Ann. Occup. Hyg., Vol. 57, No. 2, pp. 221–229, 2013

doi:10.1093/annhyg/mes066

Comparative Emissions of Random Orbital Sanding between Conventional and Self-Generated Vacuum Systems

DAVID R. LIVERSEED[1*], PERRY W. LOGAN[1,2], CARL E. JOHNSON[2], SANDY Z. MOREY[3] and PETER C. RAYNOR[1]

[1]School of Public Health, University of Minnesota, 420 Delaware Street SE Minneapolis, MN 55455, USA; [2]3M Center Saint Paul, MN 55105, USA; [3]More Consulting, Inc., 2511 Homewood Place Saint Paul, MN 55110, USA

Received 9 August 2012; in final form 21 Jun 2012; published online 12 October 2012

Conventional abrasive sanding generates high concentrations of particles. Depending on the substrate being abraded and exposure duration, overexposure to the particles can cause negative health effects ranging from respiratory irritation to cancer. The goal of this study was to understand the differences in particle emissions between a conventional random orbital sanding system and a self-generated vacuum random orbital sanding system with attached particle filtration bag. Particle concentrations were sampled for each system in a controlled test chamber for oak wood, chromate painted (hexavalent chromium) steel panels, and gel-coated (titanium dioxide) fiberglass panels using a Gesamtstaub-Probenahmesystem (GSP) sampler at three different locations adjacent to the sanding. Elevated concentrations were reported for all particles in the samples collected during conventional sanding. The geometric mean concentration ratios for the three substrates ranged from 320 to 4640 times greater for the conventional sanding system than the self-generated vacuum sanding system. The differences in the particle concentration generated by the two sanding systems were statistically significant with the two sample *t*-test ($P < 0.0001$) for all three substances. The data suggest that workers using conventional sanding systems could utilize the self-generated vacuum sanding system technology to potentially reduce exposure to particles and mitigate negative health effects.

Keywords: GSP sampler; hexavalent chromium; oak wood; random orbital sanding; titanium dioxide

BACKGROUND

Coated abrasive sanding is used globally in numerous industries, including manufacturing of durable goods, electrical and electronic equipment, fabricated metals, machinery, and transportation equipment (The Freedonia Group, 2010). Coated abrasives typically include sanding belts, sheets, discs, and wheels. Additionally, coated abrasives are used in cleaning and maintenance markets to repair and maintain commercial, industrial, and residential buildings; furniture, industrial, and other types of machinery; automobiles, motorcycles, and other transportation equipment (The Freedonia Group, 2010).

The global demand for coated abrasives in 2008 was US$10.8 billion, with a predicted increase to US$14 billion by 2013 (The Freedonia Group, 2010). One estimate of the number of workers exposed to wood dust in the European Union was 3.6 million (Kauppinen et al., 2006). Using the European Union estimate of 3.6 million workers, divided by Western Europe's 23% of global demand for coated abrasives in 2008, or US$2.5 billion, a conservative estimate of global exposure to just wood dust is in the tens of millions of workers. Other industry applications for coated abrasives beyond abrasion of wood likely result in additional millions of

*Author to whom correspondence should be addressed.
Tel: 1-651-452-8610;
e-mail: drl@usfamily.net

workers exposed to various particle inhalation hazards (Henneberger et al., 2004; Driscoll et al., 2005).

Conventional abrasive sanding is performed using a variety of sanding devices, including random orbital, belt, planar, and disc sanders. The use of random orbital sanding is widespread throughout industry as the multidirectional abrasion pattern is generally applicable in many occupational settings (The Freedonia Group, 2010). Random orbital sanding involves a hand-held device that is typically powered either electrically or pneumatically. Pneumatically powered sanders can be designed to create a self-generated vacuum to capture dust and debris by sending the exhaust air from the pneumatic sanding motor through a venturi in the exhaust air stream to a collection device, such as a filter bag (Woo, 2010). Random orbital sanders use coated abrasive sanding pads of various grit sizes and composition depending on the application, process, and substrate. Figure 1 illustrates a conventional random orbital sander, and a self-generated vacuum random orbital sander with an attached particle filtration bag.

Conventional sanding results in the generation of high concentrations of particles that are composed of the abraded substrate emitted into the ambient air surrounding the random orbit sander. Of specific concern in occupational settings is the inhalation of these particles by the user of the conventional abrasive sander. The high concentrations can often exceed applicable occupational exposure limits of a specific country and have been the subject of other control evaluation studies (Hampl et al.,1992; Heitbrink et al., 1994; Thorpe and Brown, 1994, 1995; Topmiller et al., 1996; Teitsworth and Sheehan, 1998; Englund, 2000).

Health effects of particle exposure

Exposure to wood particles and specific health effects are based on many factors, including the type of wood, occupational setting, intensity, duration, and frequency of exposure. Some common human health effects from overexposure to wood particles include decreased lung function, occupational asthma (Goldsmith and Shy, 1988), and sinonasal cancers

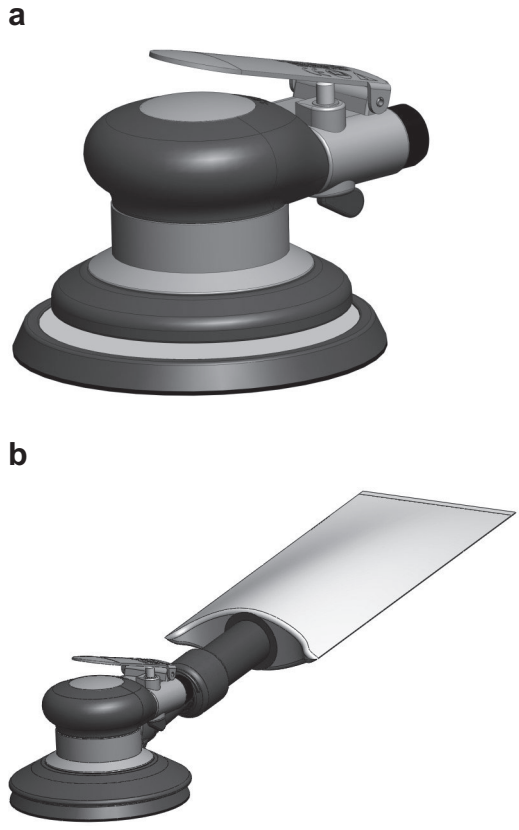

Fig. 1. (a) Random orbital sander and (b) random orbital sander with attached filtration bag.

(American Conference of Governmental Industrial Hygienists, 2010). Working with chromate paints and the resulting exposure to hexavalent chromium contained in particles during abrasion of the painted surface are documented to be a cause of lung cancer (Baruthio, 1992) and other diseases, including nasal septum ulcerations and chronic bronchitis (Carlton, 2003; American Conference of Governmental Industrial Hygienists, 2004). Exposure to titanium dioxide has historically been considered relatively harmless. Documented effects of animal correlation studies confirm that effects of pulmonary irritation are possible at elevated concentrations (American Conference of Governmental Industrial Hygienists, 2001). However, in 2010, the International Agency for Research on Cancer (IARC) released a monograph indicating that titanium dioxide is possibly carcinogenic to humans based on sufficient evidence in experimental animals and inadequate evidence from epidemiological studies (World Health Organization, 2010). In addition to the three particles of concern for this study, additional studies have documented negative health outcomes that are associated with exposure to other occupational abrasion-related particles of concern (Siemiatycki et al., 1989; Simcox et al., 1999; Akbar-Khanzadeh and Brillhart, 2002; Woskie et al., 2004; Young-Corbett and Nussbaum, 2009; Simmons et al., 2011).

Research objectives

Abrasion sanding creates particles that can cause a variety of negative health effects. The objective of this study was to compare particle emissions between a conventional sanding system and a self-generated vacuum sanding system. The experimental hypothesis was that the self-generated vacuum sanding system would generate lower particle emissions than a conventional sanding system on multiple substrates.

METHODS

The study was conducted on three different substrates that are a common concern in the industrial abrasive industry using both conventional sanding (3M Random Orbital Sander, Model 20317 with P180 Clean Sanding Disc 236U and Back Up Pad, 3M, Maplewood, MN, USA) and self-generated vacuum sanding (3M Random Orbital Sander, Model 20319 with P180 Clean Sanding Discs 236U, Back Up Pad and large Clean Sanding Filter Bag 20452, 3M, Maplewood, MN, USA) systems. Both pneumatic systems were operated with an air pressure of 620 kPa. The three substrates tested were solid oak wood, steel panels covered with chromate paint, and fiberglass panels covered with a gel coat containing titanium dioxide. The wood panels (Forest Products Supply, Maplewood, MN, USA) were 40.6 by 40.6 by 2.54 cm thick. The steel panels (ACT Test Panels LLC, Hillsdale, MI, USA) were 45.7 by 61.0 by 0.081 cm thick covered with 0.050–0.052 mm of chromate paint. The fiberglass panels (White Bear Boat Works, White Bear Lake, MN, USA) were 45.7 by 76.2 by 0.635 cm thick and covered with 0.20–0.25 mm of gel coat. Each substrate was weighed prior and subsequent to abrasion in a closed chamber with a Mettler-Toledo PR8002 balance with an uncertainty of ±0.01 g.

Testing apparatus

Because the abrading was conducted within an automated test chamber, physical and environmental conditions were strictly controlled. A similar testing apparatus was used by Thorpe and Brown (1994). The outside dimensions of the automated test chamber frame used for this study measured 213 wide by 137 deep by 137 cm high. The aluminum extruded framed structure was enclosed with clear acrylic sheeting. The front of the enclosed chamber was equipped with a door for access. Near the center of the enclosed chamber was a stationary sanding platform onto which the substrates were individually secured for each test. Above the sanding platform, the sanding system was mounted to a track system that moved in both lateral directions (parallel to the length and width of the substrate) in addition to vertically to adjust to the substrate. Pressure was applied to the sanding head to obtain results that mimic a sustained pressure a human might apply to the tooling. A force of 4.54 kp was applied to the wood and a force of 6.80 kp was applied to both the chromate painted steel and gel-coated fiberglass throughout the test trials via an automated system with feedback from the weight of the sanding head.

Sampling instruments and materials

Air sampling instrumentation was placed at three locations of varying distance and proximity to the sanding surface. Figure 2 illustrates the location of the samplers relative to the sanding platform within the chamber. Location 1 was 61 cm above and 61 cm left of the sanding head. Location 2 was 61 cm above and 61 cm right of the sanding head. Location 3 was level with the sanding platform, 30.5 cm behind and to the right from the sanding process.

Samples were collected using a Gesamtstaub-Probenahmesystem (GSP) sampler (DEHA Haan &

Wittmer GmbH, Friolzheim, Germany) with 37-mm diameter, 5-µm pore size polyvinyl chloride (PVC) (GLA 5000, SKC, Inc., Eighty Four, PA, USA) filter membranes. The GSP is a high-flow (10 l min^{-1}) inhalable sampler (Kenny et al., 1997, 1999; Aizenberg et al., 2000) constructed of cast metal with a conical aluminum inlet. The sampler has a single inlet, which faces outward toward the sampling area. Each of the GSP samplers was connected via polyethylene tubing to a GAST Model 1532-V106-G557X pump contained inside the test chamber. Flow was calibrated prior and subsequent to sampling at each location using a certified and calibrated DryCal DC-Lite MH (Bios International Corp., Butler, NJ, USA).

Sample times were calculated to provide sufficient sample collection to result in detection above the method reporting limits based on the estimated flow rate of the GSP sampler of 10 l min^{-1}. The following equation was used to determine the target sampling times in minutes: Sampling time = method reporting limit / (0.1 applicable occupational exposure limit × the estimated flow rate). The use of this equation was to estimate a sampling time that would yield a sample of measurable concentration to have meaningful data to analyze, without overloading the sampling media. The calculated sample time was also used to determine the amount of substrate needed for each test based on potential removal rates.

Samples were collected during substrate abrasion with the local exhaust ventilation system located at the back of the chamber disengaged. Local exhaust ventilation was then reconnected between each trial to facilitate adequate clearing of the test chamber.

Real-time monitoring with a TSI DustTrak DRX Aerosol Monitor (TSI Incorporated, 2011) was performed to confirm that steady-state particle conditions were achieved in the test chamber in a short period (<20 s) for each substrate test.

For each of the substrates, sample collection was completed for both of the sanding systems, abrading with the self-generated vacuum sanding first, followed by abrasion with conventional sanding on a new substrate panel. Twelve sets of sample data were collected for each substrate: six from the self-generated vacuum sanding and six from the conventional sanding.

Analysis

Each substrate panel was wiped clean to remove residual dust, and weighed prior and subsequent to abrasion. Filter bags used as part of the self-generated vacuum sanding system were also weighed prior and subsequent to abrasion. The removal rates were calculated based on the grams of material removed from the substrate and the length of time of abrasion. For the panels abraded using the self-generated vacuum sanding system, the mass collected in the filter bag was divided by the panel mass removed to determine the collection efficiency for the self-generated vacuum sanding system.

Samples for the wood substrate were analyzed for inhalable particles under modified National Institute for Occupational Safety and Health (NIOSH) 0500 methodology (Centers for Disease Control and Prevention, 1994). The NIOSH 0500 method is for total particles not otherwise regulated using a gravimetric technique for samples collected using 37-mm diameter, 5-µm pore size PVC filter membranes. Hexavalent chromium was analyzed under modified Occupational Safety and Health Administration (OSHA) 215 methodology (United States Department of Labor, 1998). OSHA 215 methodology uses 37-mm diameter, 5-µm pore size PVC filter membranes to collect hexavalent chromium particles. The hexavalent chromium is extracted using an aqueous solution of sodium carbonate, sodium bicarbonate, and magnesium sulfate. An aliquot of the extracted solution is then analyzed for hexavalent chromium by an ion chromatograph and UV-vis detector. Titanium dioxide was analyzed under modified NIOSH 7300 methodology (Centers for Disease Control and Prevention, 2003). The NIOSH 7300 method can use a 37-mm diameter, 5-µm pore size

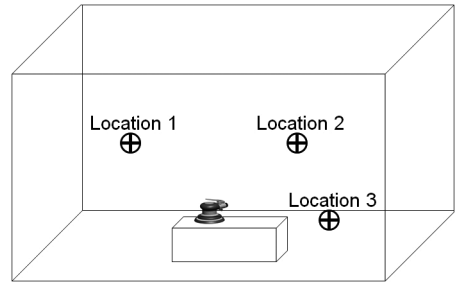

Fig. 2. Sampler locations.

PVC filter membranes to collect titanium dioxide particles for analysis with inductively coupled argon plasma atomic emission spectroscopy using an ashing acid digestion, which is a mix of nitric and perchloric acids. All of the methods were modified as the collection rates for the samples were targeted at 10 l/min, and the various methods require lower flow rates, between 1 and 4 l/min.

The data of the six sample sets from each sander for each substrate were used to calculate geometric means and geometric standard deviations. A comparison was then made between the two sander scenarios for each substrate to determine if there was a statistically significant difference in particle concentrations. A censored data analysis substitution method was used for samples reporting a concentration below the method reporting limit based on work by Hewett and Ganser (2007). Each result reported as less than the method reporting limit was substituted by dividing the method reporting limit by 2. Substitution using this method was completed for 14 wood and 7 gel coat samples from the self-generated vacuum system. No censored data analysis substitution was needed for the chromate paint data as all samples were reported above the method reporting limit.

The generation of descriptive statistics was performed using the Microsoft® Excel freeware add-on Industrial Hygiene Statistics (IHSTAT) (American Industrial Hygiene Association, 2011). Geometric mean concentration ratios were calculated using the generated descriptive statistics. To prepare the data for *t*-test analysis, the data were transformed using the log function to stabilize the variance of the dependent variable because the homoscedasticity assumption was violated. Finally, a *t*-test analysis was performed using a Microsoft Excel spreadsheet data analysis *t*-test: Two-Sample Assuming Equal Variances.

RESULTS

Removal rates and collection efficiency

Removal rates for the wood ranged from 1.60 g min^{-1} to 1.88 g min^{-1} using the self-generated vacuum sanding and from 2.35 g min^{-1} to 2.47 g min^{-1} for the conventional sanding. The chromate paint removal rates for the self-generated vacuum sanding ranged from 5.04 g min^{-1} to 6.20 g min^{-1}, whereas the conventional sanding ranged from 6.81 g min^{-1} to 7.80 g min^{-1}. Finally, the gel coat removal rates for the self-generated vacuum sanding ranged from 3.78 g min^{-1} to 4.36 g min^{-1}, whereas the conventional sanding ranged from 3.33 g min^{-1} to 3.80 g min^{-1}. The uncertainty of removal rate measurements was ±0.01 g min^{-1}. The variation in removal rate between the two systems is attributed to differences in the sanding time duration. For the oak wood, the self-generated system test period was 21 times longer than the conventional system, with chromate paint ~3 times longer, and the gel coat ~5 times longer. The removal rates for the conventional system represent an average over the peak cutting period at the beginning of the sanding disc application due to the shorter sampling time, whereas the removal rates for the self-generated vacuum system are averages over extended period of abrasion where the effectiveness of the abrasion media decreases over the time it is used.

Collection efficiencies for each substrate abraded with the self-generated vacuum sanding were calculated to be 91–93% for the wood, 96–98% for the chromate paint, and 97–98% for the titanium dioxide containing gel coat.

Sample substrate

Sample results for the oak wood, hexavalent chromium, and titanium dioxide were summarized and graphed based on the sampling locations and comparing the conventional sanding to self-generated vacuum sanding. Tables 1–3 summarize the data and Figs 3–5 present the oak wood, hexavalent chromium, and titanium dioxide results at GSP sampling locations 1, 2, and 3. The oak wood geometric mean concentration ratios for conventional sanding versus self-generated vacuum sanding ranged from 1130 to 1920, with hexavalent chromium ranging from 320 to 680, and titanium dioxide from 3990 to 4640. All sample *t*-test *P*-values were <0.0001.

Table 1. Oak wood results summary comparing conventional sanding and self-generated vacuum sanding systems.

GSP sampler location	CS concentration [geometric mean, mg m^{-3} (GSD)]	SGVS concentration [geometric mean, mg m^{-3} (GSD)]	*t*-Test *P*-value
1	143 (1.11)	0.074 (1.77)	$P < 0.0001$
2	84.1 (1.43)	0.075 (1.79)	$P < 0.0001$
3	121 (1.08)	0.104 (2.54)	$P < 0.0001$

$n = 6$ at each location for each system. CS, conventional sanding system; GSD, geometric standard deviation; SGVS, self-generating vacuum sanding system.

Table 2. Hexavalent chromium results summary comparing conventional sanding and self-generated vacuum sanding systems.

GSP sampler location	CS concentration [geometric mean, mg m^{-3} (GSD)]	SGVS concentration [geometric mean, mg m^{-3} (GSD)]	*t*-Test *P*-value
1	1.48 (1.35)	0.002 (1.55)	$P < 0.0001$
2	1.60 (2.52)	0.003 (1.59)	$P < 0.0001$
3	1.70 (1.25)	0.005 (5.17)	$P < 0.0001$

$n = 6$ at each location for each system except for CS GSP sampler locations 2 and 3. $n = 5$ for CS GSP sampler locations 2 and 3. CS, conventional sanding system; GSD, geometric standard deviation; SGVS, self-generating vacuum sanding system.

Table 3. Titanium dioxide results summary comparing conventional sanding and self-generated vacuum sanding systems.

GSP sampler location	CS concentration[geometric mean, mg m^{-3} (GSD)]	SGVS concentration [geometric mean, mg m^{-3} (GSD)]	*t*-Test *P*-value
1	17.6 (1.28)	0.004 (2.44)	$P < 0.0001$
2	25.7 (1.17)	0.006 (2.02)	$P < 0.0001$
3	22.5 (1.25)	0.005 (3.36)	$P < 0.0001$

$n = 6$ at each location for each system. CS, conventional sanding system; GSD, geometric standard deviation; SGVS, self-generating vacuum sanding system.

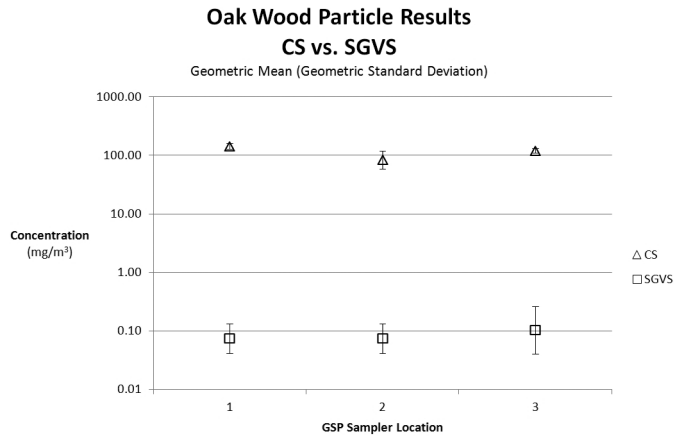

Fig. 3. Oak wood particle concentrations for conventional sanding and self-generated vacuum sanding systems.

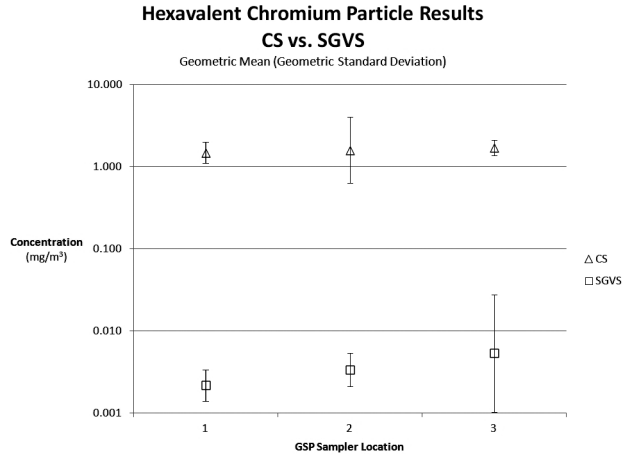

Fig. 4. Hexavalent chromium particle concentrations for conventional sanding and self-generated vacuum sanding systems.

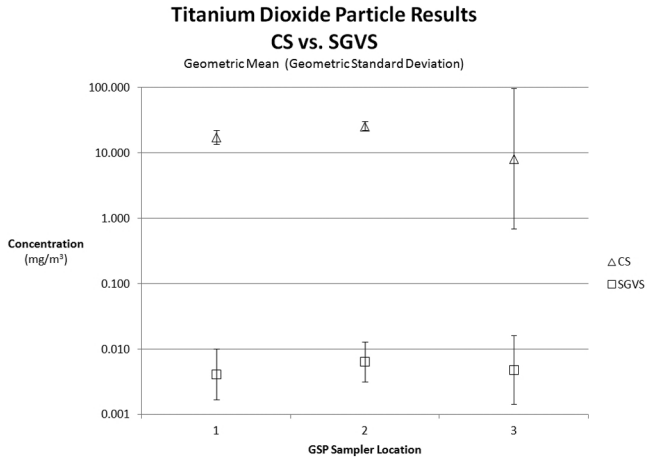

Fig. 5. Titanium dioxide particle concentrations for conventional sanding and self-generated vacuum sanding systems.

DISCUSSION

As observed in this study, conventional abrasive sanding generates high particle concentrations that can create significant exposure risks. Implementing an engineering control designed to reduce the generation of dust is a way of reducing the exposure risks to an airborne hazard (DiNardi, 2003).

These collection efficiencies ranging from 91 to 98% for the three substrates were consistent with previous observations of several methods on medium density fiberboard and gypsum sanding, ranging from 97.05 to 99.99%, and aircraft epoxy primer and polyurethane enamel, ranging from 93 to 98% (Carlton et al., 2003; Rautio et al., 2007).

The comparison of geometric means in Tables 1–3, the small *t*-test *P*-values, and high geometric mean concentration ratios, as summarized in Table 4, confirm that there is a statistically significant difference in particle concentrations generated between the self-generated vacuum sanding and conventional sanding configurations for the three substrates tested. The data generated by this study were consistent with previous research that tested non-ventilated systems, which lack a particle removal mechanism, and ventilated systems, which use a particle removal mechanism, for automobile repair dusts (Heitbrink et al., 1994), medium density fiberboard and gypsum (Rautio et al., 2007), chromate primer and polyurethane enamel (Carlton et al., 2003), and wood dust (Thorpe and Brown, 1994). Non-ventilated systems in this and other studies have been used in comparison with ventilated systems because they are the most commonly used and generally assumed to provide the least protection to workers.

The automobile repair dust study collected four ventilated sander and five non-ventilated sander samples for total dust in a glove box. The geometric mean concentration ratio on the limited data set was 42 (Heitbrink et al., 1994). The medium density fiberboard and gypsum study was sampled with an optical particle monitor only in a laboratory and had a mean concentration ratio of 2580 for the medium density fiber board 6560 for the gypsum (Rautio

Table 4. Geometric mean concentration ratios and *t*-test *P*-values summary.

	Oak wood	Hexavalent chromium	Titanium dioxide
Geometric mean concentration ratios			
CS 1/SGVS1	1920	680	4240
CS 2/SGVS 2	1130	475	3990
CS 3/SGVS 3	1170	320	4640
t-Test *P*-values			
CS 1, SGVS1	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
CS 2, SGVS 2	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
CS 3, SGVS 3	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$

CS, conventional sanding system; SGVS, self-generating vacuum sanding system.

et al., 2007). The chromate primer and polyurethane enamel study collected 12 ventilated and 12 non-ventilated samples in a glove box. The mean concentration ratios ranged from 15 to 61 depending on the varying brand of sander and abrasive grits used throughout the experiment (Carlton et al., 2003). The wood dust study collected 39 ventilated sample and 15 non-ventilated samples with a different sanding configuration, abrasion grit, and wood surface each time. No mean data were presented in the study, but several concentration ratios were calculated to range from 8 to 130 (Thorpe and Brown, 1993). The cited research showed to varying degrees, elevated concentrations of particles associated with the non-ventilated systems, similar to the conventional system used in this study, and lower concentrations associated with ventilated systems.

Based on the analytical results, it is clear that use of a conventional sanding system without respiratory protection increases exposure potential to inhaled particles that could have a negative health effect on workers depending on the type of particle, occupational setting, intensity, duration, and frequency of exposure. It is also evident that the use of an engineering control, such as the self-generated vacuum sanding system, provides a significant reduction in worker exposure concentrations by removal of particles from the air. If respiratory protection is still required after implementation of the self-generated vacuum sanding system or a similar control measure, a less expensive respirator with a lower assigned protection factor would likely be suitable more often. Additional benefits of using the self-generated vacuum sanding system include reduction of sanding waste generation and reduction of workers' hours in sanding operations setup, cleanup, and support. The collection bags increase worker efficiency in sanding operations, further reducing worker exposure time and overall intensity of particulate exposure.

The strength of this experiment was the design to control as many of the exposure variables as possible in order to isolate and test the variable of interest. Specifically, the goal was to complete a comparative study of the particle emissions of the two different systems. A result is that there are several limitations to the study's conclusions. The abrasion conducted for this study was completed on a flat and even surface, creating a maximum venturi effect. Field applications of the engineering control likely have a much larger range of surface angles and roughness that will reduce the self-generated vacuum sanding system's effectiveness. This study was conducted in a relatively small, fully enclosed chamber with no ventilation to quickly achieve steady-state conditions. Field use of the systems would likely occur in larger enclosed spaces with general ventilation or in outdoor applications. The effects of either of these assumptions would likely result in a decrease in surrounding particle concentrations. Other factors, such as individual user practices, wind speed, humidity levels, and specific composition of the substrate, may limit the effectiveness of the self-generated vacuum sanding system. Field studies could be performed to better determine the significance of each exposure determinant for a given exposure scenario. It is also important to note that bag filtration and any High-Efficiency Particulate Air (HEPA) rating of a system is based on specific flow ranges and system design, and not just an attribute of a filtration bag. A filtration bag not designed for the system in which it is used may not function as intended or provide the level of filtration desired in the use of the engineering control.

CONCLUSIONS

The geometric mean concentration ratios suggest that workers using a conventional sanding system could utilize the self-generated vacuum sanding system technology to significantly reduce exposure to particles and mitigate negative health effects. The ratios represent a concentration reduction of two to four orders of magnitude. Considering a potential reduction in the engineering control effectiveness due to the limiting factors discussed previously, the engineering control use would still provide a significant reduction in particle concentration over conventional sanding. Field study is needed to confirm these laboratory results and provide information on the effectiveness of self-generated vacuum sanding systems under actual use and in a variety of occupational conditions, with additional focus for better understanding particle size distributions. Field study opportunities could include having current users of conventional sanding systems with particle exposure data evaluate self-generated vacuum sanding systems, or current users of self-generated vacuum sanding systems with particle exposure data whose results would be compared with data generated under a controlled setting such as used in this study.

REFERENCES

American Conference of Governmental Industrial Hygienists. (2001) Threshold limit values for chemical substances and physical agents, titanium dioxide. Cincinnati, Ohio, 45240, USA.

American Conference of Governmental Industrial Hygienists. (2004) Threshold limit values for chemical substances and physical agents, chromium (VI), water-soluble fume. Cincinnati, Ohio, 45240, USA.

American Conference of Governmental Industrial Hygienists. (2010) Threshold limit values for chemcial substances and physical agents, wood dusts. Cincinnati, Ohio, 45240, USA.

American Industrial Hygiene Association.(2011) Multilingual IHSTAT+, 24 November 2011. Available at http://www.aiha.org/insideaiha/volunteergroups/EASC/Documents/EASC-IHSTAT-V225.xls.

Aizenberg V, Grinshpun SA, Willeke K *et al.* (2000) Performance characteristics of the button personal inhalable aerosol sampler. AIHAJ; 61: 398–404.

Akbar-Khanzadeh F, Brillhart RL. (2002) Respirable crystalline silica dust exposure during concrete finishing (grinding) using hand-held grinders in the construction industry. Ann Occup Hyg; 46: 341–6.

Baruthio F. (1992) Toxic effects of chromium and its compounds. Biol Trace Elem Res; 32: 145–53.

Carlton GN. (2003) Hexavalent chromium exposures during full-aircraft corrosion control. AIHA J (Fairfax, Va); 64: 668–72.

Carlton GN, Patel KB, Johnson DL *et al.* (2003) The effectiveness of handheld ventilated sanders in reducing inhalable dust concentrations. Appl Occup Environ Hyg; 18: 51–6.

Centers for Disease Control and Prevention. (1994) NIOSH manual of analytical methods, 500 particulates otherwise not regulated, total. Editor: The National Institute for Occupational Safety and Health.

Centers for Disease Control and Prevention. (2003) NIOSH manual of analytical methods, 7300 elements by ICP. Editor: The National Institute for Occupational Safety and Health.

DiNardi SR. (2003) The occupational environment: its evaluation, control and management. Virginia: Fairfax.

Driscoll T, Imel Nelson D, Steenland K *et al.* (2005) The global burden of non-malignant respiratory disease due to occupational airborne exposures. Am J Ind Med; 48: 432–45.

Englund, EC. (2000) The impact of ventilation systems on worker exposures during advanced composite material and fiberglass repair operations on military aircraft. Appl Occup Environ Hyg; 15: 391–6.

Goldsmith DF, Shy CM. (1988) Respiratory health effects from occupational exposure to wood dusts. Scand J Work Environ Health; 14: 1–15.

Hampl V, Topmiller JL, Watkins DS *et al.* (1992) Control of wood dust from rotational hand-held sanders. Appl Occup Environmental Hyg; 7: 263–70.

Heitbrink WA, Cooper TC, Edmonds MA. (1994) Evaluation of ventilated sanders in the autobody repair industry. AIHAJ; 55: 756–9.

Henneberger PK, Goe SK, Miller WE *et al.* (2004) Industries in the United States with airborne beryllium exposure and estimates of the number of current workers potentially exposed. J Occup Environ Hyg; 1: 648–59.

Hewett P, Ganser GH. (2007) A comparison of several methods for analyzing censored data. Ann Occup Hyg; 51: 611–32.

Kauppinen T, Vincent R, Liukkonen T *et al.* (2006) Occupational exposure to inhalable wood dust in the member states of the European Union. Ann Occup Hyg; 50: 549–61.

Kenny LC, Aitken R, Chalmers C *et al.* (1997) A collaborative European study of personal inhalable aerosol sampler performance. Ann Occup Hyg; 41: 135–53.

Kenny LC, Aitken RJ, Baldwin PEJ. (1999) The sampling efficiency of personal inhalable aerosol samplers in low air movement environments. J Aerosol Sci; 30: 627–38.

Rautio S, Welling I, Hynynen P *et al.* (2007) Comparison of airborne dust emission in sanding with various abrasive materials. Gefahrstoffe-Reinhaltung der Luft; 67: 33–6.

Siemiatycki J, Dewar R, Lakhani R *et al.* (1989) Cancer risks associated with 10 inorganic dusts: results from a case-control study in Montreal. Am J Ind Med; 16: 547–67.

Simcox NJ, Lofgren D, Leons J *et al.* (1999) Silica exposure during granite countertop fabrication. Appl Occup Environ Hyg; 14: 577–82.

Simmons CE, Jones RM, Boelter FW. (2011) Factors influencing dust exposure: finishing activities in drywall construction. J Occup Environ Hyg; 8: 324–36.

Teitsworth JE, Sheehan SM. (1998) The effectiveness of local exhaust-ventilated (shrouded) hand power tools used for grinding/sanding composite materials. AIHAJ; 59: 689–93.

The Freedonia Group. (2010) Freedonia focus on world abrasives. The Freedonia Group, Inc. Clevland Ohio 44143, USA.

Thorpe A, Brown RC. (1994) Measurements of the effectiveness of dust extraction systems of hand sanders used on wood. Ann Occup Hyg; 38: 279–302.

Thorpe A, Brown RC. (1995) An improved design for the dust extraction system of orbital sanders used on wood. Ann Occup Hyg; 39: 155–65.

Topmiller JL, Watkins DS, Shulman SA *et al.* (1996) Controlling wood dust from orbital hand sanders. Appl Occup Environ Hyg; 11: 1131–8.

TSI Incorporated. (2011) Dusttrak DRX Aerosol Monitor 8533. 27 October 2011. Available at: http://www.tsi.com/en-1033/products/14000/dusttrak%E2%84%A2_aerosol_monitors/14004/8533.aspx.

United States Department of Labor. (1998) Hexavalent chromium in workplace atmospheres. Editor: Occupational Safety & Health Administration, Method Number ID-215.

World Health Organization. (2010) International agency for research on cancer monographs on the evaluation of carcinogenic risks to humans. Volume 93, carbon black, titanium dioxide and talc. 93: 193-275 Lyon, France. 19 September 2012. Available at: http://monographs.iarc.fr/ENG/Monographs/vol93/mono93.pdf

Woo EJ. (2010) U. S. Patent No. 2010/0285728 A1 (11 November 2010).

Woskie SR, Sparer J, Gore RJ. *et al.* (2004) Determinants of isocyanate exposures in auto body repair and refinishing shops. Ann Occup Hyg; 48: 393–403.

Young-Corbett, DE, Nussbaum MA. (2009) Dust control effectiveness of drywall sanding tools. J Occup Environ Hyg; 6: 385–9.