Control Measures for Silica Exposures for Tuckpointing

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List of Abbreviations

CFM	cubic feet per minute
KCl	potassium chloride
lod	limit of detection
m^3	cubic meter
mg	milligrams
NIOSH	National Institute for Occupational Safety and Health
OPC	optical particle counter
p	penetration (down steam concentration/up steam concentration)
REL	Recommended Exposure Limit
rpm	rotations per minute
η	Filtration efficiency computed as 1-p

Abstract

During building renovation, mortar removal with a right angle grinder causes worker exposures to respirable crystalline silica as high as 5 mg/m^3, 100 times the NIOSH REL. To control this exposure, vacuum cleaners can be used to exhaust 80 cubic feet per minute (cfm) from a hood that partially encloses the grinding wheel. Prior laboratory studies found that exhaust rates beyond 80 cfm do not yield further reduction in dust emissions. The ability of vacuum cleaners to function as air movers and air cleaners was studied in the laboratory. Flow rate decreased linearly with increased vacuum cleaner static pressure measured just upstream of motor's inlet. As particle collection devices, the tested vacuum cleaners allowed no more than 0.2% of the particles larger than 1 μm to penetrate the vacuum cleaner. For particles smaller than 1 μm, the aerosol penetration through the vacuum cleaner was less than 5%. Field trials were conducted to evaluate the ability of vacuum cleaners to maintain this flow and to evaluate the exposure outcomes of using these control measures. Air flows were calculated from the vacuum cleaner static pressures that were measured and digitally recorded with a data-logging pressure transducer. The vacuum cleaners, outfitted with 2-inch hoses, maintained an exhaust volume greater than 80 cfm for a longer time period than those equipped with 1.5-inch diameter hose. As mortar debris was collected in the vacuum cleaner, flow rates for the vacuum cleaners equipped with 2-inch hose decreased from 95 cfm to 65 cfm and for those quipped with 1.5-inch diameter hose, the air flows decreased to 40 cfm. Clearly, the vacuum cleaners failed to maintain an air flow of 80 cfm. During the field trials, worker exposure to respirable dust and respirable crystalline silica was monitored. Geometric mean respirable dust and respirable crystalline silica exposures were, respectively, 1.07 and 0.06 mg/m^3. When mortar removal was performed without ventilation, the geometric mean respirable dust and respirable crystalline silica exposures, measured by OSHA compliance officers, were, respectively, 12 and 1.2 mg/m^3. Apparently, a control system consisting of a grinder hood connected by hose to a vacuum cleaner can provide an order of magnitude reduction in worker exposure to crystalline silica. Concurrent aerosol photometer and flow rate measurements overlaid on real-time video suggests that exposure reduction is limited by work-practices, the inability of the vacuum cleaners to maintain an air flow of 80 cfm, and a variable gap between the bottom of the hood and the mortar.

Significant Findings

Mortar removal with right angle grinders are known to cause excessive exposure to respirable crystalline silica that can exceed the NIOSH REL (0.05 mg/m^3) by a factor of 100. The blade of the right angle grinder has a diameter of 10 -12 cm (4-5 inches) and a rotational speed of 10,000–12,000 rotations per minute (rpm). To control the dust generation, a dust control system consisting of a grinder hood or shroud, flexible hose, and a vacuum cleaner is used to control this dust exposure. (See Figure 23 on page 44.) The exhaust take-off of the shroud is connected by flexible hose to the inlet of a vacuum cleaner. The vacuum cleaner moves air through the shroud and filters in the vacuum cleaner. To adequately control the dust generated by grinding the mortar, prior laboratory studies indicated that 80 cubic feet per minute were needed to capture the dust.[10] The results and discussion section of the report lists these significant findings:

1. The dust control system was able to reduce worker exposure to respirable crystalline silica by a factor of 20 as compared to compliance data collected in 1997 and 1998.
2. The respirable crystalline silica exposures were under 10 times the NIOSH REL for crystalline silica for 21 of 22 task-based exposure measurements. During this study, the geometric mean exposure to respirable crystalline silica was 0.06 mg/m^3 with geometric standard deviation of 3.2. This suggests that respirators with an assigned protection factor of 10 may be appropriate in many situations.
3. The vacuum cleaners failed to maintain a minimum flow rate of 80 cfm, limiting the exposure reduction by the dust control system. The test vacuum cleaners had initial flow rates (at minimal pressure loss) of 261 – 116 cfm. As vacuum cleaners accumulated debris, air flow rates during mortar removal decreased. Workers will need to monitor vacuum cleaner air flow rates and dislodge accumulated debris from the vacuum cleaner filters.
4. The hose connecting the exhaust hood to the vacuum cleaner should have a diameter of 5 cm (2 inches) instead of 3.75 cm (1.5 inches).
5. The tested vacuum cleaners appear to be at least 99.8% efficient for collecting particles larger than 1 μm and at least 95% efficient at collecting particles smaller than 1 μm. Because the entire system reduced worker exposure to respirable crystalline silica by a factor of 20, the vacuum cleaner performance as an air cleaner is not limiting the exposure reduction.
6. Video exposure monitoring revealed that the dust control system does not provide complete dust control when: a) the mortar is missing causing too large of gap between the exhaust take-off and the bottom of the exhaust shroud; b) the grinder is inserted into the mortar; c) the gap between the mortar and the bottom of the exhaust shroud is too large.

Translation of Findings

The dust control system for mortar removal provided incomplete dust control and further research is needed to perfect the control measures. However, this dust control system studied provided a factor of 20 reduction in exposure to respirable crystalline silica. Dust control recommendations should be transmitted to the masonry restoration industry as a NIOSH hazard control document and possibly as a video tape. Such a document should describe a comprehensive exposure control strategy involving the dust control approach evaluated during this study, respiratory protection, worker training programs, and management programs needed to ensure that the control measures are appropriately used. Such recommendations have been developed and distributed with the assistance of the Center to Protect Workers Rights.[1] After completion of the peer-reviewed journal articles, these recommendations can be revised and published without the word "Draft" in the title.

Outcomes and Impact.

As mentioned in the preceding section, draft dust control recommendations have been developed and distributed with the assistance of the Center to Protect Workers Rights.[1] These recommendations are available to the general public for a $5 fee. Summary articles describing these recommendations have appeared in newsletters and trade magazines that address the construction industry:

1. Newsletter of the Center to Protect Workers Rights, April 2005.
2. Occupational Safety and Health Reporter, February 24, 2005, page 152.
3. Protecting Tuckpointing Workers: Here Are Some Guidelines For Mitigating Dangerous Dust Exposures, Masonry Construction, Sept, 2005 by Rick Yelton.
4. BAC Journal April – May –June, Vacuum Set-Up Helps Reduce Silica Dust.

In addition, the Western Construction Group (St.Louis, MO) prepared DVD to disseminate study findings throughout the company's various branches.

Scientific Report

Background

In the construction industry, local exhaust ventilation is needed to control the dust generated when grinding concrete and mortar that contains approximately 10-20% crystalline silica (sand). The silicosis hazard associated with construction is a current issue.[2,3,4] During new building construction, grinders are frequently used to remove concrete seams caused by concrete flowing between forms. During building renovation, grinders are used to remove deteriorated mortar between bricks before new mortar is applied. This task must be done to prevent water intrusion into the building which would damage the building. The process of removing the deteriorated mortar and replacing this mortar is termed "tuckpointing". Mortar removal with grinders is frequently performed without engineering control measures. This causes excessive exposures to respirable crystalline silica.[5] Shields studied respirable crystalline silica exposures during mortar removal with grinders. Of 37 exposure measurements, 38% of the samples exceeded 1 mg/m^3 and 19% of the exposures exceeded 5 mg/m^3 of respirable crystalline silica.[6] These exposures are 20 to 100 times the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) of 50 $\mu g/m^3$.[7]

Exposures to concrete dust and respirable crystalline silica are reported to cause chronic obstructive pulmonary disease and reduced lung function among workers exposed to concrete dust.[8] To minimize the incidence of these outcomes, NIOSH has a Recommended Exposure Limit (REL) of 50 $\mu g/m^3$ for respirable crystalline silica. The present Occupational Safety and Health Administration (OSHA) standard for respirable crystalline silica is approximately 100 $\mu g/m^3$. For 45 years of exposure at the NIOSH REL, silicosis rates are estimated to be 10-20%.[9] In a single day, dusty work tasks involving concrete and mortar grinding are potentially causing the equivalent of 0.1-0.5 years exposure at a level equivalent to the NIOSH REL. Clearly, there is a need to effectively control these dust exposures.

These grinders operate at 10,000-12,000 rpm and have air-cooled electrical motors in a vented plastic body that the workers hold. Because of the electrical shock hazard, water must not be used to suppress dust emissions during these operations. To control the dust exposures, shrouds are mounted on the grinders. These hoods or shrouds partially enclose the grinding blade. Vacuum cleaners are used to exhaust air from these shrouds and to separate the dust from the air. Experimental studies have shown that an exhaust ventilation rate of 80 cfm is needed for optimal dust control these exposures.[10]

Vacuum cleaners are characterized by their water lift and flow rate. The water lift is the static pressure at zero airflow. The flow rate specification is the flow rate without hoses or an exhaust shroud. Generally vacuum cleaner manufactures do not provide airflows at various static pressures. In some vacuum cleaner motors, such the Dustcontrol Company (Norsborg, Sweden) vacuum cleaners, the air mover blades fit tightly in a motor housing.

This type of air mover has characteristics between a fan and a positive displacement pump.[11]

Specific Aims

The **long-range goal** of this research was to develop a control strategy for the dust exposures generated by mortar removal during tuckpointing. The **overall aim** of this proposal was to evaluate the effectiveness of a range of lower-cost vacuum cleaners to maintain adequate flow rates and collection efficiency of the dust generated by mortar grinding. To initiate the development of this control strategy, field evaluation of the vacuum cleaner's performance is needed to develop a realistic understanding of the control device's capabilities and limitations. In addition, laboratory investigations are needed to address into the ability of the wet-dry vacuum cleaner's filter bags and final filters to adequately capture respirable aerosol over the range 0.3 to 3 μm.

Five specific aims were undertaken to test the effectiveness of a control strategy for dust exposures during mortar removal:

Specific Aim # 1. Evaluate the loading- and use-related variations in filtration efficiency of vacuum filter bags and final filters used in wet/dry vacuum cleaners.

Specific Aim 2. Determine whether the low-cost vacuum cleaners selected for study maintain an adequate flow rate when used during actual tuckpointing jobs.

Specific Aim 3. Evaluate the use of the ventilated shroud and vacuum cleaner, operated with a flow rate of 80 cfm (2.2 m^3/min), to control the worker's exposure to respirable dust and crystalline silica.

Specific Aim 4. Identify sources of worker exposure to respirable dust and crystalline silica caused by the vacuum cleaner. These sources could be the vacuum cleaner exhaust and the act of the servicing of the vacuum cleaner.

Specific Aim 5. Identify tasks and work practices that cause temporary spikes in the worker's dust exposure.

Procedures

The **overall aim** of this project was to evaluate the ability of a range of lower-cost vacuum cleaners to maintain adequate flow rates and collection efficiency of the dust generated by mortar grinding. Laboratory studies were conducted on the filtration efficiency of the wet/dry vacuum cleaner and the relationship between the vacuum cleaner's exhaust flow rate and static pressure (Specific Aim 1). Field trials involving the vacuum cleaners and dust control shrouds were conducted to evaluate the exposure implications of using ventilated grinders to control the workers dust exposures.(Specific Aims 2-5). In addition, the flow rates provided by vacuum cleaners were measured to determine whether the vacuum cleaners maintained a flow rate in excess of 80 cfm. The exhaust shroud used at all of the field trial sites was supplied by Industrial Contractors Supply (Pittsburgh Pa). Each shroud and attached vacuum cleaner was used for four to six shifts. During each shift, air samples for respirable dust and respirable crystalline silica were collected to assess the vacuum cleaner's control of the worker's dust exposure and whether it is a dust emission source (Specific Aims 3 and 4). During the shift, air volume measurements were taken to assess whether the vacuum cleaner maintained an exhaust flow rate above 80 cfm (Specific Aim 2). For selected activities and during parts of a shift, video exposure monitoring was used to examine the relationship between work tasks, filter bag loading, and exposure (Specific Aim 5). The details of these measurement procedures are described below.

The procedures used to address the specific aims are restated because there were some noticeable changes to the protocol. Between the time that the grant application was written and the grant was funded, a pilot grant was obtained to study the performance of the low-cost vacuum cleaners. The flow rates through the vacuum cleaners generally failed to maintain air flows of 80 cfm. In some cases, air flows dropped below 10 cfm during actual field trials. The following vacuum cleaners systems were tested during this study: Altowap (model/part number SQ23 30200125 12999975/20/03), Dustcontrol (model 2700), and Bosch (model 3931) and the ShopVac (QUL 650). These vacuum cleaners are briefly described below:

Altowap (model SQ23). This vacuum cleaner required 15 amperes at 120 volts. Filtration involved a vacuum cleaner bag, an intermediate cloth filter and a final pleated cartridge filter. This vacuum cleaner has a lever which is used to shake the final filter causing dust to be dislodged. Either one or two vacuum cleaner motors can be used.

Dustcontrol (model 2700). This vacuum cleaner required 10 amperes at 120 volts. The vacuum cleaner had a cylindrical shape much a like a cyclone. In this design, the vacuum filter functioned as a vortex finder. The final filter was a pleated cartridge filter. To dislodge dust from the final filter, we pulsed the final filter to dislodge collected material. To pulse the filter, we repeatedly placed our hands over the inlet to block off the air flow. This causes a change in pressure causes the filter to pulse. Then, the flapper valve on the side of the vacuum cleaner was released and this opened a trap door on the bottom of the vacuum cleaner. The collected debris fell through a trap and into a plastic bag.

Bosch (model 3937). This vacuum cleaner required 11.1 amperes at 120 volts. The filtration involved a vacuum cleaner bag and pleated, square filter. This vacuum cleaner had an electric motor which vibrates the final filter. This vacuum cleaner became available after the completion of the field trials. However, it was tested during the laboratory trials and its ability to maintain air flow was evaluated at actual mortar removal operations.

Shop Vac (model QUL 650). This vacuum cleaner required 12 amperes at 120 volts. It can use either a conventional vacuum cleaner bag or a bag made with an electret filter media. This vacuum cleaner was retained in the study because it still maintained an air flow of 65 cfm during field trials.

Specific Aim # 1. Evaluate the loading- and use-related variations in filtration efficiency of vacuum filter bags and final filters used in wet/dry vacuum cleaners.

The filtration efficiency of unused filter bags was measured as a function of particle size over the range of 0.3 to 3 μm. The laboratory procedures were similar to the procedures used for household vacuum cleaners.[12] In this procedure, an optical particle counter was used to measure the concentration upstream and downstream of the vacuum cleaner filter bag and vacuum cleaners. An optical particle counter (Grimm PDM, model 1108, Ainring Germany) measured aerosol number concentrations upstream and down stream of vacuum cleaner bag. The optical particle counter (OPC) counted individual particles and sized each particle, based upon the amount of light scattered, into one of fifteen channels over the range 0.3 to 15 μm. A number concentration was obtained for each size channel, and filter penetration (p) was computed as the ratio of the number concentration downstream of the filter to number concentration upstream of the filter. Filter efficiency (η) is computed as 1-p.

The equipment for testing the vacuum cleaner's efficiency is shown in Figures 1 and 2. The test aerosol was generated by using a 6-jet Collison atomizer (BGI Inc, Waltham Mass) to atomize a 30% by weight potassium chloride solution. The test air aerosol was diluted with dry HEPA-filtered air at 25 lpm Q_1. Then, the test aerosol flowed through an electrostatic charge neutralizer which consisted of two 10 mCi of ^{63}Ni in a length of 5-cm diameter steel pipe. The test aerosol flows through a 5-cm diameter tube leading to a mixing tank constructed from a PVC drum. The vacuum cleaner equipped with vacuum cleaner bag exhausts air from this drum through a 5-cm diameter tube. The air supplied to the tube was conditioned to a temperature of 20-25° C and a relative humidity of 30-35% by a precision air conditioning system (Mini-mate 2, Liebert, Columbus OH). In this system, the air was cooled and then heated and humidified to obtain the desired temperature and humidity. The testing for the vacuum cleaner bags and the vacuum cleaner systems had different configurations as shown in Figures 1 and 2.

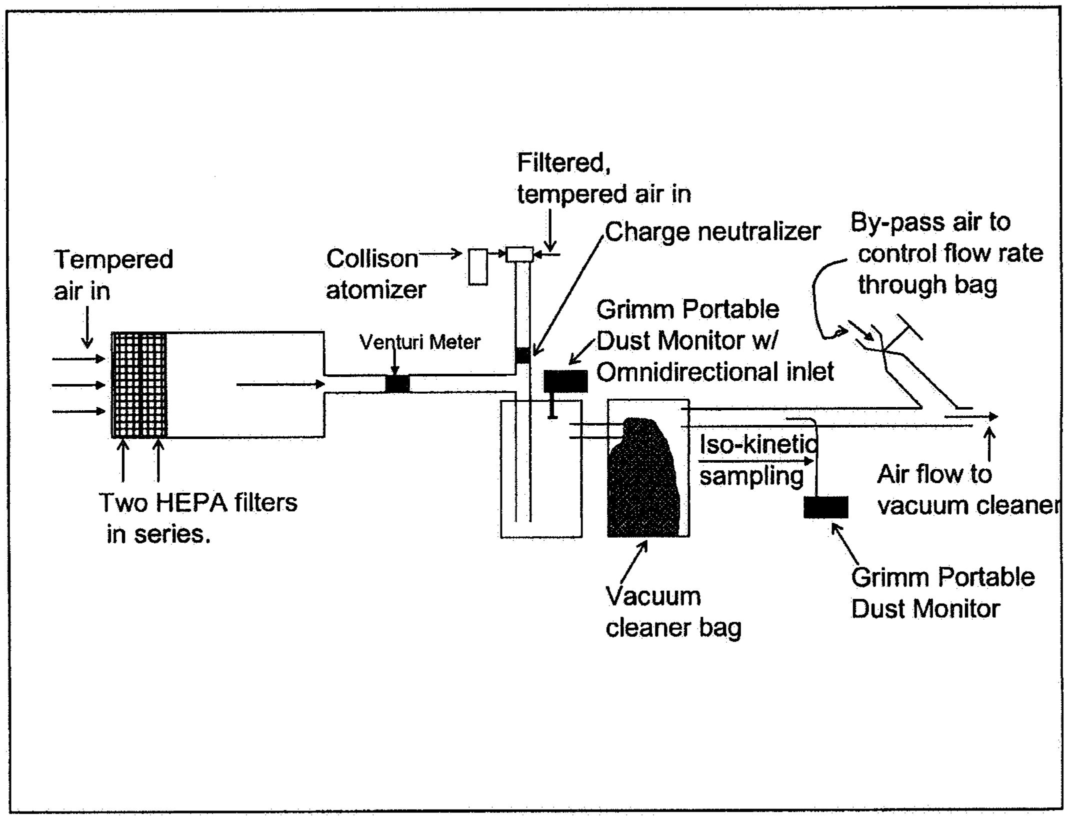


Figure 1. Schematic of test stand for measuring aerosol penetration through vacuum cleaner bags.

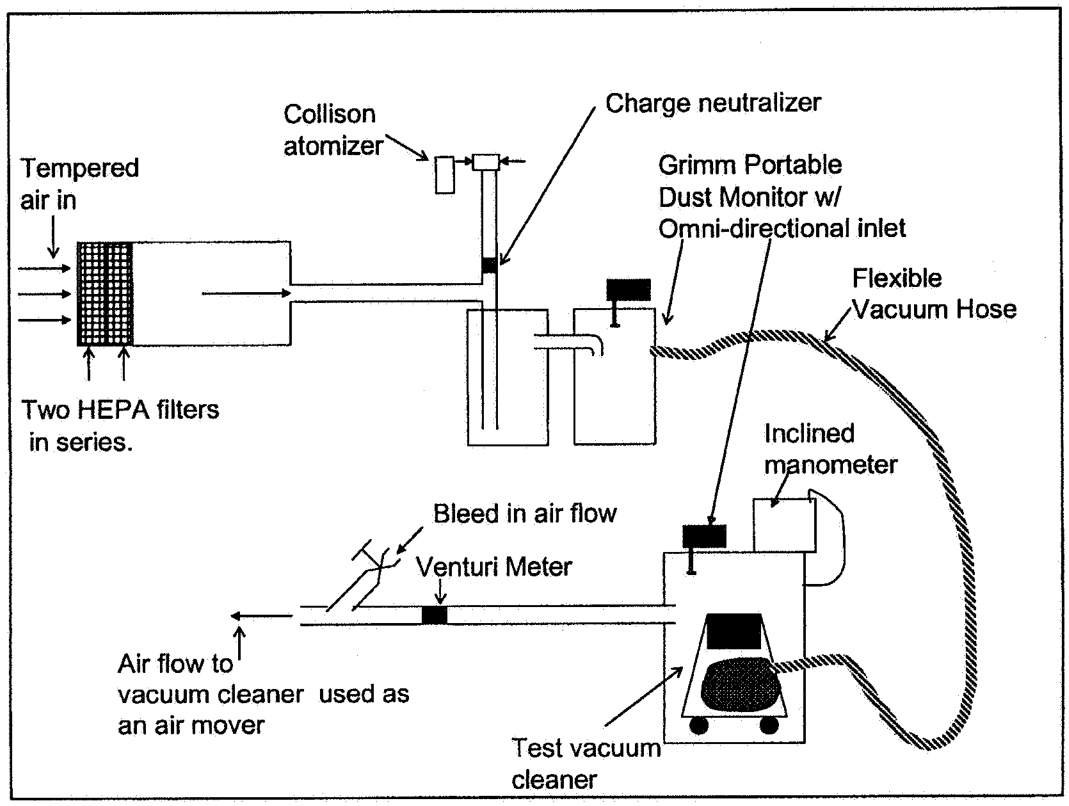


Figure 2. Schematic of test system for measuring size dependent aerosol penetration through vacuum cleaner systems.

Testing of Vacuum Cleaner Filter Bags. The vacuum cleaner filter bags were tested using the apparatus shown in Figure 1. The output of the aerosol generator was adjusted to keep the test aerosol under 500 particles/cm^3 to prevent the occurrence of coincidence errors. [13]

To measure penetration through the vacuum cleaner bags, a bag was placed in the second drum and aerosol penetration through the bag was measured for a period of several minutes. The OPCs measured the aerosol concentration upstream of the vacuum cleaner in the first drum and downstream of the vacuum cleaner bag in the pipe shown in Figure 1. This pipe had a diameter of 5 cm. The sampling nozzle had a diameter of 0.15 cm. The vacuum cleaner bags were tested at flow rates of 100, 80, 60, and 40 cfm. The concentrations measured downstream of the vacuum cleaner bags were adjusted for anisokinetic sampling conditions by using the formulae summarized by Brockman.[14] These flow rates were obtained by adjusting the bypass valve to obtain the desired flow rate as measured by the venturi meter (2 HVT-FV, Primary Flow Signal). The pressure across the venturi meter was measured with either a u-tube or an inclined manometer. The chart supplied by Primary Flow Signal provided the conversion between the pressure differential across the venturi meter to air flow. As discussed in the procedures addressing Specific Aim 2, venturi meters measure air flow based upon the nearly frictionless conversion of static pressure to velocity pressure.

For each flow rate, the aerosol penetration through the bags was measured twice. During the second test, the two OPCs switched locations.

Testing of Vacuum Cleaner Systems. This test stand is shown in Figure 2. The Collison atomizer was used to generate a KCl test aerosol. The OPCs were used to measure the aerosol concentration upstream and downstream of the vacuum cleaners. The upstream concentration was measured in the drum that was upstream of the vacuum cleaner. The down stream concentration was measured in a box that totally encloses the vacuum cleaner. The vacuum cleaner being tested moved air through the equipment upstream of the box. A second vacuum cleaner removed air from this box. The air flow exhausted from this box was controlled by the gate valve downstream of this box. The gate valve is adjusted so that the static pressure in this box was slightly positive (0.01 to 0.1 inches of water). This prevented air infiltration that would dilute the particle number concentration.

The concentrations measured downstream of the vacuum cleaner in the box also included aerosol generated by the vacuum cleaner's motor. This aerosol will include debris from the carbon brushes that may be a component of the vacuum cleaners motor.[15] To minimize the bias caused by the motors, a much higher aerosol test concentration was used. In addition, during the course of these experimental runs, the aerosol concentration generated by the vacuum cleaner was measured before and after the tests were conducted. Actual test concentrations exceeded the 5% coincidence limit of the OPCs. This limit is 1000 particles/cm^3 greater than 0.3 μm. To control coincidence error, the aerosol concentration measured upstream of the OPC was reduced by using a dilutor fabricated from a cartridge filter (6702-7500, Whatman Inc., Florham Park, NJ) .

A 0.04 cm diameter hole was drilled through the endcap allowing some air to flow through the hole. Experimentally, this dilutor provided approximately a factor of 35 reduction in concentration. The dilutor was calibrated for size-dependent aerosol penetration. To measure aerosol penetration through this dilutor, the two OPCs simultaneously sampled the aerosol present in the first drum. The aerosol generator was adjusted so that the concentration in the first drum was under 1000 particles/cm^3. One of the OPCs sampled directly from the drum. The other OPC sampled through the dilutor. These OPCs simultaneously sampled the aerosol in the first drum for a period of at least 2 minutes. Then, this test was repeated with the dilutor switched to the second OPC.

The vacuum cleaners were tested with the following loading of mortar debris that was obtained from a construction site: 0, 5, 10, 15, 20, and 25 pounds of debris. For each loading, 5 pounds (2.27 Kg) of material was weighed-out using an Ohaus SP-6000 Scout Pro Balance. The vacuum cleaner sucked this debris into its tank. Then, the aerosol penetration through the vacuum cleaner was measured. The hose from the vacuum cleaner was placed into the drum outlet and the vacuum cleaner was turned on. The air flow out the box (see Figure 2) containing the vacuum cleaner was adjusted so that the box's static pressure was slightly positive. Then aerosol penetration into vacuum cleaner was measured. The OPCs measured aerosol concentration in the second drum and in the box that is shown in Figure 2. The OPC used to measure the aerosol concentration in the drum drew air from the drum and through the dilutor for a period of at least two minutes. The location of the OPCs was switched and the test was repeated.

<u>Specific Aim 2</u>. **Determine whether the low-cost vacuum cleaners selected for study maintain an adequate flow rate when used during actual tuckpointing jobs.**

During field trials, the vacuum cleaner's airflows were measured with a velometer (Velocicalc , TSI, St. Paul, MN). The velometer was used to measure air velocities at the inlet to the exhaust shroud which had a two inch diameter. Air flow volume was estimated as the product of area and velocity. Generally, the workers were suspended on swing stages. As result, air flow measurements with a velometer were impractical. To continuously record air flow during actual mortar removal, static pressure was measured just downstream of the final filter and just upstream of the vacuum cleaner motor. The latter measurement involved running a tube from a pressure transducer (Smart Reader Plus 4, SPR-004-5G, ACR Systems, Surrey, British Columbia, Canada) into the space between the final filter and the vacuum cleaner motor. The resulting holes were sealed with a silicone caulk. The static pressure was periodically measured with a pressure transducer that uses 12-bit data logging and has 32 kilobytes memory. This device is a digital barometer that records absolute pressure to the nearest 0.2 inches of water. The vacuum cleaner static pressure was computed as the difference between atmospheric pressure and the pressure just down stream of the vacuum cleaner final pressure. The pressure logged when the vacuum cleaner was not powered was the atmospheric pressure. Pressures were logged every 8 seconds. Prior to conducting the field trials, the relationship between flow rate and static pressure was experimentally established as described for the laboratory work conducted to establish the relationship between vacuum cleaner static pressure and flow rate. This is essentially the fan curve for a vacuum cleaner.

Procedure developing vacuum cleaner fan curve. For the vacuum cleaner used during the field trials, the relationship between flow rate and vacuum cleaner static pressure was determined using the device in Figure 3. The vacuum cleaner was probed and a manometer (u-tube type slack manometer, Dwyer, Michigan City, IN) was used to measure the static pressure in the vacuum cleaner canister between the final filter and the vacuum cleaner motor. Any holes were sealed with a silicone caulk. The vacuum cleaner's inlet was attached by flexible tubing to a rigid 2-inch diameter PVC pipe that contains a gate valve and a probe for a velometer (Velocicalc, TSI, St. Paul, MN) or a venturi meter (2 HVT-FV, Primary Flow Signal). The gate valve was used to vary the air flow and static pressure between the vacuum cleaner final filter and the vacuum cleaner motor. Air flow was measured with either a velometer or a venturi meter. To measure air flow with a velometer, the air velocity was measured at the location shown in Figure 3. The airflow was the product of the pipe factor, the cross sectional area of the duct times and the air velocity measured with the velometer. In this work a pipe factor of 0.9 was used to be consistent with the **Industrial Ventilation Manual.**[16] The duct air velocity is measured upstream of the gate valve to reduce measurement errors caused by reduced air density when the pressure loss is greater than 20 inches of water.

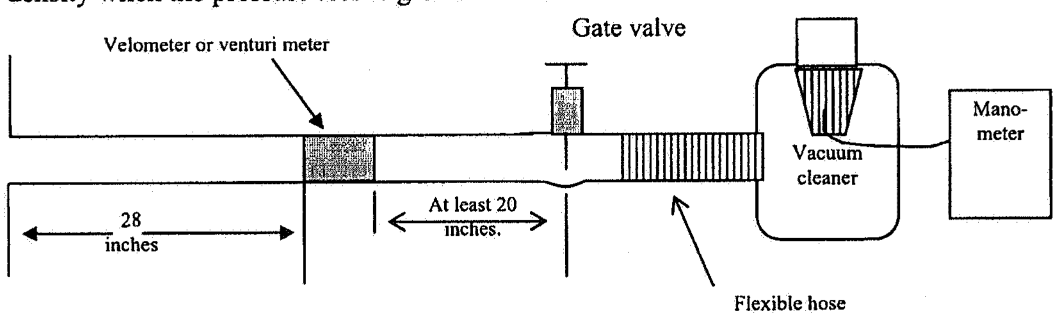


Figure 3. Experimental measurement of pressure loss as a function of airflow rate for commercially available vacuum cleaners. The pipes used in this study are 2 inch diameter schedule 40 PVC pipe. The vacuum cleaner static pressure is measured between the final filter and the inlet to the vacuum cleaner motor.

The air flow measured with a venturi meter was obtained from a table relating air flow to pressure differential. Figure 4 describes the venturi meter (2 HVT-FV, Primary Flow Signal, Tulsa Oklahoma).[17] In this venturi meter, the air flows through a gradual, nearly frictionless reduction in diameter. For this venturi meter, the diameter is reduced from 2.067 to 1.088 inches at an angle of 30 degrees. As the diameter is reduced, the air velocity is increased, producing a static pressure difference between the 2.067 inch section and the throat of the venturi meter. Because the angle of the flow restriction and smoothness of the venturi meters interior surfaces, the conversion of static pressure to velocity pressure is nearly frictionless. As a result, the air flow measured by a venturi meter is a direct function of the diameters of the pipe and throat, the measured pressure differential, fluid density, and the venturi meter discharge coefficient. The discharge coefficient accounts for the energy lost in compressing the fluid flow. Uncertainty in the discharge coefficient is a source of the uncertainty in measuring fluid flow rates with a venturi meter. The venturi meter coefficient is between 0.98 and 0.99 when the pipe Reynolds number is larger than 75,000. In this study, the venturi meter was used to measure air flows in the range of 20 to 120 cfm. As flow rate decreases from 100 cfm to 20 cfm, the Reynolds number decreases from 75,000 to 20,000 and the venturi meter coefficient decreases from 0.99 to 0.94.[18] Thus, as flow rate decreases from 100 to 20 cfm, the error in ignoring the reduction in the venturi meter coefficient increases from 0 to 5%. At 20 cfm, this bias is 1 cfm.

Formulas relating the pressure differential produced by the venturi meter to air flow, q_v, are presented in fluid mechanics text books, chemical engineering text books and an engineering standard published by the American Society of Mechanical Engineers (ASME). The air flow measured by the venturi meter can be computed as specified by an ASME standard.[19] This formula is stated:

$$q_v = 0.099701910CYd^2(h_w/\rho/(1-\beta^4))^{0.5} \tag{5}$$

$$Y = (r^{2/k}(k/(k-1)((1-r^{(k-1)/k})/(1-r))((1-\beta^4)(1-\beta^4 r^{2/k})))^{0.5} \tag{6}$$

Where;

C = venturi meter discharge coefficient, dimensionless;

d = diameter of venturi meter throat (feet);

h_w = differential pressure in inches of water;

q_v = volume flow rate air ft^3/second;

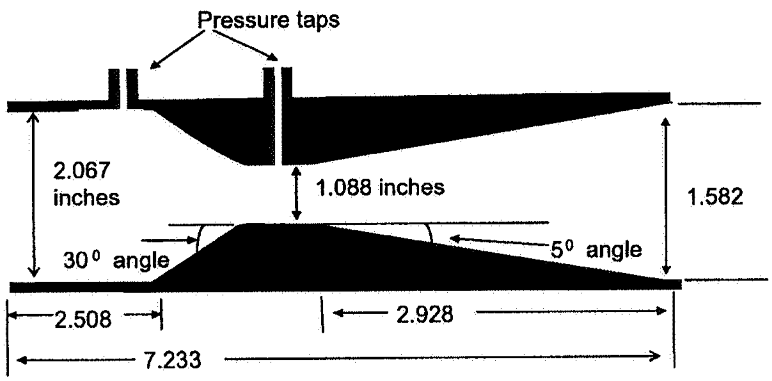
k = ratio of gas heat capacity at constant pressure to heat capacity at constant volume, dimensionless (for air this is 1.41);

r = ratio of gas pressure in venturi meter nozzle to gas pressure in venturi meter inlet, dimenionless;

Y = fluid compressibility factor, dimensionless;

ρ = fluid density in pounds/foot^3; and

β = ratio of throat to inlet diameter.



Note: machined from type 304 stainless steel, all dimensions are in inches. Wall thickness is 0.23 inches. The exterior shape is a nominal schedule 40 pipe with national pipe threads on the ends. Dimensions measured with a dial caliper. Mitutoya, Sao Paulo, Brazil)

Figure 4. Description of a venturi meter with dimensions measured in inches and angles from suppliers drawings.

Data analysis was conducted by plotting airflow rate as a function of static pressure. The objective is to evaluate whether the flow rate at a pressure loss can be obtained by interpolating between the static pressure at no flow (snf) and the flow rate at no pressure loss. Regression analysis was used to evaluate whether the data fits this model:

$$Q = A + B(\Delta P) + \varepsilon \tag{7}$$

Where:
A = intercept or flow rate at zero static pressure;
B = slope (these slopes were less than zero);
ΔP= the pressure difference ambient pressure and the space between the vacuum cleaner motor and the final filter;
Q = the flow rate predicted from the regression model; and
ε = the residuals, the difference between the observed and predicted or modeled flow rates. This term has mean of zero and is normally distributed.

The term, ΔP, is termed the vacuum cleaner static pressure throughout this report. The equation or curve describing the relationship between air flow and vacuum cleaner static pressure was termed the vacuum cleaner fan curve. The regression analysis was performed using the Regression data analysis tool available in Microsoft Excel.

Specific Aim 3. Evaluate the use of the ventilated shroud and vacuum cleaner, operated with a flow rate of 2.2 m^3/min, to control the worker's exposure to respirable dust and crystalline silica.

Specific Aim 4. Identify sources of worker exposure to respirable dust and crystalline silica caused by the vacuum cleaner. These sources could be the vacuum cleaner exhaust and the act of the servicing of the vacuum cleaner.

Concentrations of respirable dust and crystalline silica were measured on the workers, near the air discharge ports of the vacuum cleaner and away from the grinding operations at a location termed a "background measurement". To address low sample weights caused by the intermittent nature of construction activities, the BGI GK2.69 cyclone, which operates at a flow rate of 4.2 lpm, was be used for these measurements. This cyclone is currently used by United Kingdom's Health and Safety Executive to measure respirable dust and crystalline silica exposure.[20] A battery-operated pump pulled 4.2 liters/minute through a pre-weighed 37-mm diameter, and a 5-µm pore-size polyvinyl chloride filter that 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 mounted on a BGI GK2.69 cyclone, which was clipped to the worker's outer garment in their breathing zone (typically clipped to their lapel). The mass of material collected on the filters was determined as described by NIOSH methods 600.[21] Then, the samples were analyzed for crystalline silica by x-ray diffraction using NIOSH method 7500.[22] The limit of quantitation is 0.03 mg for both quartz and cristobalite on filters. The limits of detection in bulk samples are 0.8% for quartz and 1% for cristobalite. The limit of quantitation is 2% for both forms of crystalline silica in bulk samples.

Respirable dust and crystalline silica concentration measurements on the worker determined whether the control measures provide an adequate environment for the worker. The concentration difference between the background measurement location, and the vacuum cleaner's air discharge provided a qualitative indication of the control measures performance.[23] If concentration at the vacuum cleaner's discharge is significantly higher than the background concentration, the vacuum cleaner may be a source of dust emissions and it could expose workers to respirable crystalline silica. If the concentration measured on the worker is higher than the background concentration, the worker's job is contributing to his exposure to respirable dust and respirable crystalline silica. These measurements were made during four to six full-shift sampling sessions. Because industrial hygiene concentration data are usually log-normally distributed, the concentration data was log-transformed before analysis.[24] Analysis of variance and multiple comparison tests were be used to examine the significance of the observed concentration differences.[25] The SAS General Linear Models procedure was used to perform these analyses.[26]

Specific Aim 5. Identify tasks and work practices that cause temporary spikes in the worker's dust exposure.

Video exposure monitoring has been used to evaluate how work activities affect exposure and control measure performance.[27] An aerosol photometer (Microdust Pro, Casella, Bedford, UK) was mounted on the worker's chest and air was drawn through the sensing chamber of this instrument by a battery-operated pump. The dust in the sensing chamber scatters light from a light-emitting diode, which is detected by a photomultiplier tube. The analog output of the aerosol photometer was recorded every 2 seconds. In this study, video exposure monitoring was done during routine mortar grinding. The worker's dust exposure was digitally recorded while the worker's activities were concurrently recorded on videotape. The videotapes and the digital exposure records were reviewed to identify exposure sources that occur despite the use of ventilation control. The videotapes were adjusted slightly for the delay between activity and changes in dust concentration. To prepare these plots, one must realize that instruments do not instantaneously respond to events that cause changes in concentration.[27] The air contaminant must be transported to the instrument. After the air contaminant arrives in the instrument's sensing volume, the instrument requires some time to respond to the change in concentration. The aerosol photometer used on this project had a time constant of 0.25 second. In a period of two time constants, a first-order system completes 86% of its response to a step change in concentration.[28]

Results and Findings-Specific Aim 1

Results: In Figures 5-11, aerosol penetration through vacuum cleaner bags and systems were plotted as a function of an estimated aerodynamic diameter. Optical particle counters generally provide a volumetric diameter. To obtain aerodynamic diameter, the measured diameter was multiplied by the square root of the particle specific gravity.[29] The specific gravity of for KCl is 1.49 relative to water.[30]

Figures 5-8 present the efficiency of vacuum cleaner bags that were observed during field trials. With the exception of the plot shown in Figure 8, the vacuum cleaner bags provided little collection of particles smaller than 10 µm. In Figures 5-7, aerosol penetration increased from 0.1 to 0.8 as particle size decreases from 10 to 1 µm. These bags do not appear to involve electrostatic effects as penetration decreases with increasing flow rate. In Figure 8, the aerosol penetration through the bag was only 0.01 at 0.5 µm. In Figure 8, aerosol penetration increases with increasing flow rate. This suggests that particle collection involves electrostatic effects. These vacuum cleaner bags are referred as the yellow vacuum cleaner bags supplied by ShopVac. Unfortunately, these bags ruptured during testing of the vacuum cleaner systems.

In Figures 9-11, particle penetration through three vacuum cleaner systems is presented. In each figure, separate graphs show particle penetration without correction for motor aerosol generation and with a correction for aerosol generation. Without correction for the aerosol generation by vacuum cleaner motor, aerosol penetration through the vacuum cleaners was as high as 0.1. However, number concentrations measured downstream of the vacuum cleaners were not noticeably increased when the generation of the test aerosol was started. The particle number concentrations were measured down stream of the vacuum cleaners before initiating aerosol generation. During this time period, the particle concentration upstream of the vacuum cleaners was under 1 particle/cm^3 and the particle concentrations downstream of the vacuum cleaner was greater than 5 particles/cm^3. This indicates that the vacuum cleaners are generating aerosol. The average concentration downstream of the vacuum cleaner motor prior to aerosol generation was computed. The adjusted aerosol penetration P_{adj} was computed for each particle size as:

$$P_{adj} = (C_{d,a} - C_{d,b})/(C_{u,a} - C_{u,b})$$

Where
$C_{d,a}$ = Concentration measured down stream vacuum cleaner during aerosol generation
$C_{d,b}$ = Concentration measured down stream vacuum cleaner without aerosol generation
$C_{u,a}$ = Concentration of aerosol measured upstream of vacuum cleaner during aerosol generation.
$C_{u,b}$ = Concentration measured upstream of vacuum cleaner without aerosol generation.

The development of this equation is described elsewhere.[31] This was a very large adjustment to the calculated penetrations. Some of the individual values of the adjusted penetration were less than zero. This was caused by the variability in the aerosol generation by the vacuum cleaner motor. An upper 95% confidence limit for the average penetration at each size was computed and this result is shown in the lower half of Figures 9-11. These results indicate that at least 99.8% of the respirable particulate larger than 1 μm is being collected by the vacuum cleaners that were tested.

Findings: The worker performing mortar removal with right-angle grinders outside need control measures that reduce there exposure to respirable dust by a factor of at least 100. The vacuum cleaner bags results presented in Figures 5-7 do not provide efficient particle collection for particles smaller than 5 μm. However, the vacuum clean bag results presented in Figure 8 indicate that it is possible to obtain acceptable collection of respirable dust with a vacuum cleaner bag. Unfortunately, this bag ruptured during the testing of vacuum cleaner system. Although the vacuum cleaner bags do not efficiently capture respirable dust, they collect much of the larger dust and protect the final filters from overloading. An excessive accumulation of debris on the final filters reduces the air flow provided by the vacuum cleaners.

Figures 9-11 present particle penetrations measured through vacuum cleaner systems. These vacuum cleaners had been used during field trials. The penetration of particles larger than 1 μm through these vacuum cleaners was less than 0.01 before adjusting the penetration measurements for emissions from the vacuum cleaner motor. After adjusting for the aerosol generation by the vacuum cleaner motor, the upper 95% confidence limits on aerosol penetration through the vacuum cleaner were under 0.002. For particles smaller than 1 μm, the upper confidence limit on aerosol penetration through vacuum cleaners was less than 0.05. This may not actually represent increased aerosol penetration through the vacuum cleaner as the dust emissions from carbon brushes is known to produce an aerosol that is smaller 1 μm.[31] Thus, we can only conclude that the penetration is less than this upper confidence limit. However, these vacuum cleaners had all been used during field trials. For purposes of discussion, assume that average penetration through these vacuum cleaners is 0.001. Suppose a vacuum cleaner had been used to collect 100 kg of mortar debris and the aerosol penetration through the vacuum cleaner was 0.001. Approximately 100 grams of debris would either pass through the vacuum cleaner motor or accumulate in the motor. This accumulated debris could eventually be dispersed. This suggests that the vacuum cleaner motor can become an emission source of silica containing dust.

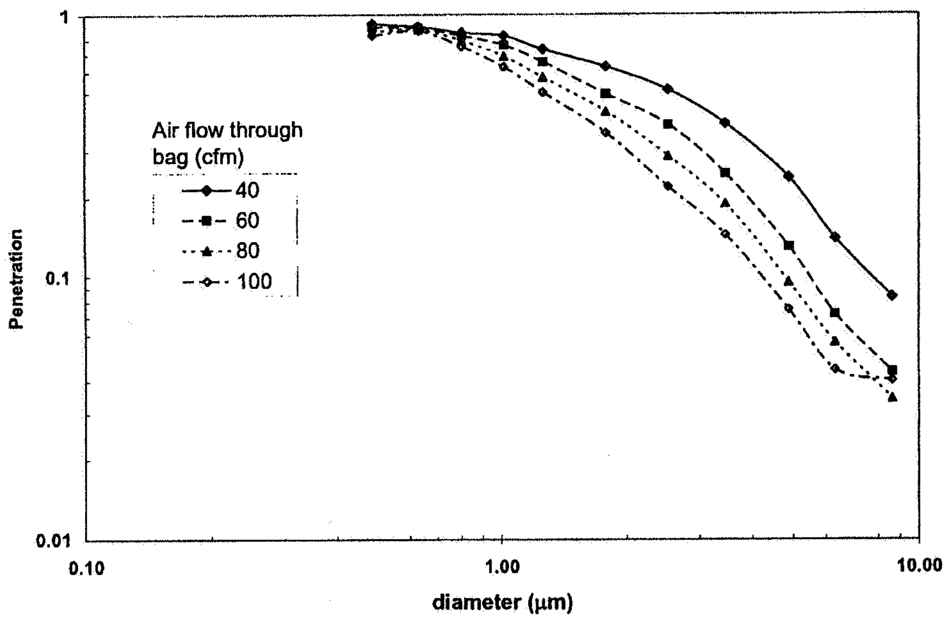


Figure 5. Particle penetration through a vacuum cleaner bag supplied with the Industrial Contractor's Supply Vacuum Cleaner (Pittsburg PA). This had the same part number as the ShopVac bag in Figure 6.

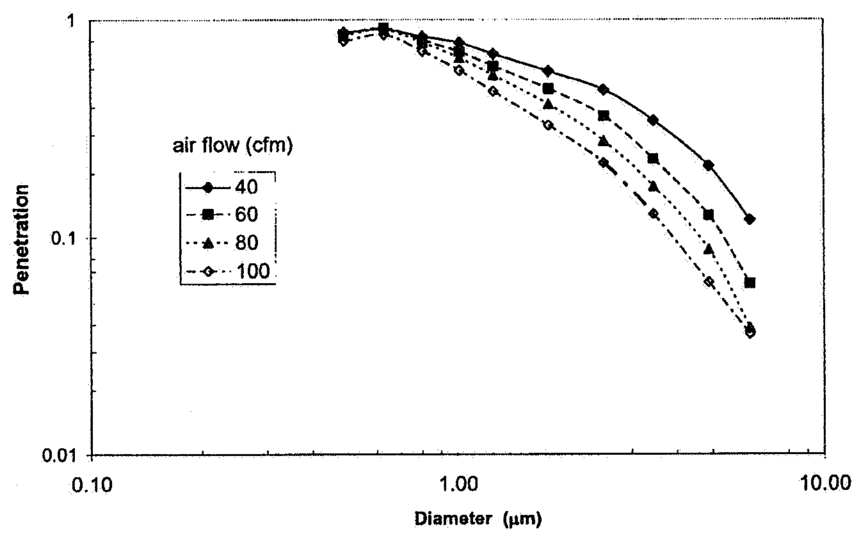


Figure 6. Aerosol penetration through a ShopVac Vacuum Cleaner Bag (16-22 gallon part 49540-05).

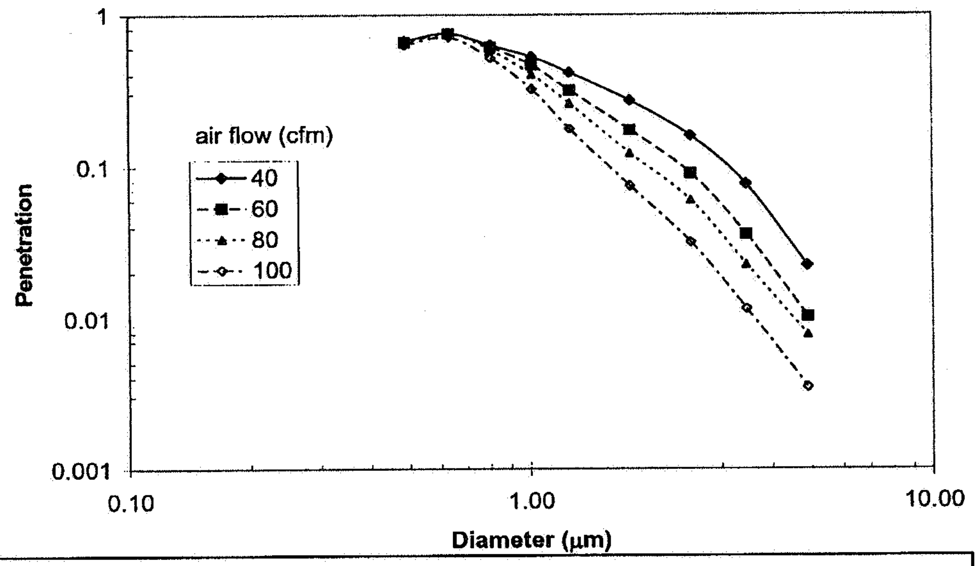


Figure 7. Particle Penetration through vacuum cleaner bag supplied for Altowap vacuum cleaner. (Bag labeled BIA nach ZH1/487, Abs.2)

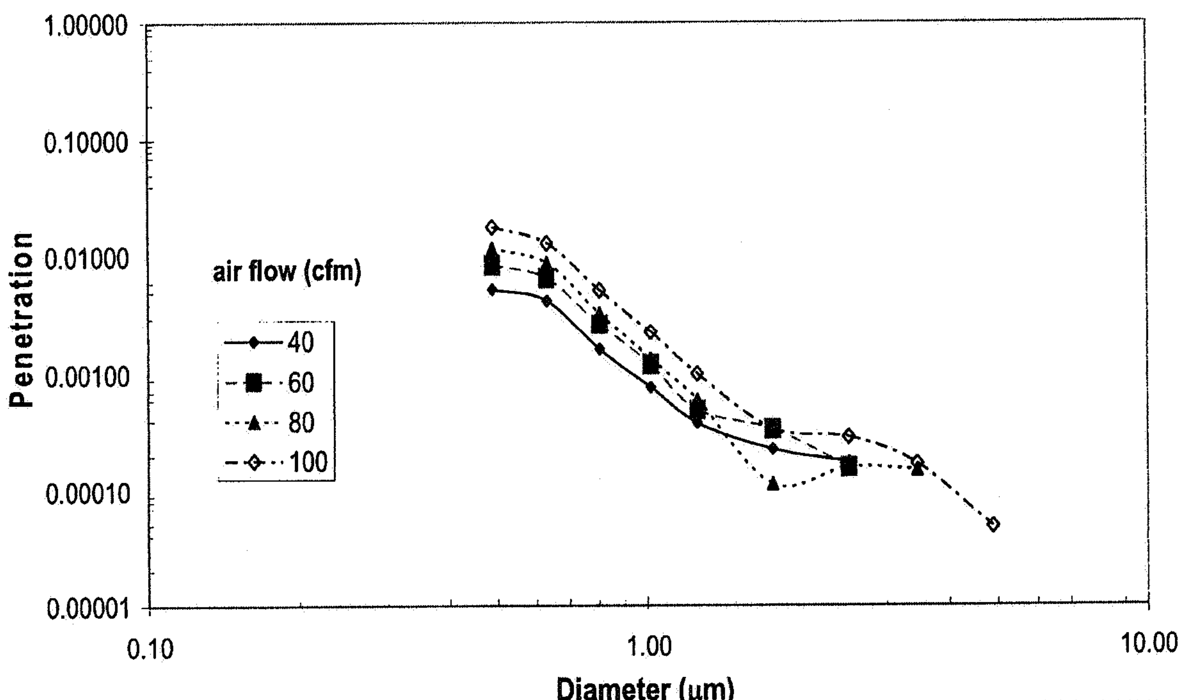
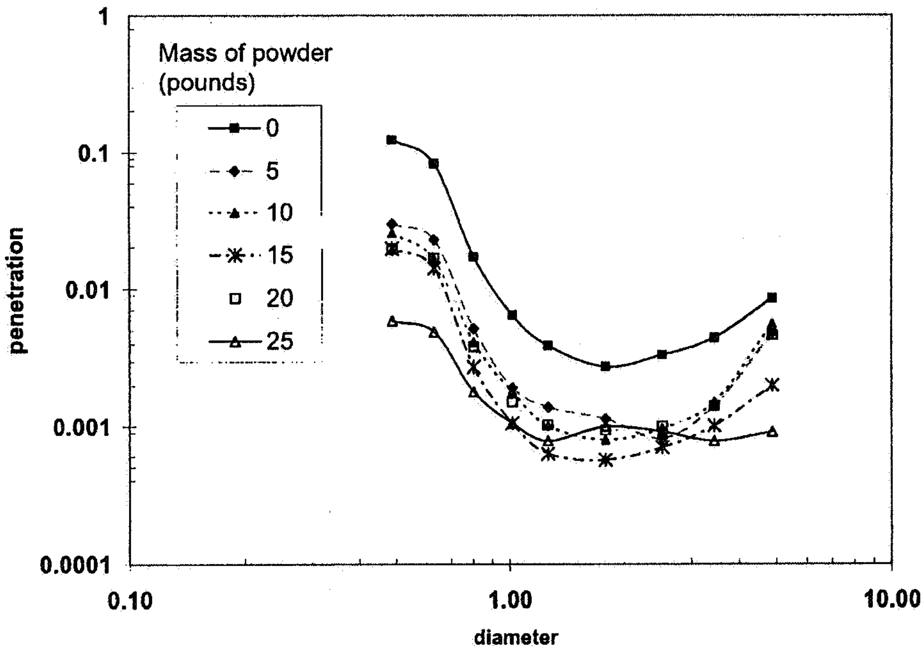


Figure 8. Yellow vacuum cleaner bag is supplied by ShopVac. The part number is 49540-25. This bag is reportedly made from an electret material.

A. Without correction for aerosol generation by vacuum cleaner.



B. With correction for aerosol generation by vacuum cleaner.

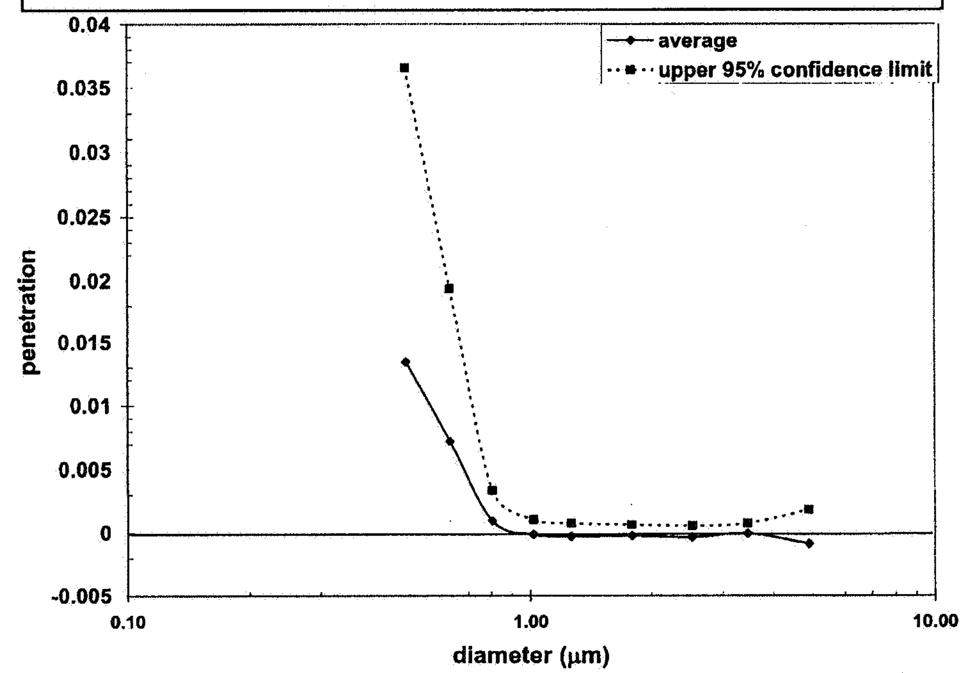
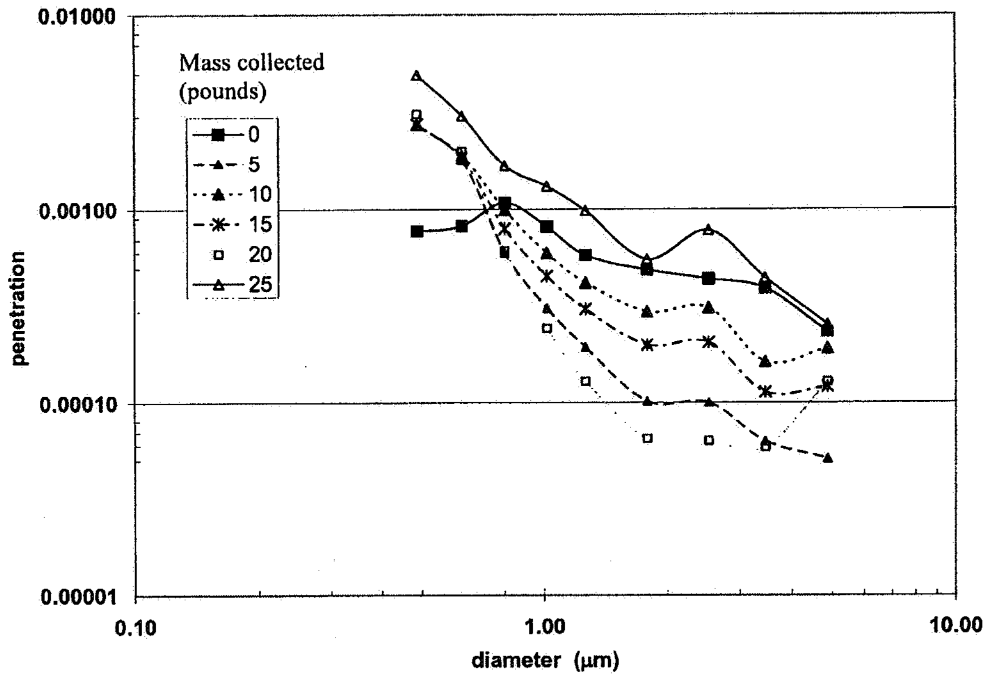


Figure 9. Particle penetration through an Altowap vacuum cleaner.

A. Without correction for aerosol generation by vacuum cleaner motor.



B. With correction for aerosol generation by vacuum cleaner motor.

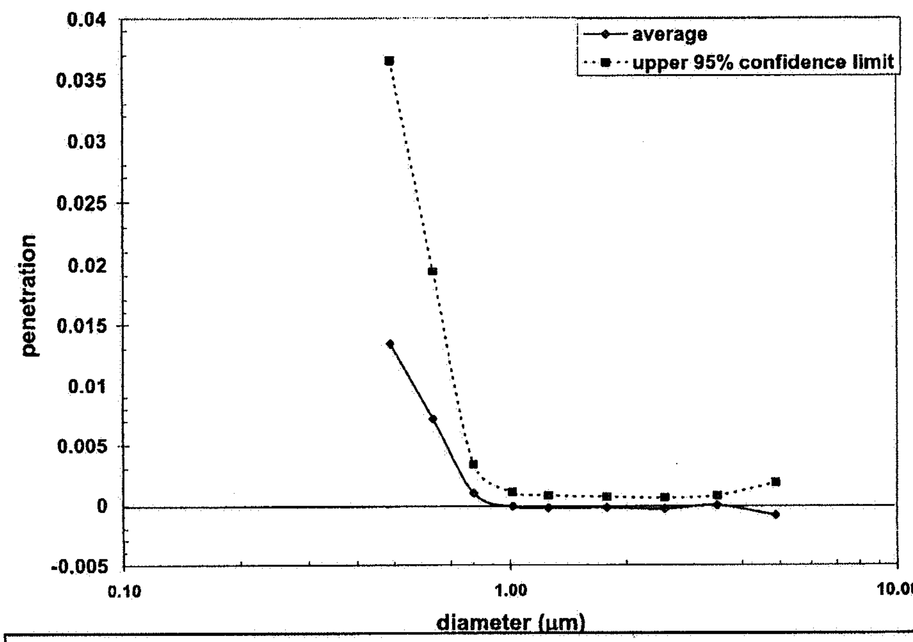
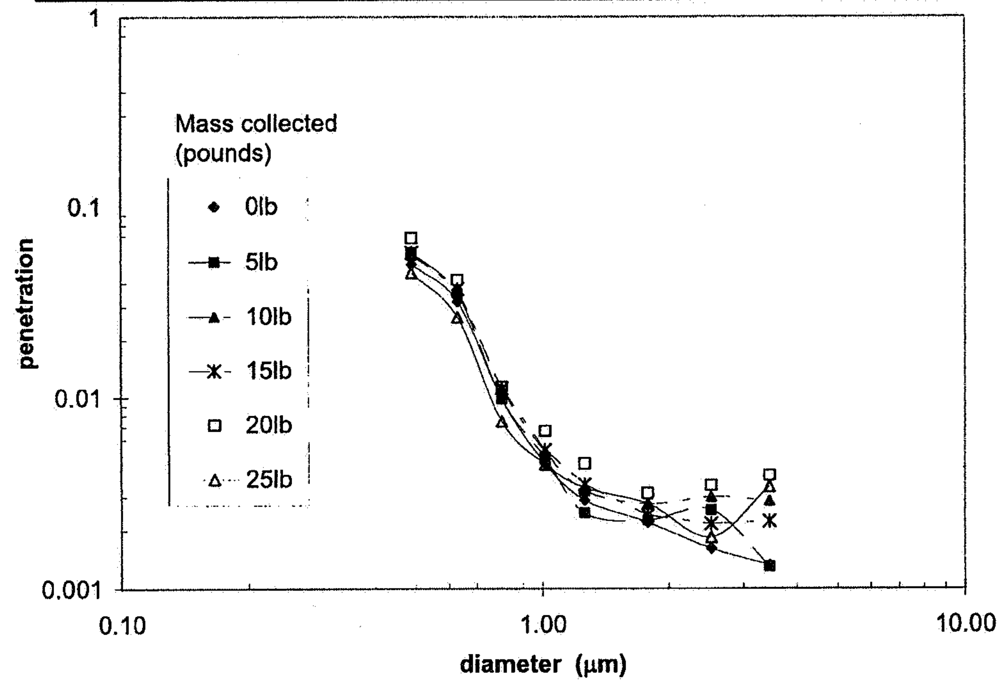


Figure 10. Particle penetration through a Bosch model 3931 vacuum cleaner.

A. Without correction for aerosol generation by vacuum cleaner motor.



B. With correction for aerosol generation by vacuum cleaner.

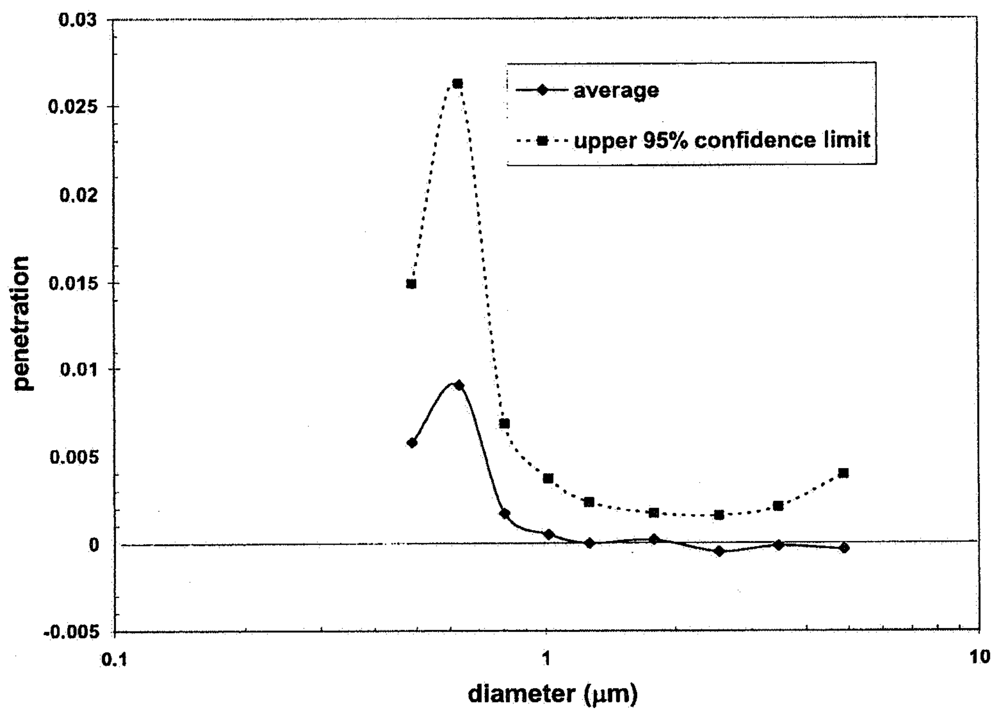


Figure 11. Particle penetration through a Dustcontol model 2700 vacuum cleaner.

Results and Findings – Specific Aim 2.

Results: Table 1 and Figures 12 and 13 describe the relationship between vacuum cleaner static pressure and flow rate. In Figures 12 and 13, the vacuum cleaner air flow is a straight-forward linear function of vacuum cleaner static pressure. Table 1 presents regression analysis results from modeling vacuum cleaner air flow as a linear function of static pressure. Regression analysis was performed using the regression analysis features in a spreadsheet (Excel 2002, Microsoft). Based upon the value of R^2, the regression models summarized in Table 1 explain, after adjusting for the mean, 99.9 to 98.5% of the variability observed in measured air flow. The postulated model fits the data. This showed that the vacuum cleaner's fan curve can be estimated from a vacuum cleaner's water lift at zero air flow and the air flow measured with no obstruction. The intercept from regression analysis is an estimate of air flow at no pressure loss.

The slope of the regression line describes the change in vacuum cleaner air flow with increased pressure loss through the shroud, hose, and vacuum cleaner filter. The Dustcontrol and Porter-Cable vacuum cleaners moved less air flow than the other vacuum cleaners at zero pressure loss. However, these two vacuum cleaners were less sensitive to changes in vacuum cleaner static pressure. For example, the slope for the fan curve for the Dustcontrol vacuum cleaner was -1.3 cfm/inch of water versus -5.7 cfm/inch of water for the ShopVac vacuum cleaner.

Table 1. Regression analysis results for modeling air flow as a function of vacuum cleaner static pressure.

vacuum cleaner	R^2	n	standard error of estimate (cfm)	slope cfm/inch of water	intercpt (cfm)	air flow measurement
ShopVac (model QUL 650)	0.989	22	6.57	-5.17	261	velometer
Altowap one blower (SQ23)	0.997	11	2.82	-3.59	198	venturi meter
Alto Wap two blower (SQ23)	0.987	12	7.38	-3.58	257	venturi meter
Dust Director	0.997	12	1.64	-4.39	222	venturi meter
Dustcontrol (model 2700)	0.995	34	2.42	-1.48	130	velometer
Dustcontrol (model 2700)	0.999	11	0.64	-1.33	120	venturi meter
Portar-Cable (model 7814)	0.989	13	4.85	-1.61	116	velometer
Bosch (model 3937)	0.985	17	3.85	-1.6	120	Venturi meter

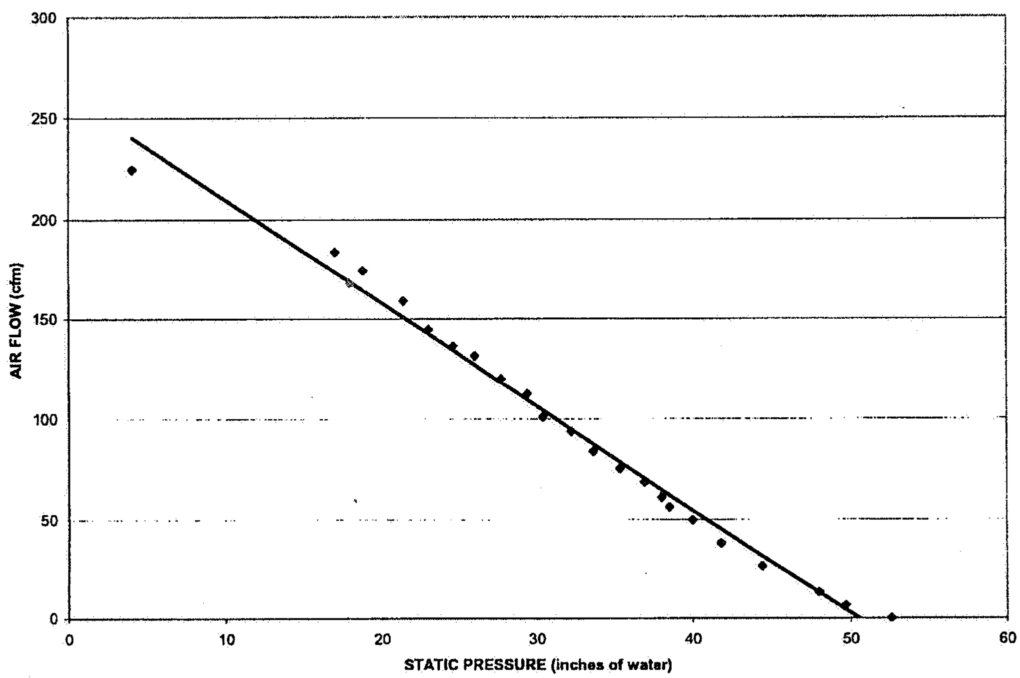


Figure 12. Fan curve for a ShopVac vacuum cleaner.

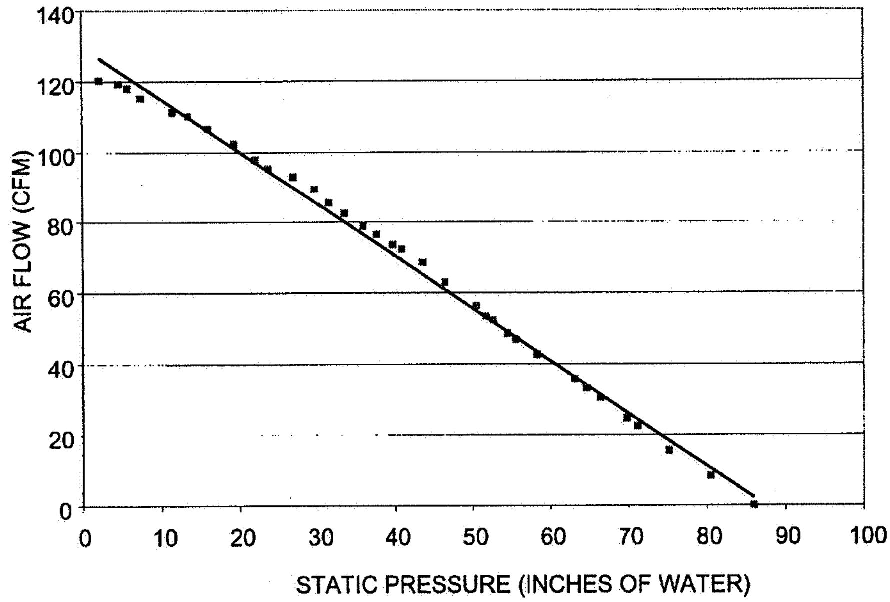


Figure 13. Fan curve for the DustControl 2700 vacuum cleaner. Note the lack of fit at the higher flow rates where the static pressure is less than 10 inches of water.

Vacuum Cleaner Flow Rates During Mortar Removal: Figures 14-18 present air flows measured during mortar removal. These air flow measurements were based upon vacuum static pressure and the vacuum cleaners fan curves that are summarized in Table 1. The vacuum cleaners equipped with 2-inch diameter hose were able to maintain more than 65 cfm of air flow. When the hose diameters were reduced to 1.5 inches diameter, the vacuum cleaners were able to maintain more than 40 cfm. Thus, a two-inch diameter hose should replace the 1.5-inch diameter hose so that higher exhaust flow rates can be maintained. However, the worker will need to periodically shake the hose so that settled dust is transported to the vacuum cleaner's filters.

Findings: The vacuum cleaners did not succeed in maintaining air flows above 80 cfm during this study. The vacuum cleaners used during this study required between 10 and 15 amperes to operate. Because the vacuum cleaner and the grinder will be on the same circuit, it may not be practical to increase the size of the vacuum cleaner motor. To maximize the air flow provided by the vacuum cleaners, 2-inch diameter hoses should be used instead of 1.5-inch diameter hoses. The pressure loss through ventilation systems varies inversely with the fourth power of duct diameter.[32] Thus, reducing duct diameter from 2 to 1.5 inches increases the pressure loss by a factor of 3.2. The workers will need to monitor to the vacuum cleaner static pressure so that they know when to change bags or to dislodge accumulate debris from filters.

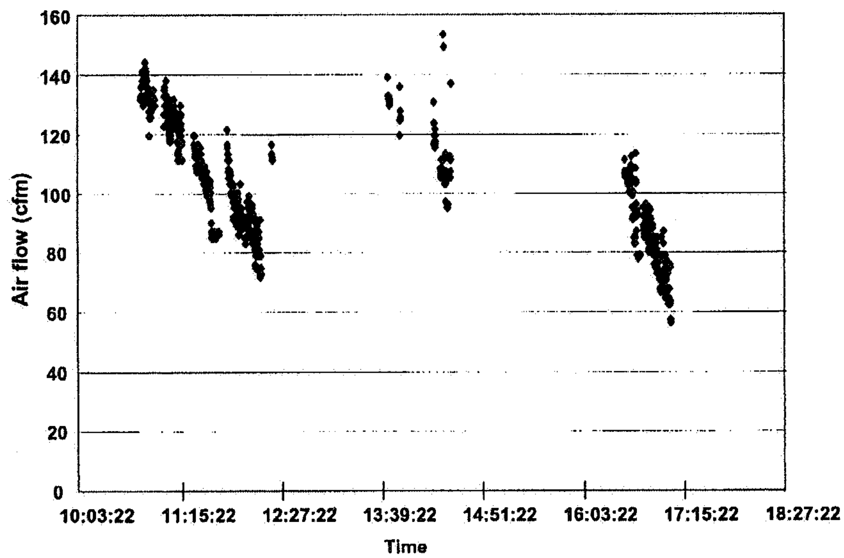


Figure 14. Air flow moved by a Shop Vac through 12 feet of 2-inch ID corrugated hose and Dust Director shroud.

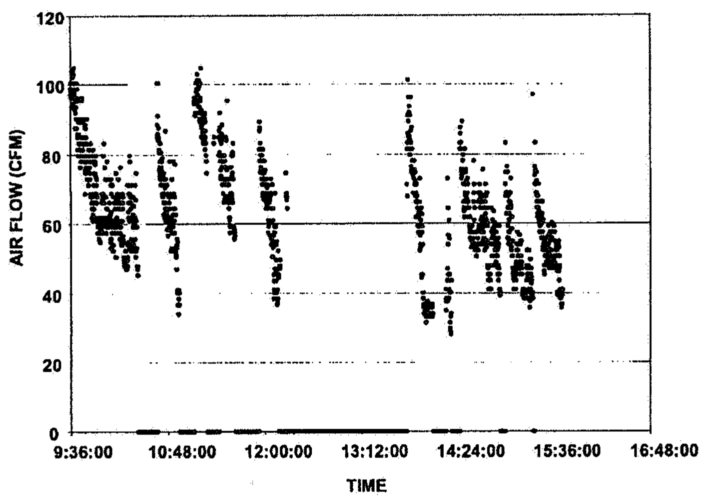


Figure 15. Air flow estimated from vacuum cleaner static pressure during mortar removal. The vacuum cleaner was a Dust Director operated with a 1.5 inch diameter corrugated hose.

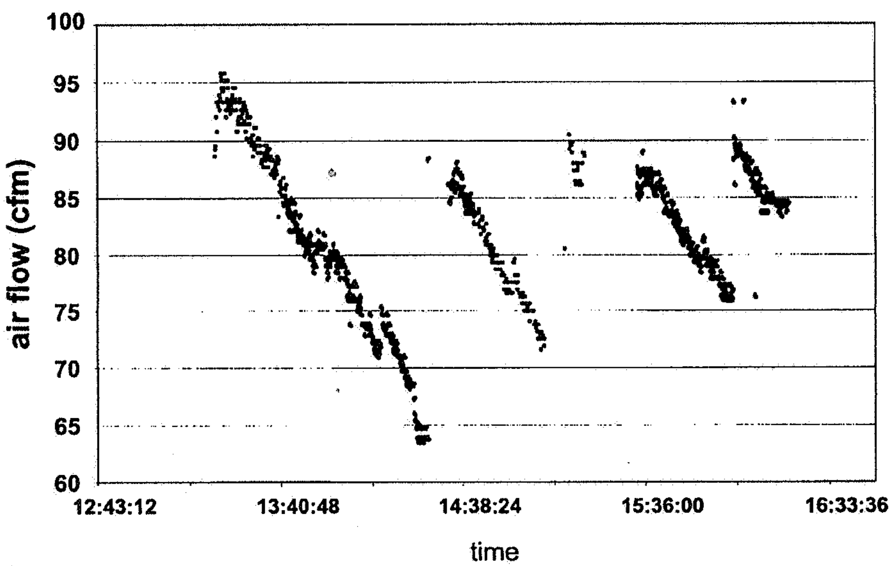


Figure 16. Air flow through DustControl 2700 with new filters, and a cyclonic preseparator. This vacuum cleaner drew air through a Dust Director Shroud and 16 feet of 2-inch diameter exhaust hose.

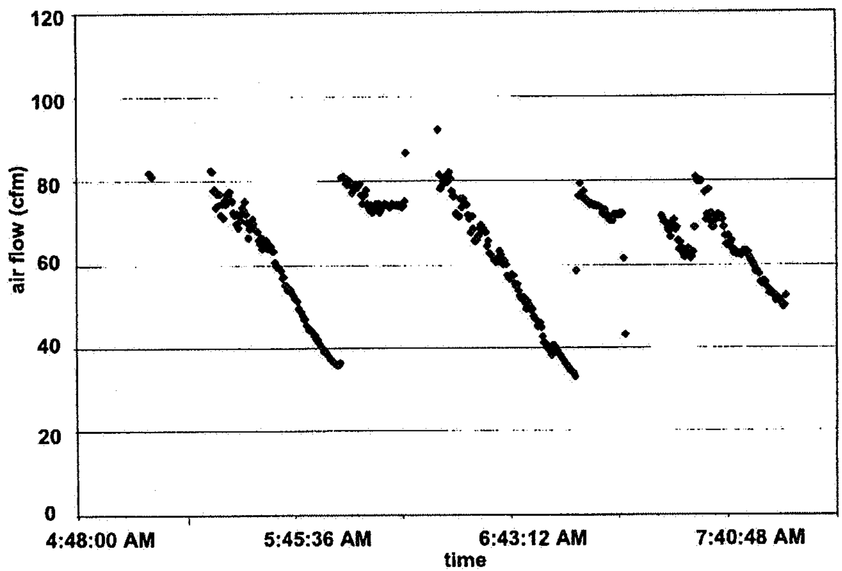


Figure 17. Air Flow moved by DustControl 2700 vacuum cleaner through 10 feet of 1.5-inch ID hose and a Dust Director shroud.

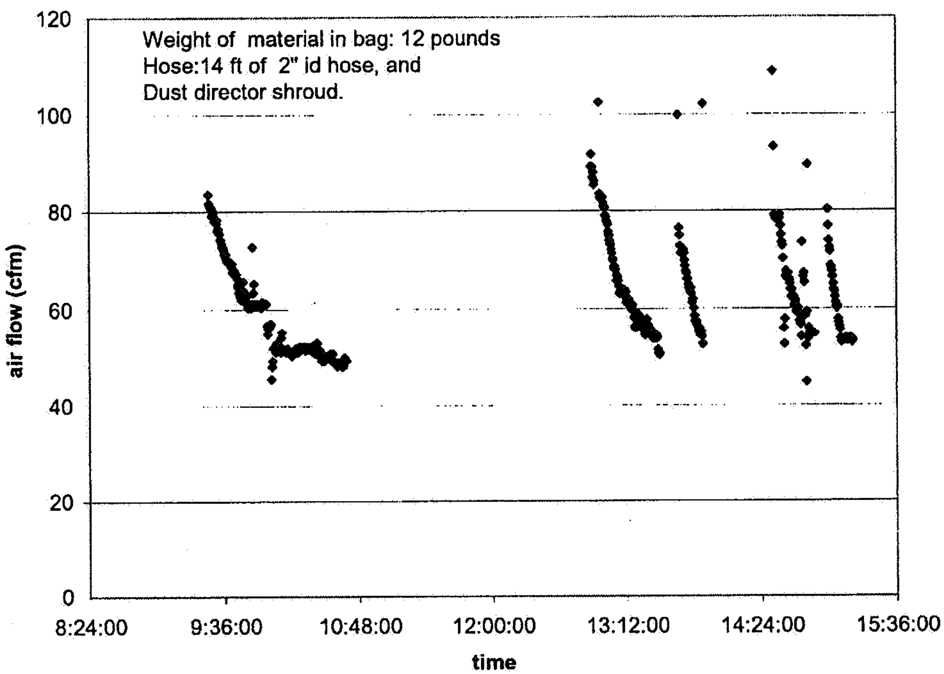


Figure18. Air flow moved by Bosch vacuum cleaner (model 3931) that is equipped with mechanical vibration.

Results and Findings - Specific Aim 3

Results: Table 2 summarizes the exposure measurements made during this study, a preceding pilot study, and from OSHA compliance sampling in the Chicago area during 1999 and 1998. The latter data set was supplied by Mr. Charles Shields.[33] Appendix A lists the concentrations measurements made during this study and the preceding pilot study which occurred during June of 2002. The concentration data and the mass of mortar collected during each sampling session is listed in Appendix A. As mortar was collected in the vacuum cleaner, the vacuum cleaner flow rate decayed from over 90 cfm to 65 or 40 cfm for, respectively, the 2-inch and 1.5-inch diameter hose. However, these exposures are greatly reduced from the exposures observed during uncontrolled mortar removal with a grinder. Perhaps, exposures could be further reduced by ensuring that flow rates remained above 80 cfm.

The respirable dust and respirable crystalline silica exposures measured during this study and the pilot study in St. Louis were much lower than the compliance exposures collected by OSHA in the Chicago area. The compliance samples were largely full shift samples and the air samples collected during this study and the pilot study were collected only during mortar removal. Thus, comparison of these task-based exposure measurements to compliance samples will understate the effectiveness of the control measures. Based upon a Smith-Satterthwaite t-test for unequal variances, respirable dust and respirable crystalline silica exposures measured during compliance sampling differed significantly from task based exposure measurements conducted during this study and the pilot study ($P < 0.0001$).[34]

Findings: Thus, the use of the vacuum cleaners and ventilated hoods on the grinder appear to significantly reduce the workers exposure to respirable dust and crystalline silica. However, the exposures are still excessive in terms of the NIOSH Recommended Limit (REL) for respirable crystalline silica which is 0.05 mg/m^3. However, only one of the samples collected during this study and one of the samples collected during the pilot study conducted in St. Louis exceeded 10 times the NIOSH REL. This situation suggests that most workers will receive adequate exposure reduction with a combination of a respirator with an assigned protection factor of 10 and ventilated grinders. However, exposure monitoring is needed to ensure that the exposures are less than the 10 times the NIOSH REL. If engineering control measures are not used for mortar grinding, respirators with an APF greater than 100 will be needed. Apparently, the control measures reduced the workers' respirable silica exposure by a factor of 20.

Table 2. Summary of Exposures During Mortar removal from this study, a preceding pilot study, and OSHA Compliance Data from 1998-1999.					
Data Source	Geometric mean (mg/m^3)	Geometric Standard Deviation	n	Range mg/m^3	comment
respirable crystalline silica					
this study	0.06	3.22	22	0.86- lod	Air flow maintained between 40 and 100 cfm, task-based air sampling
Heitbrink and Floit (Heartland Center Pilot Study)	0.14	2.4	11	0.68- 0.06	Some vacuum cleaner failures with flows as low as10 cfm, task-based air sampling.
Compliance Data from Charles Shields in 1998-1999.[33]	1.20	6.09	37	76-lod	These exposures did not involve control measures and were compliance samples that are nearly full shift.
respirable dust					
this study	1.07	2.09	22	4.50- 0.32	air flow maintained between 40 and 100 cfm, task-based air sampling
Heitbrink and Floit (Heartland Center Pilot Study)	1.88	2.40	11	5.6- 0.48	Some vacuum cleaner failures with flows as low as 10 cfm, task based air sampling'
Compliance Data from Charles Shields in 1998.[33]	12.33	4.13	37	349- 0.25	These exposures did not generally involve control measures and were compliance samples that are full shift.
Lod – less than limit of detection of about 0.01 mg/m^3.					

Results and Findings-Specific Aim 4.

Results: During most of the sampling sessions, respirable dust concentrations were measured on the vacuum cleaner in the discharge air flow. To evaluate whether the vacuum cleaner may be an emission source, the ratio of the concentration on the vacuum cleaner to the background concentration was computed. The natural logarithm of these ratios was computed and a t-test was conducted to evaluate whether the mean of the log-transformed ratios differed from zero. Table 3 presents the geometric mean ratios and that chance caused these ratios to differ from 1. (The natural logarithm of 1 is zero.)

Table 3. Geometric mean of the ratio of respirable dust concentration measured on the vacuum cleaner to the respirable dust concentration measured away from the mortar grinding.

Description	Geometric Mean	Geometric Standard Deviation	n	Probability of a larger student's t statistic
Western Construction Group June 2003 (Dustcontrol 2700 vacuum cleaners)	7.16	2.99	5	0.016
McGough Construction Minneapolis (Altowap SQ23 vacuum cleaners)	0.78	3.61	10	0.553
Western Construction Group,St Louis, 2002. Various low cost vacuum cleaners.	33.42	3.54	4	0.012
Nickoangelo Tuckpointing	13.46	7.39	5	0.044

Findings: Whether these vacuum cleaners were an emission source is unclear. The vacuum cleaners were close to the workers and possibly the dust plumes from the grinding may have contributed to the increased concentrations measured on the vacuum cleaners. As discussed in the findings for Specific Aim 1, the vacuum cleaners are collecting much material as document in Appendix A. During some shifts, as much as 35 kg were collected in a vacuum cleaner. This could lead to an accumulation of respirable silica in the vacuum cleaner that could eventually be dispersed. Given the uncertainty as to whether these vacuum cleaners were emission sources, one should be careful when these vacuum cleaners in enclosed spaces that lack adequate ventilation.

Results and Findings- Specific Aim 5.

Results: Video exposure monitoring was conducted while an inexperienced worker removed mortar from a deteriorated municipal stadium. The stadium wall had some missing mortar. As, result, the dust frequently flowed between the bottom of the exhaust take-off and the wall (See Figures 19-22.) Occasionally, the worker was able to move the grinder down the wall so that the grinder swarf was directed into the exhaust shroud (Figure 19). During this ideal use of the grinder, the shroud appears to capture the grinder swarf. Figure 22 displays how air flow and dust concentration varied with time and work tasks. The output of the aerosol photometer is mg/m^3 of dust. During most of the monitoring period, the grinder was used in non-ideal situations such as:

1. Moving the grinder in and out of the wall.
2. Grinding mortar where the mortar was missing. This causes the grinding debris to escape between the bottom of the take-off and the mortar.
3. Grinding the mortar in corners.

In Figure 22, these activities caused dust peaks as a high as 100 mg/m^3. During ideal grinding when the worker was able to move the grinder through a solid mortar joint, the dust concentrations remained below 1 mg/m^3.

As this video exposure monitoring session progressed, the vacuum cleaner flow rate decreased from 120-90 cubic feet per minute (cfm) to 60-40 cfm. Because the worker's activities were dominated by non-ideal grinding, this data does not provide clear information as to whether the decreasing flow rate adversely affected exposure. However, the results in Figure 22 appear to indicate a drift to higher dust concentrations near the end of the sampling session when the vacuum cleaner air flow was below 60 cfm.

Video exposure monitoring was also conducted while an experienced worker was performing mortar removal on a brick wall where the deteriorated mortar was mostly present. This enhanced the collection of the mortar debris by the vacuum cleaner. Aerosol photometer measurements and vacuum cleaner static pressure were concurrently measured. These results are presented in Figure 23. There were very few exposure peaks above 0.3 mg/m^3. As noted in the plot, the workers dust exposure appears to be occasionally elevated by vertical cuts and by deteriorated mortar. In addition, the air flow was greater than 100 cfm during this time period. When the mortar was largely intact, the grinder swarf is directed at the exhaust take-off and the exposure peaks appear to be much less than the exposure peaks observed in Figure 22.

Findings: The video exposure monitoring shows that the exhaust shroud and vacuum cleaner greatly minimizes the dust exposures generated by mortar removal when the mortar on the wall is intact. However, when the mortar is so deteriorated that some mortar is missing, the dust control efforts are less effective and significant exposure peaks will occur. In order for the ventilation system to capture the mortar debris, it must be directed into the exhaust take off by the uncut mortar. If the gap between the mortar and the bottom of the exhaust take-off is too large, the dust plume is observed to escape capture.

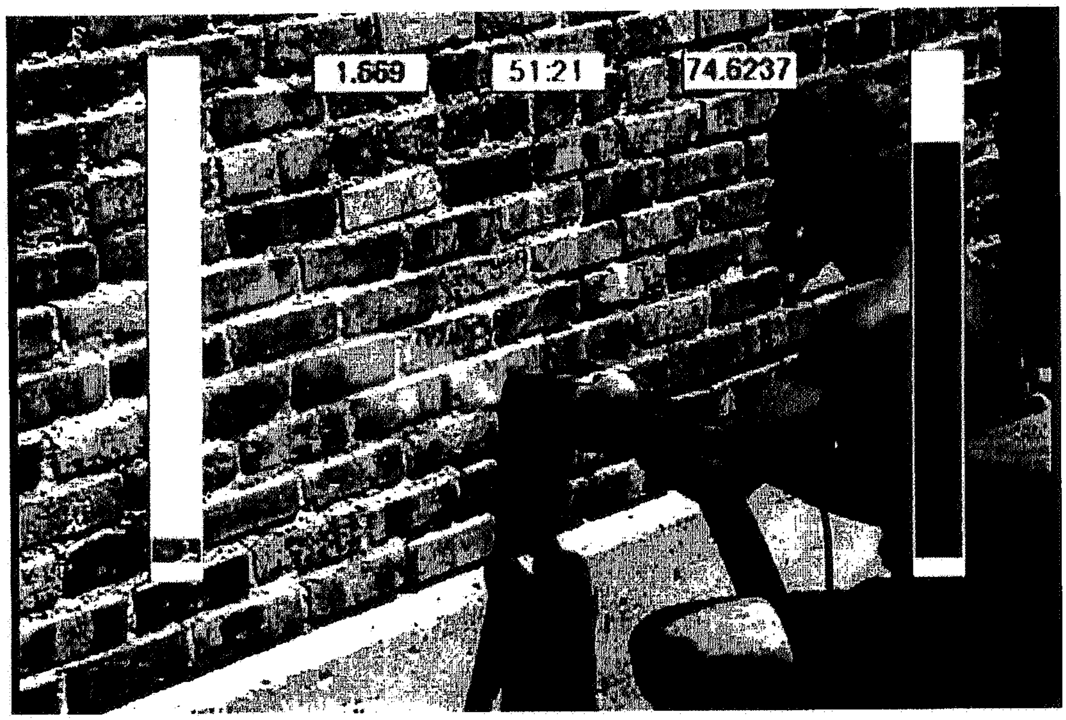


Figure 19. Worker is removing mortar from a horizontal joint. Because some mortar is missing, the dust flows under the exhaust take-off. The numbers on the top of the picture from left to right are: the aerosol photometer measurement in mg/m^3, time in minutes and seconds, and air flow in cfm. The gap between the exhaust take-off and the mortar was quite variable.

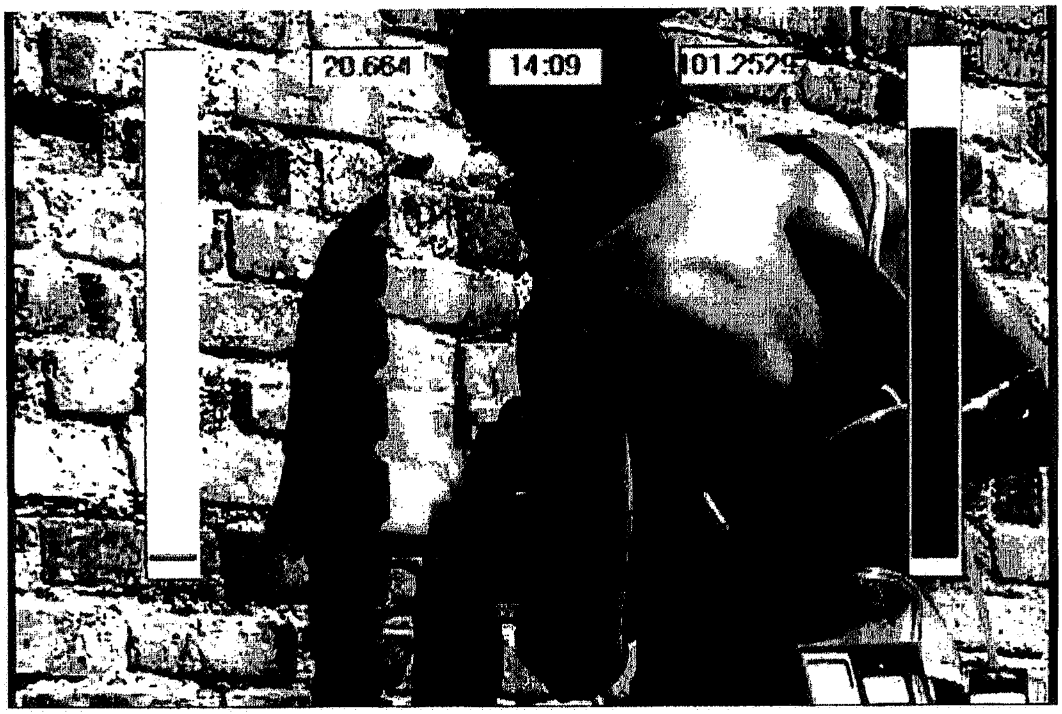


Figure 20. The worker is cutting a vertical joint in a corner. The horizontal joint under the exhaust take-off is missing. The mortar dust escapes the shroud and causes the workers dust exposure to increase dramatically.

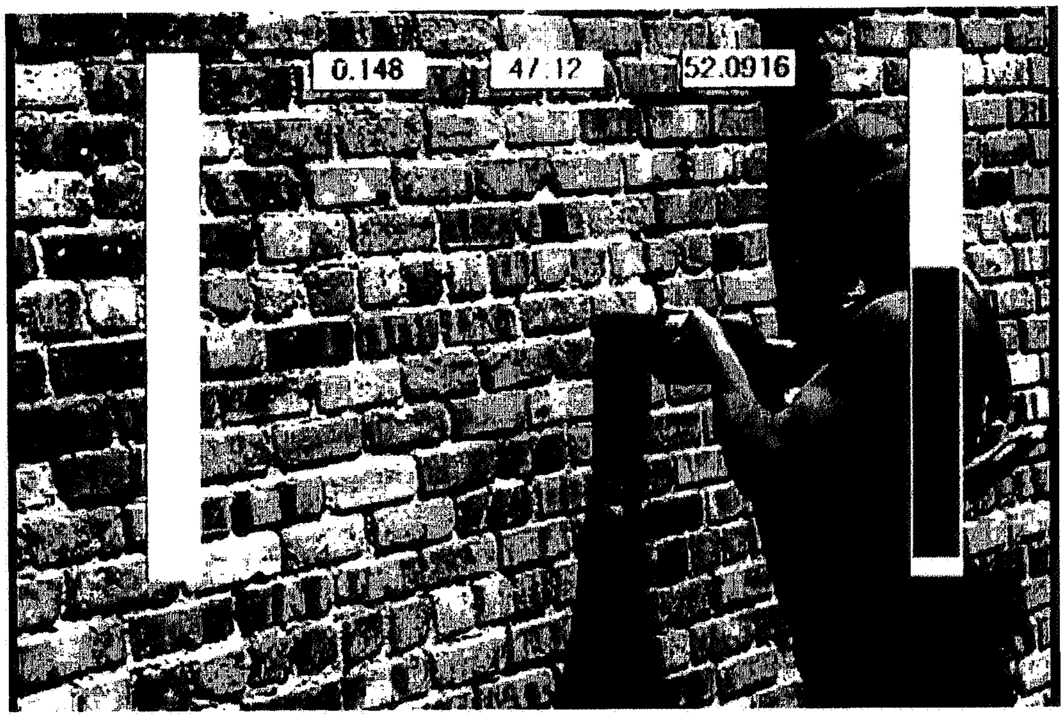


Figure 21. Routine horizontal cut. The mortar debris was being efficiently captured at a flow rate of 52 cfm and the worker's dust exposure was 0.14 mg/m^3.

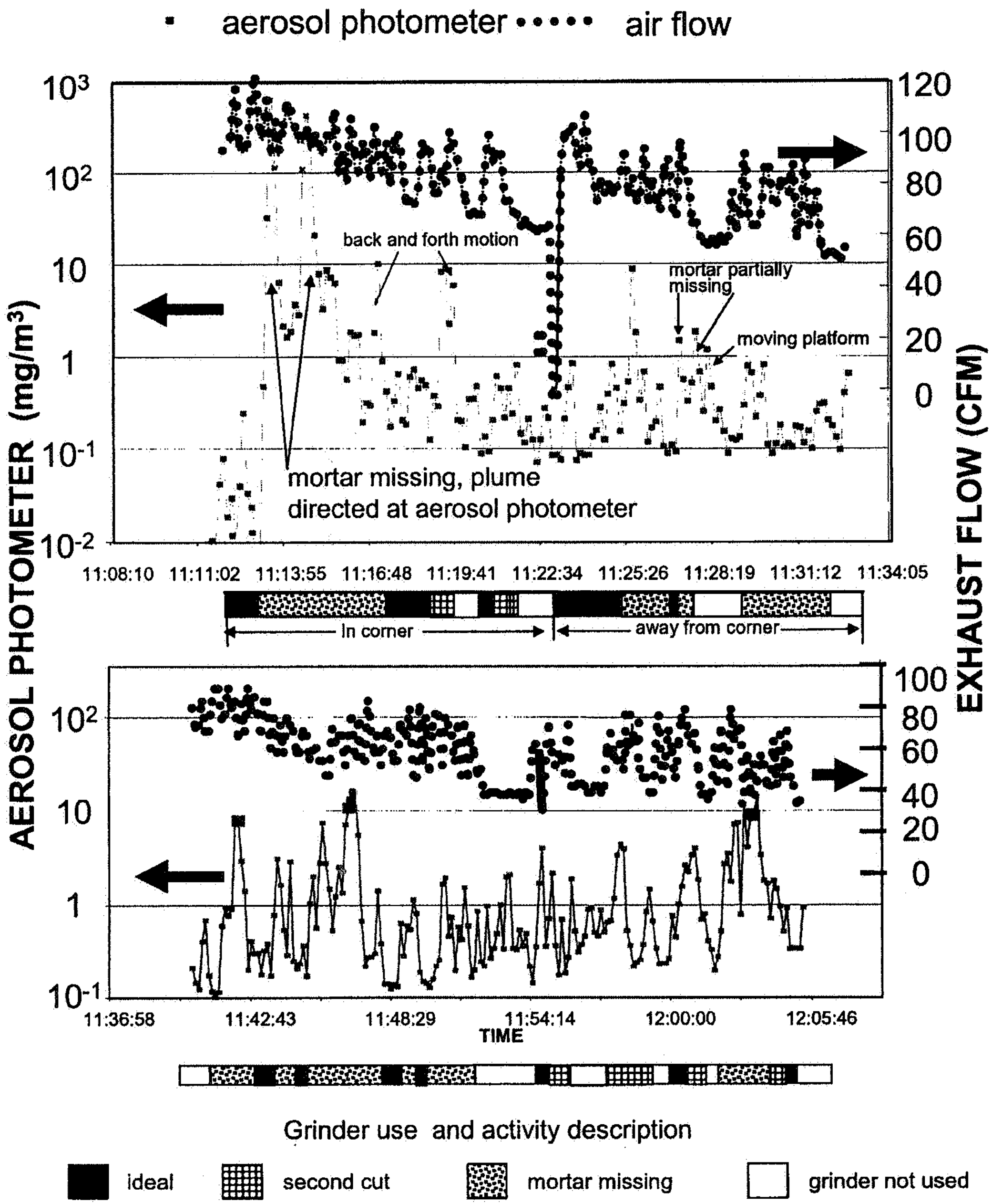


Figure 22. Video exposure monitoring showing aerosol photometer response and vacuum cleaner air flows estimated from fan curve for a ShopVac exhausting air flow from the Dust Director Shroud and 2" ID corrugated hose.

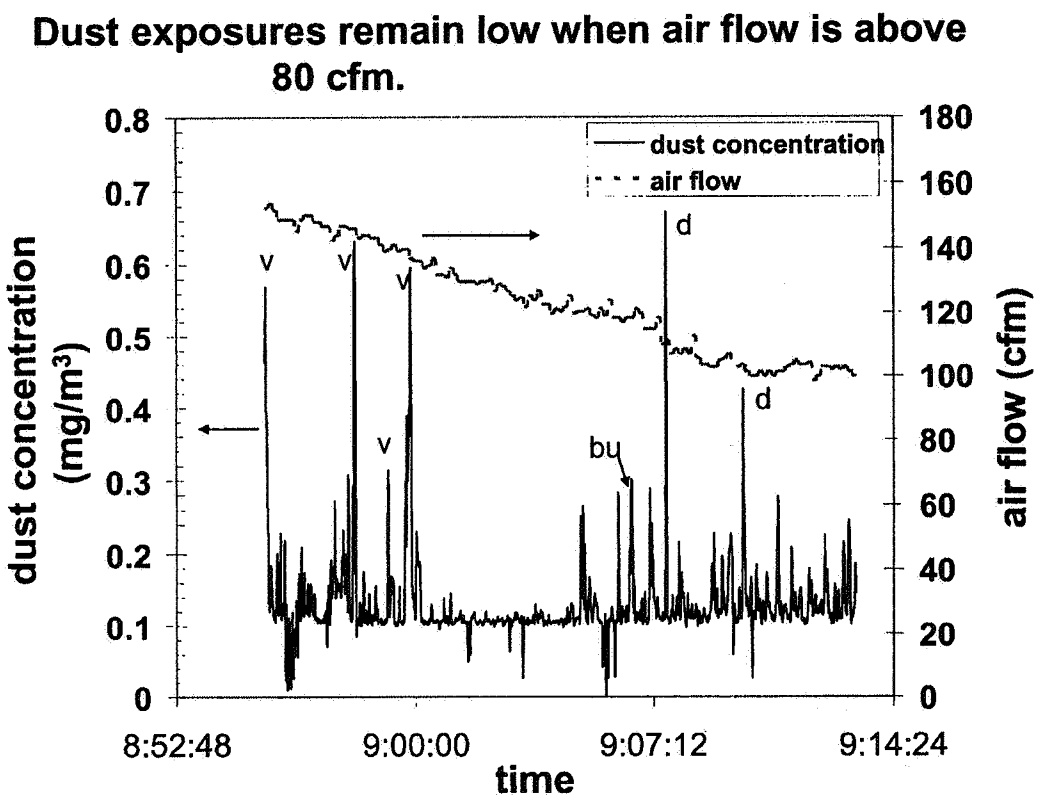


Figure 23. Video exposure monitoring showing aerosol photometer response and vacuum cleaner air flow. The plot is annotated with the symbols: v (for a vertical cut), d (for deteriorated mortar), and bu (back up during grinding). The optics of the aerosol photometer appears to be dirty causing a constant background of 0.1 mg/m^3.

Discussion and Conclusions

Control Measure Performance: The respirable crystalline silica exposure measurements reported in Table 2 are much less than the exposures reported by Shields.[6] Uncontrolled mortar removal with grinders can cause respirable crystalline silica exposures that exceed 5 mg/m^3 which is 100 times the NIOSH recommended exposure limit. With the exception of one short-term example, the respirable crystalline silica exposures reported in Appendix A were less than 10 times the NIOSH Recommended Exposure Limit of 0.05 mg/m^3. Such exposures can be managed with half-face piece air purifying respirators. To achieve this exposure reduction, the vacuum cleaners used in this study were able to maintain air flows above 40 cfm and 65 cfm when, respectively 1.5- and 2-inch diameter hose were used.

Based upon the available laboratory data, increasing exhaust air flow above 80 cfm did not yield further reductions in grinder emissions.[10] It is unclear whether further reductions in respirable crystalline dust exposures could be obtained by maintaining vacuum cleaner air flow rates at 80 cfm or above. The video exposure monitoring data presented in Figures 22 and 23 does not provide insights as to minimum air flow rate. Apparently, the gap between the bottom of shroud and the mortar affects the capture of the mortar dust. Perhaps, the hoods capture efficiency varies with flow rate and the size of this gap. The experimental study did not consider this possibility. [10]

The video exposure monitoring indicated that, during many mortar removal activities, the ventilated grinders effectively capture the dust. However, the systems provided noticeably incomplete dust exposure control during the following tasks:

1. Grinding in the presence of partially missing mortar;
2. Inserting and removing grinder blades from the wall;
3. Repeating cut in the same joint;
4. Working in an area with poor natural ventilation, such as enclosed corner.

Dust Control Recommendations: Dust control recommendations from this study have been distributed to the Center to Protect Workers Rights in form of draft recommendations.[35] The draft recommendations are unchanged and need to be distributed to the construction community. Figure 23 describes the control scenario. The worker moves the grinder against the natural rotation of the grinding wheel. As the grinding wheel emerges from the uncut mortar, the debris moves in a direction that is tangential with respect to the grinding wheel as it emerges from the mortar. This allows the hood to capture the debris. If the distance between the exhaust take-off and the point where the grinding wheel is too large, the debris is not captured by the exhaust hood.

In order to capture the dust, the vacuum cleaners must move some minimum air flow that probably varies with the size of the gap between the mortar and the bottom of the exhaust hood. The available laboratory data indicated that this air flow is 80 cfm.[10] Figures 14-

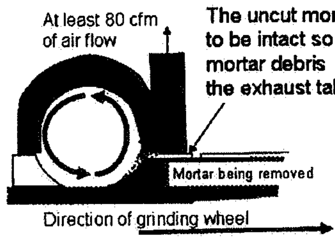
18 showed that vacuum cleaners did not maintain this flow during actual use. To maximize the flow through these vacuum cleaners, hose diameters of 2 inches should be used so that pressure loss through the hose is minimized. Workers need to monitor the air flow provided by the vacuum cleaners so they know when to change vacuum cleaner bags or dislodge accumulated debris from vacuum cleaner final filters. There are two means for judging the adequacy of the air flow:

1. Obvious dust emissions.
2. Vacuum cleaner static pressure. Some vacuum cleaners such as the Dustcontrol 2700 are supplied with a vacuum gauge and curves may be available that relate vacuum cleaner static pressure to air flow. When the static pressure is larger than the static pressure for 80 cfm of flow, the pressure loss for the accumulated debris needs to be dislodged. Occasionally the build-up on the filter can be dislodged by simply moving or shaking the vacuum cleaner or by turning the motor off and on a few times. In some cases, one can repeatedly block the vacuum cleaner inlet, causing the filter to pulsate which dislodges the prefilter cake.

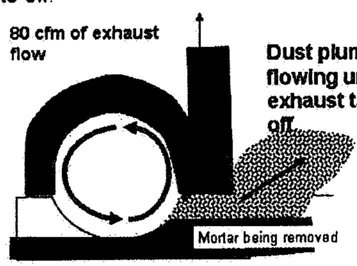
As the vacuum cleaner accumulates debris, the air flow decreases. To maintain air flow and the capture of mortar debris and respirable crystalline silica, the workers need to periodically dislodge the pre-filter cake that accumulates on filter surfaces. This can be done by turning the vacuum cleaner on and off, pulsing the vacuum cleaner filter, or shaking the vacuum cleaners, or using the mechanical vibration supplied with the vacuum cleaner.

The available results show that an exhaust system affixed to a grinder can reduce the silica exposures of workers by a factor of 20. However, worker silica exposures may still be excessive in terms of the NIOSH REL and the OSHA PEL. Thus, both ventilated grinders and respiratory protection are required. These control approaches must be part of a comprehensive silica control program containing the elements described below:

- Exposure monitoring is needed to evaluate whether the control measures are providing adequate worker protection.
- Equipment maintenance is necessary to ensure that the vacuum cleaner moves an adequate amount of air. Final filters in many vacuum cleaners will eventually become plugged and need to be replaced to maintain sufficient flow rates.
- Adequate respiratory protection. The exposure monitoring results suggest that respirators with an assigned protection factor of 10, such as half-facepiece respirators, would provide sufficient protection under conditions similar to those in the field trials. However, tuckpointing can generate extremely high silica dust levels and the respiratory protection must be appropriate for the site conditions. Exposure measurements are needed to verify respirator selection.
- Worker training must be provided on the proper use of the available control measures. This includes both respirators, the vacuum cleaner exhaust systems, and work practices.



A. Schematic illustration of grinder hood capturing the mortar debris. About 80 cfm of air is exhausted through the grinder. The uncut mortar is intact and directs the mortar debris into the exhaust take-off.



B. When the gap between the mortar and the exhaust take-off is too large, mortar debris escapes between the exhaust take-off and the mortar. In the picture on the left, the grinder take-off is not flush against the wall and a dust plume is faintly visible between the exhaust take-off and the wall.

Figure 23. Basic concepts for use of ventilation to control worker dust exposure during mortar removal.

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Appendix A.

Personal Exposure Measurements, Vacuum Cleaners and Hoses Used, and Mass of Mortar Collected at the various sites.

Site Description	date	Mortar removed (kg)	Working time (min)	personal		vacuum cleaner exhaust		ambient away from the task		description of vacuum cleaner used
				Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	
Western construction group at a medical clinic in Rochester MN	7/8/03	35.2	216	*lost*	*lost*	6.28	0.26	1.14	0.04	Dust Control w/ 2"hose
	7/8/03	35.2	215	0.85	0.11	0.37	0.03	0.11	LOD	Dust Control w/ 2"hose
	7/8/03	27.3	161	0.41	0.04	0.21	LOD-LOQ	0.03	LOD	Dust Control w/1-1/2"hose
	7/9/03	38.6	176	1.49	LOD-LOQ	2.89	0.49	0.36	0.03	Dust Control w/1-1/2"hose
	7/9/03	38.6	177	0.38	0.04	0.41	0.09	< LOD	LOD	Dust Control w/1-1/2"hose
	7/9/03	23.6	14	3.74	0.86	0.17	0.02	0.07	LOD	Dust Control w/1-1/2"hose
Nikoangelo Tuckpointing at a school site in Fort Dodge Iowa	7/17/2003	32.3	287	1.24	0.19	9.56	0.44	0.04	LOD	Yellow Shop Vac w/ 2"hose
	7/17/2003	12.3	273	0.96	LOD	0.13	0.02	LOD	LOD	Dust Director w/ 1-1/2"hose
	7/16/2003	26.4	353	0.32	0.05	0.44	0.05	0.01	LOD	Dust Director w/ 1-1/2"hose
	7/16/2003	10.5	339	0.33	0.03	0.07	lod	0.01	LOD	Yellow Shop Vac w/ 2"hose
	6/12 /2003	13.6	370	1.35	0.19	0.03	lod	0.01	LOD	Dust Director w/ 1-1/2"hose; vac bag broke
		11.4	185	4.50	0.50	0.06	lod	0.03	LOD	Dust Director w/ 1-1/2"hose **included unconventional tuckpointing on cement 'drain'

Site Description	date	Mortar removed (kg)	Working time (min)	personal		vacuum cleaner exhaust		ambient away from the task		description of vacuum cleaner used
				Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	
McGough Construction at the University of Minnesota Power Plant	11/14/2003	5.2	60	0.48	0.07	0.03	LOD	0.12	lod	Altoap with 2 inch diameter hose
	11/14/2003	4.5	57	0.71	0.06	0.04	LOD	0.04	lod	
	11/13/2003	12.2	141	0.84	LOD	0.20	0.03	0.28	lod	
	11/13/2003	11.4	143	1.52	0.09	0.02	LOD	0.02	lod	
	11/13/2003	24.5	179	2.13	0.15	2.13	0.15	0.19	0.02	
	11/13/2005	10.8	124	1.11	0.05	LOD	LOD	0.10	0.00	
	11/13/2005	10.0	10	1.45	0.06	0.03	LOD	0.08	lod	
	9/9/2003	.	124	2.50	0.20	0.18	LOD	0.91	0.09	
	9/9/2003	.	160	1.46	0.11	0.05	0.00	0.19	0.00	
	9/10/2003	5.0	256	0.66	0.04	0.66	0.04	0.17	0.02	
	9/10/2003	3.2	254	0.75	0.04	0.07	0.01	0.13	0.02	
Western Construction at the FDA laboratory in St. Louis Federal Center	6/12/2002	15.7	374	0.55	0.055	0.58	0.0232	0.027	LOD	Fein with 1.5 hose
	6/12/2002	13.2	389	1.7	0.0986	0.17	0.017	0.021	LOD	Portar Cable with 1.5 hose
	6/12/2002	16.4	252	5.6	0.4816	0.93	0.1209	0.024	LOD	Shop Vac with 2 inch hose.
	6/25/2002	12.7	105	1.3	0.143	4.9	0.1666	0.03	LOD	Dust Control with 1.5 inch hose
	6/25/2002	6.8	107	0.48	lod	.	.	0.03	LOD	Fein with 1.5 inch hose
	6/26/2002	35.0	212	4.05	0.077063	4.9	0.167	0.03	LOD	Dustcontrol with 1.5 inch hose
	6/26/2002	7.3	351	1.1	0.198	.	.	0.02	LOD	Fein with 1.5 inch hose
	6/27/2002	35.9	345	2.8	0.2296	.	.	0.02	LOD	Dustcontrol with 1.5 inch hose
	6/27/2002	5.0	283	1.5	0.18	.	.	0.03	LOD	Fein with 1.5 inch hose

Site Description	date	Mortar removed (kg)	Working time (min)	personal		vacuum cleaner exhaust		ambient away from the task		description of vacuum cleaner used
				Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	Respirable dust (mg/m^3)	Respirable Silica (mg/m^3)	
Western Construction at the FDA laboratory in St. Louis Federal Center	6/28/2002	.	257	0.9	0.084	.	.	0.03	LOD	Fein with 1.5 inch hose
	6/28/2002	.	140	5.2	0.676	.	.	0.02	LOD	Dustcontrol with 1.5 inch hose