected is needed.

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TABLE AI. Conversion from English to Metric Units

English Unit	Factor	Metric Unit
inch	2.54	cm
ft^3/min/inch of water	1.146×10^{-4}	m^3/min/pascal
ft^3/min	0.0283	m^3/min
ft^3/min/min	0.0283	m^3/min^2

Note: Multiply English unit by the "factor" to convert to metric unit.

APPENDIX A

Conversion of English Units to Metric Units

In the United States, retail equipment specifications are still commonly given in English units. To aid American readers, ventilation results reported in Tables III–V are given in English units. However, readers outside the United States will need these results converted to metric units. Table A1 provides the conversion factors.

APPENDIX B

Pressure Loss Estimation for Flow into Vacuum Cleaner Tank

The pressure loss for airflow through a hood, hose, and into a vacuum cleaner can be estimated by summing the individual pressure losses through the grinder hood, hose, and entry into the vacuum cleaner tank. These pressure losses are computed as the product of velocity pressure (VP) and a loss coefficient, F. Thus, for airflow into the vacuum cleaner tank, the pressure loss (ΔP) can be computed:[1]

$$\Delta P = VP(F_{hood} + F_{hose} + F_{tank}).$$

The various values of F are dimensionless, and VP is computed in units of inches of water using this formula at 70°F and at 1 atmosphere is stated:[2]

$$VP = (V/4005)^2$$

TABLE BI. Pressure Loss Factors for Flow into Vacuum Cleaner Tank

Component	Reference No.	F
Grinder hood	1	1.6
Hose, 0.19 VP per foot, 12-ft length	2	2.3
Loss of velocity pressure due to flow into tank. The air velocity in the tank of a vacuum cleaner is nil.	1	1.0
Total pressure loss in terms of velocity pressure		4.9

where V = air velocity in feet per minute; VP = velocity pressure in inches of water.

The formula for velocity pressure in pascals (kg/m/sec^2) is

$$VP = 0.5\rho v^2$$

where ρ = air density in kg/m^3; v = air velocity in m/sec.

The pressure loss coefficients are given in Table BI. In a 2 inch diameter duct, the pressure loss at 85 ft^3/min is 4.6 inches of water (1.15 kPa). In contrast, the pressure loss for 1.5 inch diameter duct is 14.6 inches of water (3.64 kPa). Depending on the slope of the fan curve in Table III, the reduced hose size causes a flow rate loss of 15–50 ft^3/min.

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