



Comprehensive Report

Evaluation of the dust generation and engineering control for cutting fiber-cement siding

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Abstract

Workplace exposure to respirable crystalline silica can cause silicosis, a progressive lung disease marked by scarring and thickening of the lung tissue. Quartz is the most common form of crystalline silica. Crystalline silica is found in several construction materials, such as brick, block, mortar and concrete. Construction tasks that cut, break, grind, abrade, or drill those materials have been associated with overexposure to dust containing respirable crystalline silica. Fiber-cement products can contain as much as 50% crystalline silica and cutting this material has been shown to cause excessive exposures to respirable crystalline silica. NIOSH scientists conducted this study to develop engineering control recommendations for respirable crystalline silica from cutting fiber-cement siding.

Detailed characterization of the dust generated from cutting fiber-cement siding was conducted in a laboratory setting. Respirable dust was sampled and analyzed using a variety of instruments based on both a real-time direct reading technique and gravimetric methods. The dust size distribution and the silica distribution in the dust of different sizes were analyzed in detail for cutting fiber-cement siding from four major manufacturers. The generation rate of respirable dust was analyzed and compared for cutting fiber-cement siding using different power tools (a power shear, four miter saws, and three circular saws), different blades, differing the saw cutting feed rate, and cutting different numbers of boards in the stack. It was found that two circular saws with a 4-tooth polycrystalline diamond-tipped (PCD) blade of 18.4 centimeter (cm, 7.25 inch) diameter generated the least amount of dust under the same test conditions. A local exhaust ventilation (LEV) system was also tested for all the power saws used in the laboratory evaluation. The generation rate of respirable dust and dust removal efficiency were recorded for each power saw when used with the LEV operating at different volumetric flow rates. In most test conditions of the miter saws, the dust removal efficiency was about 65% or lower, even at the highest test flow rate of the LEV (3.97 cubic meter per minute, m³/min; or 140 cubic feet per minute, CFM). The three circular saws evaluated in this study featured a built-in dust collection container or shroud, which served as a hood and partially enclosed the saw blade for collecting dust while cutting. The dust removal efficiency for the circular saws was greater than 78% even at a low flow rate of 0.83 m³/min (29 CFM). The results from the laboratory evaluation suggested that connecting a dust-collecting circular saw to a basic shop vacuum with built-in air filters had the potential to provide a simple and low-cost engineering control measure for the dust generated from cutting fiber-cement siding.

Four field surveys were conducted to validate the effectiveness of the engineering control measure suggested from the laboratory evaluation. The survey results showed that the 10-hour time weighted average (TWA) exposure to respirable crystalline silica for the workers who mainly cut fiber-cement siding on the job sites was well under control, with the 95% upper confidence limit being only 24% of the NIOSH Recommended Exposure Limit (REL) of 0.05 milligrams per cubic meter (mg/m³). This engineering control measure effectively reduced occupational silica

exposures, and provided an effective, simple and low cost solution for workers cutting fiber-cement siding.

Introduction

Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Applied Research and Technology has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control. Since 1976, EPHB has conducted a number of assessments of health hazard control technologies on the basis of industry, common industrial process, or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for or availability of an effective system of hazard control measures.

These studies involve a number of steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concept techniques. Next, in-depth surveys are conducted to determine both the control parameters and the effectiveness of these controls. The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

Background for this Study

Crystalline silica refers to a group of minerals composed of silicon and oxygen; a crystalline structure is one in which the atoms are arranged in a repeating three-dimensional pattern [Bureau of Mines 1992]. The three major forms of crystalline silica are quartz, cristobalite, and tridymite; quartz is the most common form [Bureau of Mines 1992]. Respirable crystalline silica refers to that portion of airborne crystalline silica dust that is capable of entering the gas-exchange regions of the lungs if inhaled; this includes particles with aerodynamic diameters less than approximately 10 micrometers (μm) [NIOSH 2002]. Silicosis, a fibrotic disease of the lungs, is an occupational respiratory disease caused by the inhalation and

deposition of respirable crystalline silica dust [NIOSH 1986]. Silicosis is irreversible, often progressive (even after exposure has ceased), and potentially fatal. Because no effective treatment exists for silicosis, prevention through exposure control is essential.

Crystalline silica is a constituent of several materials commonly used in construction, including brick, block, and concrete. Many construction tasks have been associated with overexposure to dust containing crystalline silica [Chisholm 1999, Flanagan et al. 2003, Rappaport et al. 2003, Woskie et al. 2002]. Among these tasks are tuckpointing, concrete cutting, concrete grinding, abrasive blasting, and road milling [Nash and Williams 2000, Thorpe et al. 1999, Akbar-Khanzadeh and Brillhart 2002, Glindmeyer and Hammad 1988, Linch 2002, Rappaport et al. 2003]. Fiber-cement products can contain as much as 50% crystalline silica. Cutting this material has been shown to cause excessive exposures to respirable crystalline silica [Lofgren et al. 2004, Qi et al. 2013a].

The use of fiber-cement siding in construction and renovation is undergoing rapid growth. From 1991 to 2010, the market share of fiber-cement siding has climbed from 1% to 13% [US Census Bureau 2013]. In contrast, the market share of wood siding in residential construction has decreased from 38% to 8% [US Census Bureau 2013]. The durability and appearance of fiber-cement siding, which simulates wood without the maintenance issues associated with wood siding, is appealing and reportedly provides a competitive advantage over other building materials [Bousquin 2009]. The use of fiber-cement siding is expected to continue to increase. The number of workers exposed to dust containing crystalline silica as a result can also be expected to increase as the use of fiber-cement siding displaces other siding products. Cellulose fiber, sand or fly ash, cement, and water are the principal ingredients used in the manufacture of fiber-cement products. James Hardie (Mission Viejo, California), CertainTeed (Valley Forge, PA), Maxitile (Houston, TX), GAF (Wayne, NJ), and Nichiha (Norcross, GA) are the major manufacturers of fiber-cement products.

Fiber-cement board is cut using three methods: scoring and snapping the board, cutting the board using shears, and cutting the board using a power saw. When scoring and snapping the board, a knife is used to score the board by scribing a deep line into the board. The board is bent, and it breaks along the scored line. This method should be relatively dust-free. The score and snap method can be used when installing fiber-cement board used for tile underlayment, but is not applicable to siding. Commercially available tools used to shear fiber-cement siding include foot-powered shears and hand-held shears that may be manual or use a power source. These shears are reported to provide a relatively dust-free method of cutting fiber-cement siding. However, slow production rates and low precision limit the use of shears by siding contractors [Bousquin 2009].

Power saws, such as circular saws and compound miter saws, are used to cut fiber-cement siding. These saws are normally used with 4-8 tooth polycrystalline diamond-tipped (PCD) blades specifically designed to cut fiber-cement siding and

minimize dust generation. Several commercially available saws are manufactured with hoods and exhaust take-offs that can be connected to vacuum cleaners or to dust-collection bags. These hoods partially enclose the saw blade. Available blade diameters are 5, 7.25, 10, and 12 inches.

The study by Lofgren et al. [2004] reported that fiber-cement board cutters' uncontrolled exposures to respirable crystalline silica ranged from 0.02 milligrams per cubic meter (mg/m^3) to $0.27 \text{ mg}/\text{m}^3$ during sampling, and 8-hour (hr) time weighted average (TWA) exposure ranged from $0.01 \text{ mg}/\text{m}^3$ to $0.17 \text{ mg}/\text{m}^3$ depending on the length of exposure on the day sampled. The highest result was 3.4 times the NIOSH Recommended Exposure Limit (REL) for respirable crystalline silica of $0.05 \text{ mg}/\text{m}^3$.

In an in-depth field survey, Qi et al. [2013a] reported that a cutter's uncontrolled exposures to respirable crystalline silica ranged from 0.06 to $0.13 \text{ mg}/\text{m}^3$ during sampling, and 8-hr TWA exposure ranged from $0.02 \text{ mg}/\text{m}^3$ to $0.13 \text{ mg}/\text{m}^3$ depending on the time of exposure on the day sampled. The highest result was 2.6 times the NIOSH REL for respirable crystalline silica of $0.05 \text{ mg}/\text{m}^3$.

The data from both field surveys suggested excessive exposures to respirable crystalline silica occurred when an engineering control was not used for cutting fiber-cement siding. In August 2013, OSHA proposed a new Permissible Exposure Limit (PEL) of $0.05 \text{ mg}/\text{m}^3$ for 8-hr TWA exposures to respirable crystalline silica [OSHA 2013]. Thus, the objective of this study was to provide practical recommendations for effective dust controls that will prevent overexposures to respirable crystalline silica while cutting fiber-cement siding. The specific aims of the project were: 1) determine the dust generation rate from cutting fiber-cement siding in the lab; 2) experimentally develop local exhaust ventilation (LEV) recommendations for power saws used to cut fiber-cement siding; 3) validate, at actual construction sites, the recommendations developed from the laboratory studies; and 4) disseminate the information in the form of technical reports, journal articles, a NIOSH Workplace Solutions Document, trade journal articles, home remodeling publications, and other media. The dissemination efforts are directed at the construction and remodeling industries, including the do-it-yourself market, to promote the use of the recommendations. This comprehensive report includes the results from both the laboratory study and field surveys.

Materials and Methods in the Laboratory Evaluation

Laboratory Testing System

A worker's exposure to respirable crystalline silica during construction work can vary due to weather conditions, construction materials involved, work location, type of work performed, task duration and frequency, work practices, personal protective equipment (PPE), and whether or not dust control measures were used. Laboratory evaluation of dust generation and dust controls is an approach to control testing that permits those sources of variation to be controlled. Figure 1 illustrates

a diagram of the laboratory testing system used in this study. The overall dimension and components of the system were similar to those used by Beamer et al. [2005], Heitbrink and Bennett [2006], and Carlo et al. [2010], and they were consistent with European Standard EN 1093-3 [CEN, 2006]. A dust collection air handling unit (PSKB-1440, ProVent LLC, Harbor Springs, MI) was used as an air mover for the system. The air handling unit was connected to an automatic tool testing chamber through a 0.3 meter (m) diameter duct about 6.4 m long. A funnel section connected the duct to the automatic tool testing chamber, which had a square cross section of 1.2 m wide and 1.2 m high. A blast gate upstream of the air handling unit was used to adjust the air flow rate passing through the testing system by allowing the excessive air to enter the air handling unit through the gate. Once turned on, the air handling unit was set to draw room air into the testing system at a flow rate of 0.64 m³/second (m³/sec, equivalent to 1350 cubic feet per minute, CFM). This flow rate was set by manually adjusting the blast gate valve and was monitored by a micromanometer (PVM100 Airflow Developments Ltd., UK) connected to a delta tube (306AM-11-AO, Midwest Instrument, Sterling, MI). The delta tube functioned as an averaging pitot tube and has four pressure-averaging ports on the front and backside of a tear-shaped or circular cylinder [Miller 1989]. The delta tube was mounted on the duct about 2.4 m downstream (8 times of the duct diameter) of the funnel section (not shown in Figure 1 for clarity). The accuracy of the flow rate measured by the Delta tube was verified by comparing the flow rate obtained from its manufacturer's calibration equation [Mid-West Instrument, 2004] and that measured by Heitbrink and Bennett [2006] using a 10-point pitot tube traverse of the duct performed in the horizontal and vertical planes (about 0.8% difference). Two aerosol sampling ports were open on the duct for mounting the sampling probes of all the sampling instruments used in this study. These two ports and the delta tube formed the sampling section of the system. The location of this sampling section on the duct was designed to meet the requirement of European Standard EN 1093-3 [CEN, 2006] for taking representative samples.

The air flow that entered the system first passed through a filter panel, which had the same cross section as the automatic tool testing chamber and was 0.7 m long. The filter panel included one bank of four pre-filters and another bank of four HEPA filters that removed all the particles in the room air so that they did not interfere with the analysis of the dust generated inside the testing system. The filters also helped ensure that the air that entered the system had a uniform velocity profile across the panel's cross section. After the filtration section was the automatic tool testing chamber, which was 4.7 m long and was specifically designed and constructed for this study. Under the operating air flow rate, the flow velocity in the chamber was 0.44 m/sec, which is sufficient to transport respirable dust to the sampling section of the system, according to European Standard EN 1093-3 [CEN, 2006]. The Reynolds numbers for the chamber and duct are 34,000 and 170,000, respectively, indicating turbulent flow, which helped maximize mixing to obtain an appropriately representative sample at the sampling section. The air handling unit collected all the dust generated in the testing system with two filter cartridges

(P25.20, ProVent LLC, Harbor Springs, MI) before the cleaned air was discharged back into the room.

The walls of the automatic tool testing chamber were transparent so the operation inside could be visually observed. The chamber featured automatic control using Programmable Logic Controller (PLC) and Human Machine Interface (HMI). All the power tools evaluated in this study for cutting fiber-cement siding were mounted in the chamber using a variety of fixtures. The operations of these power tools were controlled using a two-dimensional actuator through the PLC. One to six fiber-cement siding boards were mounted on a chain-driven feed plate, and the feed rate was automatically controlled through the PLC. Board feed rate and power tool operation were programmed through the HMI so that automatic and repeatable cuts were achieved.

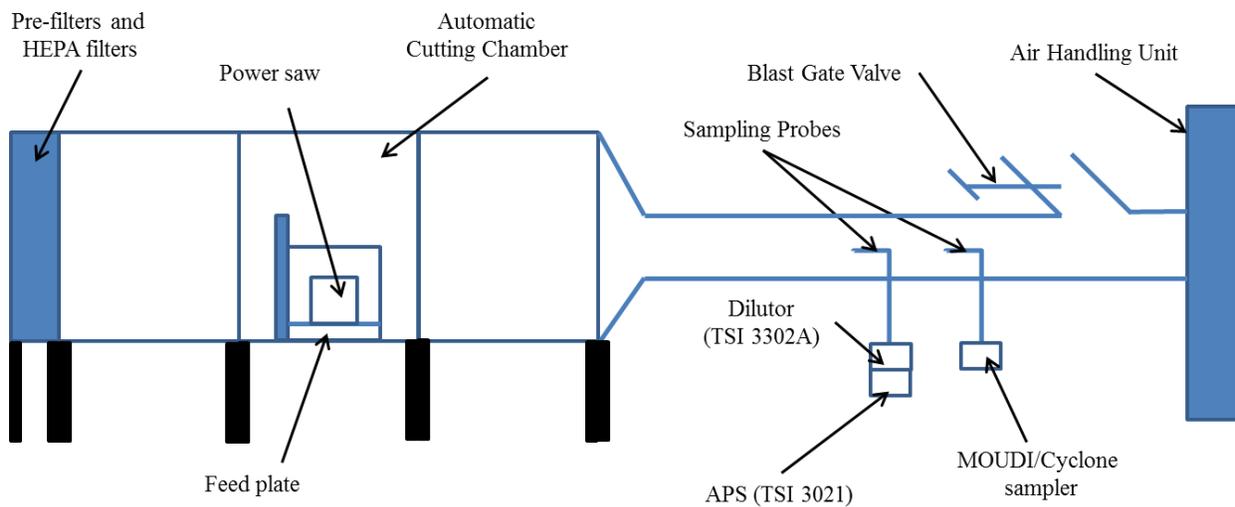


Figure 1. Diagram of the Laboratory Testing System.

Fiber-cement siding

Fiber-cement siding from four different manufacturers was evaluated in this study. Detailed specifications of these products are listed in Table 1. Since they may contain a different amount of silica in their respective formulations, which may also vary from time to time by the manufacturers, the manufacturing dates stamped on the siding boards, were recorded if available. The bulk density of the siding board was obtained by measuring the volume and mass of at least three boards from each manufacturer.

Table 1. Fiber-cement siding evaluated in the study.

Manufacturer	Manufacturing Date	Measured Board Width, W (cm, inch)	Measured Board thickness (cm, inch)	Measured Board Density (g/cm ³)
CertainTeed	05/27/2012	21.0, 8.25	0.76, 0.30	1.31±0.03
James	08/21/2010	21.0, 8.25	0.76, 0.30	1.27±0.01

Manufacturer	Manufacturing Date	Measured Board Width, W (cm, inch)	Measured Board thickness (cm, inch)	Measured Board Density (g/cm ³)
Hardie				
Maxitile	09/30/2010	21.0, 8.25	0.79, 0.31	1.31±0.02
Nichiha	n/a	21.0, 8.25	0.79, 0.31	1.25±0.01

Note: cm – centimeter; g – gram; n/a – “not available”.

Power tools

A variety of power tools for cutting fiber-cement siding were evaluated in this study and their specifications are listed in Table 2. These tools were categorized into three groups: compound miter saw, circular saw and power shear. All four compound miter saws listed in Table 2 used a 12 inch (30.5 cm) diameter blade. Each of these saws had an exhaust port designed to be attached to an external dust collector or shop vacuum, which provided LEV for removing dust while cutting. The dimension and shape of the exhaust port, its location on the miter saw, as well as the overall dimension of the miter saw may all affect the effectiveness of the dust removal efficiency. The three circular saws listed in Table 2 included a dust collecting feature with a built-in dust collection container or shroud, which served as a hood and partially enclosed the saw blade. When fiber-cement siding was cut, the flow induced by the spinning blade caused a large portion of the dust generated to be collected within the container or shroud and also directed the dust to an exhaust port, which could be connected to an external dust collector or shop vacuum. The Ridgid circular saw (Model R3400, Ridge Tool Company, Elyria, OH) had a small built-in blower that pushed air through its exhaust port. This feature may have reduced the requirement of the external LEV. The specified no-load rotating speed listed in Table 2 for each saw was taken from the manufacturer’s technical specification. The actual no-load speed for each saw was measured using a Pocket Tachometer (Model TAC2K, Dwyer Instruments Inc., Michigan City, IN) and is also listed in Table 2. An abbreviation was assigned to each power tool and is listed in Table 2 so that these tools can be more easily referred to in the subsequent text.

Table 2. Power tools used in the study and their specifications

Manufacturer	Model #	Type	Blade Diameter (cm, inch)	Specified No Load Rotating Sped (RPM)	Measured No Load Rotating Sped (RPM)	Abbreviation
Bosch	GCM12SD	Compound Miter	30.5, 12.0	3800	3714	M-B
Dewalt	DW718	Compound Miter	30.5, 12.0	3600	3922	M-D
Makita	LS1216L	Compound Miter	30.5, 12.0	3200	3224	M-M
Hitachi	C12LSH	Compound Miter	30.5, 12.0	3800	4200	M-H
Hitachi	C7YAH	Circular	18.4, 7.25	5500	5663	C-H

Manufacturer	Model #	Type	Blade Diameter (cm, inch)	Specified No Load Rotating Sped (RPM)	Measured No Load Rotating Sped (RPM)	Abbreviation
Makita	5057KB	Circular	18.4, 7.25	5800	5500	C-M
Ridgid	R3400	Circular	12.7, 5.0	9250	9068	C-R
PacTool International	404	Power Shear	DNA	DNA	DNA	SH

Note: RPM — Revolutions Per Minute; DNA — Does Not Apply

Sampling Methods

In this study, the automatic tool testing chamber was set to make a fixed number of repeat cuts of the fiber-cement siding board for each test condition. An Aerodynamic Particle Spectrometer (APS, model 3321, TSI Inc, Shoreview, MN) provided real-time direct reading measurement of the size distribution of the dust generated with a 1 second time resolution. The APS continuously collected an aerosol stream from one of two available duct sampling ports at a 5 Liter per minute (L/min) flow rate. The APS used a time-of-flight technique to measure the aerodynamic diameter of the individually counted particle in the range from 0.5 to 20 micrometers (μm). The APS output connected to a computer and the Aerosol Instrument Manager[®] Software (AIM V8.1, TSI Inc., Shoreview, MN) collected and analyzed the APS data. In this study, an isokinetic sampling probe was designed for the APS with a matching flow velocity for the inlet of the sampling probe and the duct. The sampling probe bent 90 degree and vertically connected to an aerosol dilutor (model 3302A; TSI Inc, Shoreview, MN), which sat on top of the APS. The dilutor was configured to provide a 100 to 1 dilution so that measurement uncertainty caused by high concentration aerosols was minimized. The dust size distribution directly measured by the APS is based on number concentration, and it can be used to derive the mass concentration of respirable dust by the following equation:

$$C_m = \sum_{i=1}^{52} \frac{\rho_p f_i \pi d_{e,i}^3 N_i}{6 \eta_{di,i} \eta_{sp,i}} \quad (1)$$

where,

C_m is the mass concentration of respirable dusts

$d_{e,i}$ is the equivalent volume diameter of channel i in APS and can be calculated by

$$d_{e,i} = d_{a,i} \sqrt{\rho_0 X / \rho_p}$$

$d_{a,i}$ is the aerodynamic diameter of channel i in APS

ρ_0 is the unit density

ρ_p is the density of the dust

χ is the dynamic shape factor of the dust

f_i is the respirable fraction of the dust with $d_{a,i}$

N_i is the number concentration of dust with $d_{a,i}$

$\eta_{dil,i}$ is the the transportation efficiency of dust with $d_{a,i}$ through the diluter

$\eta_{sp,i}$ is the the transportation efficiency of dust with $d_{a,i}$ through the sampling probe

The APS directly measures the aerodynamic diameter of the sampled dusts and it classifies the entire size range into 52 channels with $d_{a,i}$ representing the aerodynamic diameter for each specific channel i ($i = 1-52$). In order to obtain the mass of a dust in each channel, its density (ρ_p) is needed and its equivalent volume diameter needs to be calculated with the knowledge of its density (ρ_p) and dynamic shape factor (χ). In this study, all the dusts generated from cutting fiber-cement siding were assumed to be spherical so their dynamic shape factor was 1. The dust density was also needed for the Stokes correction of the APS data because the APS was calibrated in factory using Polystyrene Latex (PSL) spheres with a density close to 1.05 g/cm^3 . Since the APS measures the aerodynamic diameter in a flow velocity of approximately 150 m/sec instead of a still air, the Reynolds numbers of the sampled dusts are outside the Stokes regime and a sizing inaccuracy is caused when the dust density is different from 1.05 g/cm^3 . The Stokes correction for the APS data can be done by the AIM software with an input of the dust density. However, it is not straightforward to obtain the actual dust density in this study as the bulk material of fiber-cement siding is a mixture of a few different ingredients, and the density might vary depending on the size of the dust. Thus, the measured board density listed in Table 1 was used as the dust density. With the assumed dynamic shape factor and density for the sampled dust, the mass concentration of respirable dusts derived from the APS data and Equation (1) could be different from the actual value. However, this difference should be consistent among all the APS data and should not affect the comparison of the generation rate of respirable dust derived from the APS data under different testing conditions.

In this study, the generation rate of respirable dust (G_{APS}) is defined by the following equation:

$$G_{APS} = \frac{\sum_{t=1}^{T_s} C_{m,t} Q}{n_b W} \quad (2)$$

where,

$C_{m,t}$ is the mass concentration of respirable dusts at time t

Q is the volume flow rate in the testing system, $0.64 \text{ m}^3/\text{sec}$

T_s is the total sampling time of the APS for one cut

n_b is the number of board per cut

W is the board width, listed in Table 1

Since all fiber-cement siding in this study were cut by making cross cuts across the board width, the product of n_b and W represents the total linear length for one cut. The total linear length cut is commonly used in practice to account for cutting productivity. The APS data contains one set of dust size distribution for every second during the test, which leads to a $C_{m,t}$ data point for each second using Equation (1). Thus, the summation of $C_{m,t}Q$ during the sampling time T_s results in the total mass of respirable dust generated for one cut. The generation rate of respirable dust defined in Equation (2) represents the mass of respirable dust generated per unit linear length cut.

In this study, the transportation efficiency of dust with $d_{a,i}$ through the diluter ($\eta_{dil,i}$) was provided by the diluter manufacturer and incorporated within the AIM software. The transportation efficiency through the sampling probe ($\eta_{sp,i}$), however, must be analyzed separately. The loss of dust inside the sampling probe can be attributed to the settling loss in the horizontal part of the probe, the inertial loss at the 90 degree bend, and the diffusion loss throughout the probe. These losses are size dependent so the overall loss of respirable dust depends on the size distribution of the dust generated during cutting fiber-cement siding. The overall loss of respirable dust was calculated using the equations summarized by Brockman [2011] and the size distribution data from the APS, and it was found to be less than 1% combining all three aforementioned losses. Thus, $\eta_{sp,i}$ was assumed to be 1 in this study for simplicity.

In addition to the APS, a GK4.162 RASCAL cyclone sampler (BGI, Waltham, MA) was used to take air samples of respirable dust from the second duct sampling port on the testing system. A Leland Legacy Sample Pump (SKC Inc., Eighty Four, PA) provided a sampling flow rate of 9.5 L/min for the cyclone. The pump connected via Tygon® tubing to a pre-weighed, 47-mm diameter, 5- μ m pore-size polyvinyl chloride (PVC) filter supported by a backup pad in a three-piece conductive filter cassette sealed with a cellulose shrink band (in accordance with NIOSH Methods 0600 and 7500) [NIOSH 1998, NIOSH 2003]. The front portion of the cassette was removed and the cassette was attached to the cyclone sampler. The mass of the collected respirable dust on the PVC filters was obtained by post-weighing the filters and subtracting their pre-weights. Compared to the APS, the cyclone sampler offered a direct measurement of the mass of the respirable dust. The performance of the GK4.162 cyclone was characterized experimentally by the Health and Safety Laboratory [2011]. At a flow rate of 9.5 L/min, the cyclone has a 50% cut point (D_{50}) of 3.7 μ m. D_{50} is the aerodynamic diameter of the particle at which penetration into the cyclone declines to 50% [Vincent 2007]. The GK4.162 cyclone conforms to the respirable sampling convention defined in EN481 [1993] by Comite ´ Europe ´ en de Normalisation (CEN), American Conference of Industrial

Hygienists [ACGIH, 2013] and the International Organization for Standardization document 7708 [ISO 7708, 1995]. Both the experimental respirable fraction for the GK4.162 cyclone and the respirable convention curve are illustrated in Figure 2, demonstrating a reasonably good agreement between the two. A sampling probe was designed to provide isokinetic sampling for the cyclone at 9.5 L/min. By using the equations from Brockman [2011], the transportation efficiency of respirable dust in this sampling probe was estimated to be very close to 1. The generation rate of respirable dust from the cyclone data (G_{Cyc}) can be described as:

$$G_{Cyc} = \frac{M_{res}}{n_c n_b W} \quad (3)$$

where,

M_{res} is the mass of the respirable dust collected on the filters

n_c is the number of repeating cut during the cyclone sampling

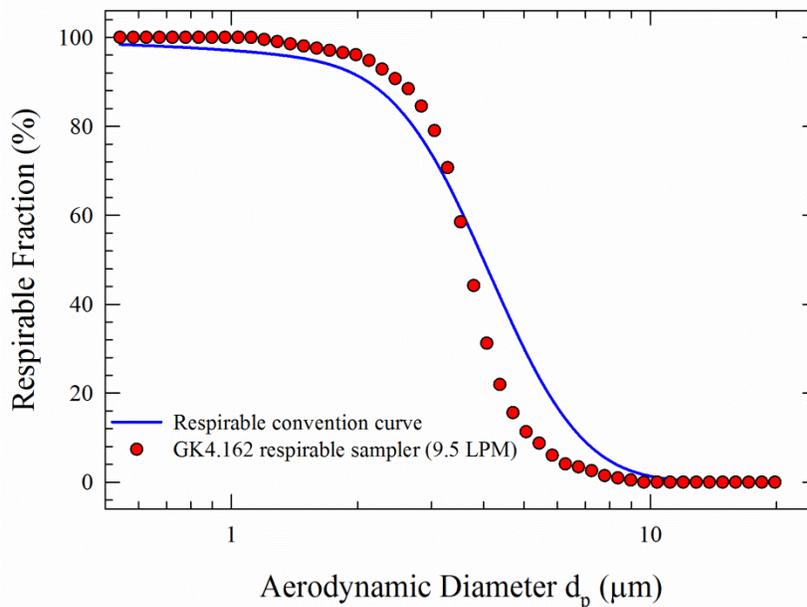


Figure 2. Comparison of the respirable fraction from the convention curve and the GK4.162 cyclone.

A trial test in this current study found that 15-30 repeated cuts using the testing system were optimal to collect sufficient respirable dust without overloading the filter. For the cutting test using the fiber-cement siding from each manufacturer, two bulk dust samples were also collected from the dust settled on the floor of the automatic tool testing chamber in accordance with NIOSH Method 7500 [NIOSH 2003]. Crystalline silica analysis of the air and bulk samples was performed using X-ray diffraction according to NIOSH Method 7500 [NIOSH 2003]. The limit of

detection (LOD) for quartz, cristobalite, and tridymite were 5 µg/sample, 5 µg/sample, and 10 µg/sample, respectively. The limit of quantitation (LOQ) for quartz, cristobalite, and tridymite were 17 µg/sample, 17 µg/sample, and 33 µg/sample, respectively. Quartz was found to be the only form of crystalline silica in the dust in this study.

Sharing the same sampling port on the duct of the testing system as the GK4.162 cyclone sampler, a Micro-Orifice Uniform Deposition Impactors (MOUDI, Model 110, MSP Corp, Shoreview, MN) sampler was used alternatively to collect size-selective filter samples. An isokinetic sampling probe was also designed for the MOUDI with negligible loss of respirable dust at its sampling flow rate of 30 L/min based on the calculations following Brockman [2011]. The MOUDI is an inertial cascade impactor with 10 stages. It collects dusts according to their inertia on the substrates of the ten corresponding impaction plates with the D_{50} ranging from 0.056 µm to 10.0 µm. It has an additional inlet stage with a D_{50} of 18 µm. In this study, 47-mm diameter, 5-µm pore-size PVC filters were used as the substrates. A 37-mm diameter, 5-µm pore-size PVC filter was used as the final filter collecting all the residual dust. By pre-weighing and post-weighing the PVC filters, the mass of dust collected on each stage was obtained and a mass-based size distribution of the sampled dust was derived. Crystalline silica analysis of the filter samples was also performed using X-ray diffraction in accordance with NIOSH Method 7500 [NIOSH 2003]. Thus, the content of crystalline silica in the dust of different sizes was obtained from the MOUDI samples. This additional information helped determine an optimal approach aimed at reducing the generation rate of respirable crystalline silica.

Local Exhaust Ventilation (LEV)

An exhaust port on the bottom of the automatic tool testing chamber allowed connection of the exhaust port on the power saws evaluated in this study to an external vacuum cleaner (Model 3700, Dustcontrol, Sweden) through flexible hoses. The external vacuum cleaner provided LEV of up to 5.0 m³/min (175 CFM) to the power saws. In the Dustcontrol 3700 vacuum cleaner, larger dusts collect in an attached dust bag after running through an internal cyclone collector, and the escaped smaller dusts collect in a HEPA filter cartridge downstream of the cyclone collector. Figure 3 shows how the LEV system was regulated and monitored. A T-shape PVC pipe connected to the vacuum cleaner and a gate valve was installed on the two branches. By adjusting the two gate valves, a ventilation flow rate in the full range of the vacuum cleaner's suction capacity was obtained for the test. The flow rate was monitored by a micromanometer (PVM100 Airflow Developments Ltd., UK) connected to a delta tube (307BZ-11-AO, Midwest Instrument, Sterling, MI).

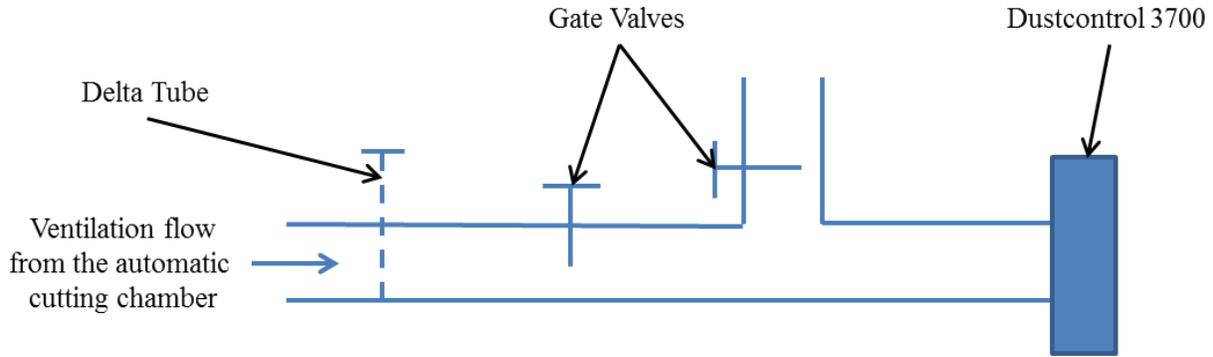


Figure 3. Diagram of the Local Exhaust Ventilation (LEV) system used in this study.

Dust removal efficiency (DRE)

When connected to a power saw, the LEV system removed the generated dust by the ventilation flow. Dust removal efficiency (DRE) was defined in this study as following:

$$DRE = \frac{\overline{G_{APS}(Q_{LEV})}}{\overline{G_{APS,non-LEV}}} \quad (4)$$

where,

$\overline{G_{APS}(Q_{LEV})}$ is the average generation rate of respirable dust when the flow rate of the LEV system is Q_{LEV}

$\overline{G_{APS,non-LEV}}$ is the average generation rate of respirable dust when the LEV system is not connected

Operating procedure for a cutting test

Before conducting a cutting test, the automatic tool testing chamber was programed to perform a pre-determined number of cuts. Each cut included the following steps: 1) the feed plate fed the board; 2) power was supplied to the tool; 3) the 2D actuator moved the tool and made a cut; 4) the tool was turned off; and 5) the 2D actuator moved the tool back to its original position. A waiting time about 5 seconds was programmed between steps 2) and 3) to ensure the blades of the power saws reached their designed rotating speed before making a cut. For a circular saw or a power shear, the cut was made only by sliding the tool through a board. A compound miter saw can make a cut by either chopping and/or sliding. In this study, we tested the miter saws with both "chopping only" and "chopping and sliding" modes. The "chopping only" mode cannot make a complete cut of the board with the board width of 30.5 cm (8.25 inch) so the actual length of the cut was measured and used in the place of board width (W) for Equation (2). Due to the size limit of the testing chamber, the "chopping and sliding" mode for the miter saws was configured to cut about 9 cm (3.5 inch) by chopping and cut the rest of

the board by sliding. The sliding speed for all the tools can also be varied and regulated by the PLC, and it is referred to as the cutting feed rate in this report.

For each cutting test, the air handling unit was turned on and the flow rate set to 0.64 m³/sec by adjusting the blast gate valve. For a test involving the LEV system, the Dustcontrol 3700 vacuum cleaner was turned on and the flow rate of the LEV system set to a desired point by adjusting the two gate valves. The flow rates of both the testing system and the LEV were stable throughout each individual test of this study. Once the flow rates in the testing chamber and the LEV system reached the desired values, the sampling instruments began sampling and the automatic tool testing chamber was started. Upon finishing a test, the air handling unit and the vacuum cleaner were turned off and the collected samples were removed from the instruments.

During each cut, a dust cloud was generated, and it was carried downstream by the air flow through the tool testing chamber and measured by the instruments through their respective sampling probes on the duct of the testing system. The APS collected size distribution measurements at 1-second intervals and its data indicated that no dust was detected when no cutting was conducted. The flow rate in the testing chamber (0.64 m³/sec) was optimal so that the APS data with 1-second time resolution captured the entire profile of the dust cloud from each individual cut without overlapping the dust clouds between any two adjacent cuts for all the testing conditions in this study. This ensured the calculation of the respirable dust generation rate (G_{APS}) using Equation (2) for each individual cut.

Experimental Design for the Laboratory Evaluation

Analysis of the APS data from a trial test with at least 15 cuts under the same testing condition revealed that the relative standard deviation (RSD, the ratio of the standard deviation to the mean) for G_{APS} was about only 3.1%, demonstrating excellent repeatability of the test. With the high repeatability, 3 or more repeated cuts under the same testing condition were considered sufficient to provide statistically reliable results. Thus, 5-10 cuts were conducted for the testing conditions when APS was the only instrument used. When the GK4.162 cyclone sampler or the MOUDI was used, 15-30 cuts were conducted to ensure sufficient respirable dust could be collected without overloading the filters.

Cutting fiber-cement siding from different manufacturers

Fiber-cement siding boards from the four manufacturers listed in Table 1 were cut under the same testing condition without the use of the LEV system, and the respectively generated dusts were evaluated. The M-H saw and an 8-tooth PCD blade (Model 18109, Hitachi Power Tools, Valencia, CA) were used to conduct all the cuts for this test. The M-H saw was used under the "chopping and sliding" mode with the cutting feed rate set at 2.54 cm/sec. For the board of each manufacturer, three respirable dust samples were collected by the GK4.162 cyclone sampler, and three sets of MOUDI samples were also collected. APS data were recorded

corresponding to each sample from the GK4.162 cyclone sampler and the MOUDI, with the averaged G_{APS} calculated for each testing condition.

Dust generation from cutting fiber-cement siding using different saw blades

A limited number of saw blades were tested in this study to evaluate their effects on the dust generation. The aforementioned 8-tooth PCD blade and a 60-tooth carbide tipped blade (Model A-93712, Makita U.S.A., Inc., St. La Mirada, CA) were tested on the M-M saw. These two saw blades both have a 12-inch diameter. The M-M saw was used under the "chopping and sliding" mode, and the saw cutting feed rate was set at 2.54 cm/sec. In addition, three saw blades of 7.25 inches diameter, including a 4-tooth PCD blade (Model 18008, Hitachi Power Tools, Valencia, CA), a 28-tooth (Model A-90451, Makita U.S.A., Inc., St. La Mirada, CA) and a 6-tooth (Model D0706CH, Freud Tools, High Point, NC) carbide tipped blades, were tested on the C-M saw. Only one saw blade of 5 inches diameter, i.e., a 6-tooth (Model D0706CH, Freud Tools, High Point, NC) carbide tipped blade, was tested on the C-R saw. A saw cutting feed rate of 2.54 cm/sec was used in the test of the C-M and C-R saws. Only APS data were collected for the saw blade test. An average G_{APS} was calculated and compared for each testing condition. The fiber-cement siding boards used in these tests were from CertainTeed.

Dust generation from cutting fiber-cement siding using different power tools

All the power tools listed in Table 2 were tested to evaluate the dust generation when they were operated under different conditions. During these tests, the four miter saws were tested using the same 8-tooth PCD blade (Model 18109, Hitachi Power Tools, Valencia, CA); the C-M and C-H saws were both tested using the 4-tooth PCD blade (Model 18008, Hitachi Power Tools, Valencia, CA); and the C-R saw was tested using the 6-tooth (Model D0706CH, Freud Tools, High Point, NC) carbide tipped blade. The four miter saws were tested under both "chopping only" and "chopping and sliding" modes. For the three circular saws and the M-H saw when operated under the "chopping and sliding" mode, a saw cutting feed rate in the range of 1.27 to 12.7 cm/sec was tested to evaluate the effect of the saw cutting feed rate on the dust generation. For the test of the power shear and the other three miter saws when operated under the "chopping and sliding" mode, the saw cutting feed rate was fixed at 2.54 cm/sec. Only APS data were collected for these tests, and an average G_{APS} was calculated and compared for each testing condition. The fiber-cement siding boards used in these tests were from CertainTeed.

Dust generation from cutting different number of fiber-cement siding boards at once

If not specified in this study, only one board at a time was cut for each of the tested power tools. In addition, up to six boards were stacked and cut for the M-B, C-H, and C-M saws to evaluate the effect of the number of boards in one cut on the dust generation. During these tests, the 8-tooth PCD blade (Model 18109, Hitachi

Power Tools, Valencia, CA) was used on the M-B saw; and the 4-tooth PCD blade (Model 18008, Hitachi Power Tools, Valencia, CA) was used on the C-H and C-M saws. The M-B saw was tested under the “chopping and sliding” mode only. The saw cutting feed rate for all these tests was fixed at 2.54 cm/sec. Only APS data were collected for these tests, and an average G_{APS} was calculated and compared for each testing condition. The fiber-cement siding boards used in these tests were from CertainTeed.

Testing the effectiveness of the LEV

The effectiveness of the LEV was tested for all the power tools listed in Table 2 except the power shear. The LEV system was connected to each of the tested power tools and its volume flow rate was varied as described earlier. Only APS data were collected for these tests, and an average G_{APS} and the corresponding dust removal efficiency (DRE) were calculated for each testing condition. The fiber-cement siding boards used in these tests were from CertainTeed. During these tests, the 8-tooth PCD blade (Model 18109, Hitachi Power Tools, Valencia, CA) was used for all the four miter saws; the 4-tooth PCD blade (Model 18008, Hitachi Power Tools, Valencia, CA) was used for the C-H and C-M saws; and the 6-tooth (Model D0706CH, Freud Tools, High Point, NC) carbide tipped blade was used for the C-R saw. The M-H saw was tested under the “chopping and sliding” mode only; and the other three miter saws were tested under both “chopping only” and “chopping and sliding” modes. The saw cutting feed rate for the C-R saw and all the miter saws operated under the “chopping and sliding” mode was fixed at 2.54 cm/sec, and it varied in the range of 2.54 to 12.7 cm/sec for the C-H and C-M saws. Both the C-H and C-M saws were also tested when up to six boards were stacked and cut at once.

Results and Data Analysis for the Laboratory Evaluation

Figure 4 shows typical size distributions of the dust generated and observed in one testing condition of this study. The size distributions represent the dust concentration (number or mass) per unit width of size channel at different aerodynamic diameters. The MOUDI data were obtained by using the following equation:

$$\frac{dM}{d\log(d_p)} = \frac{m_i}{Q_M T_M \Delta d_p} \quad (5)$$

where,

m_i is the mass of the dust collected on the filter of stage i of the MOUDI

Q_M is the sampling flow rate of the MOUDI (30 L/min)

T_M is the total sampling time of the MOUDI for one test

Δd_p is the width of the size channel for the MOUDI

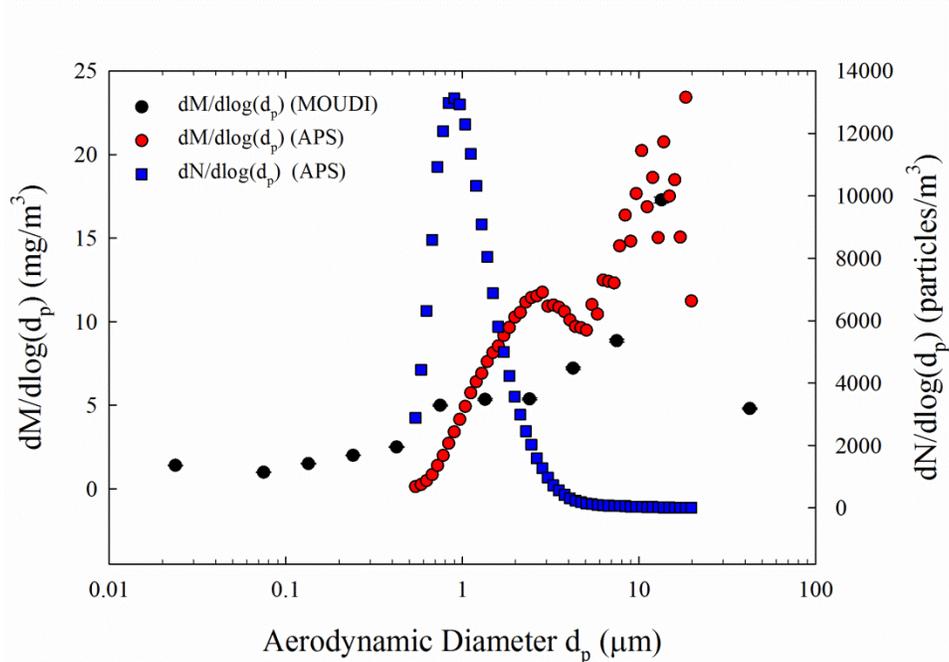


Figure 4. Typical size distribution of the dust from cutting fiber-cement siding. Power tool: M-H; Blade: Hitachi 18109; Saw cutting feed rate: 2.54 cm/sec; Siding: James Hardie.

The MOUDI data illustrated in Figure 4 are the averaged results from three replicate measurements with the small error bars representing the standard deviation of the three measurements. The APS data are also averaged results from all of its data collected concurrently with the MOUDI data. The number-based size distribution obtained from the APS show a lognormal distribution with the geometric mean diameter of $0.97 \mu\text{m}$ and the geometric standard deviation of 1.5. The mass-based size distributions from the MOUDI and the APS are generally in agreement. They both show a bimodal lognormal distribution with a larger mode around $13 \mu\text{m}$, and another mode smaller than $5 \mu\text{m}$. The smaller mode is less apparent in the MOUDI data and it shows lower concentrations compared to the APS data for the dust larger than about $1 \mu\text{m}$. These observations most likely result from the loss of larger dust inside the MOUDI. Larger inertia for the larger dust particles led to a higher fraction of them bouncing off the substrates where they were supposed to be collected, resulting in a smaller amount of mass collected on the filters. All the size distributions show that an apparent fraction of the airborne dust was respirable (smaller than $10 \mu\text{m}$). Note that the concentration level shown in Figure 4 is that monitored in the laboratory setting, which can be very different from those experienced in practice, although the shape of the size distribution is expected to be similar.

Dust generation from cutting fiber-cement siding from different manufacturers

Figure 5 shows the size distribution data obtained from the MOUDI for the dust generated from cutting fiber-cement siding from the four manufacturers listed in Table 1. Since three sets of MOUDI samples were collected for each manufacturer's siding, the data points shown in Figure 5 are the average of the three replicates and the error bars represent the standard deviations of the corresponding data points. In general, the MOUDI data showed reasonably good repeatability and the dust size distributions are very similar among the four manufacturers, except that the one from James Hardie has obviously higher concentrations for the dust in the three stages between 4.2-13.4 μm . All of the data sets show a bimodal lognormal distribution with a larger mode around 13 μm , and another mode between 1-3 μm . Combining the size distribution data shown in Figure 5 and the respirable fraction from the respirable convention curve, the overall respirable fraction of airborne dust was estimated to be 43.1%, 40.9%, 48.8% and 37.8% for cutting fiber-cement siding from CertainTeed, James Hardie, Maxitile, and Nichiha, respectively.

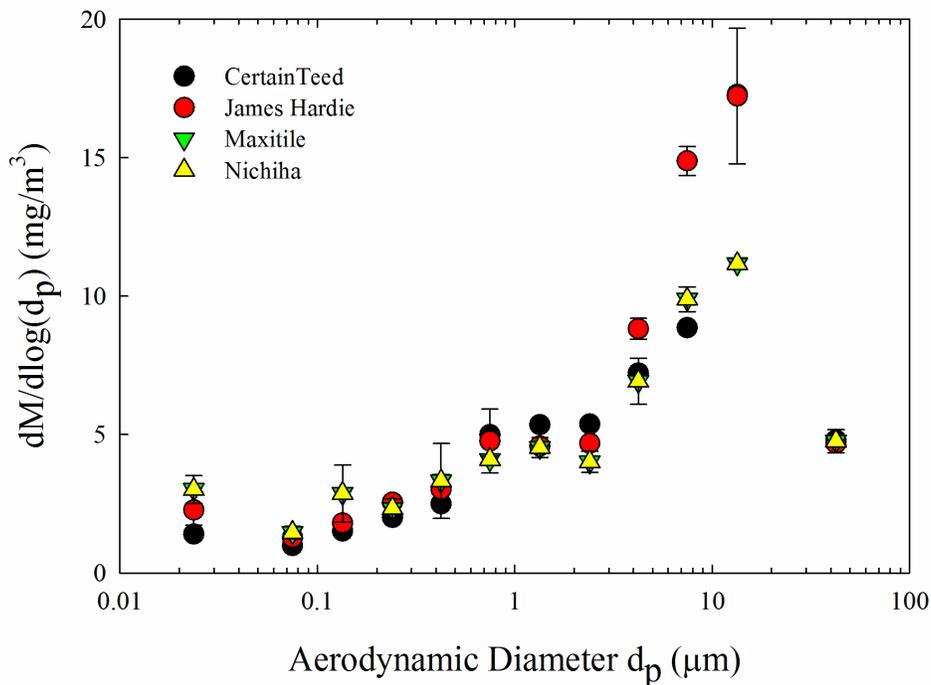


Figure 5. Size distribution obtained from the MOUDI for the dust from cutting fiber-cement siding of different manufacturers. Power tool: M-H; Blade: Hitachi 18109; Saw cutting feed rate: 2.54 cm/sec.

The generation rate (G_{APS} and G_{CYC}) and the crystalline silica content of the respirable dust for the four siding manufacturers are illustrated in Figure 6. Each data point is the average obtained from either the three respirable samples

collected by the GK4.162 cyclone sampler or the APS data collected simultaneously. The error bars represent the standard deviation of the three replicates.

Besides using the respirable fraction from the respirable convention curve, the APS data was also processed using the experimental respirable fraction (sampling efficiency) for the GK4.162 cyclone sampler (as shown in Figure 2). The G_{APS} based on the respirable fraction from the respirable convention curve was between 0.60 to 0.62 g/m; and the one based on the experimental respirable fraction for the GK4.162 cyclone sampler was between 0.56-0.60 g/m. These results show that the difference of G_{APS} obtained by the two respirable fractions is minimal ($4.4\% \pm 0.8\%$ for the four sets of data in Figure 6). It suggests that the small differences between the two respirable fractions lead to negligible deviation on the respirable dust generation rate for the dusts analyzed in this study. For the analysis of the remaining APS data, only the respirable fraction from the convention curve was used.

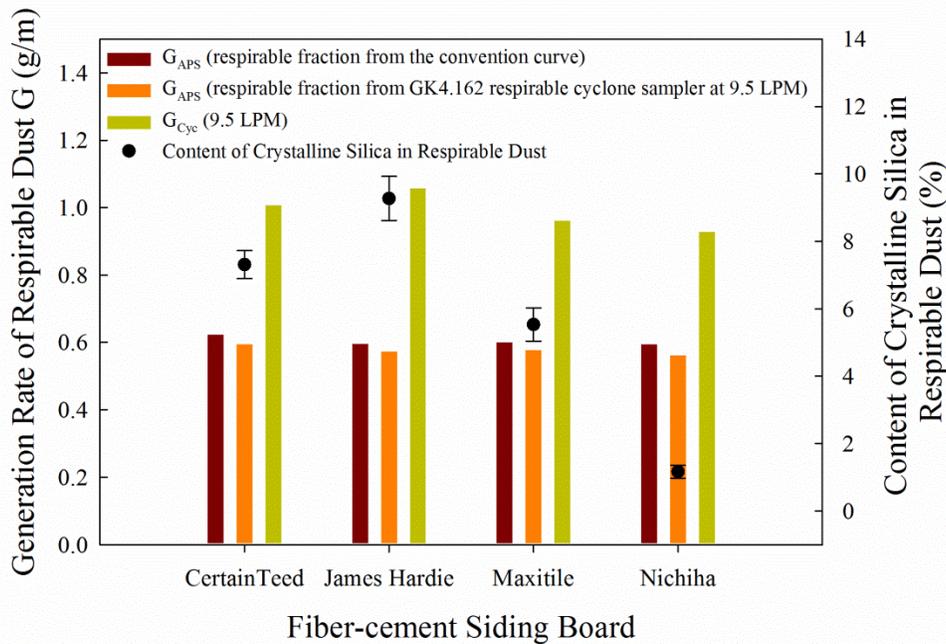


Figure 6. Comparison of the generation rate of respirable dust from cutting fiber-cement siding from different manufacturers. Power tool: M-H; Blade: Hitachi 18109; Saw cutting feed rate: 2.54 cm/sec.

The above analysis also verifies indirectly that the respirable dusts collected by the GK4.162 cyclone sampler were well representative. Compared to the generation rates derived from the APS data (G_{APS}), those obtained from the cyclone sampler (G_{Cyc}) were apparently higher (between 0.93-1.06 g/m). The average of G_{Cyc} was about $63.6\% \pm 9.3\%$ higher than the average of G_{APS} derived based on the convention respirable fraction for the dusts of the four manufacturers. Since the cyclone sampler offers a direct gravimetric measurement of the sampled respirable

dusts, G_{Cyc} should be considered more representative of the actual generation rates. The smaller values for G_{APS} might be attributed to the counting efficiency of the APS being less than 100%, possibly underestimated loss of dust in the sampling line, as well as the bias introduced by the assumptions that the dust density is equal to the board density, and that all the dusts were spherical. Although the difference between G_{Cyc} and G_{APS} is obvious, this difference is consistent among the four cases shown in Figure 6. Thus, the G_{APS} results obtained under different testing conditions should be considered comparable.

The results in Figure 6 also suggest that the respirable dust generation rate for the boards of the four manufacturers are very close to each other, with a maximum difference of 13.8% for G_{Cyc} and 5.9% for G_{APS} among the four sets of data. This result is also consistent with the observation in Figure 5. The content of crystalline silica in respirable dust, however, varied in a relatively wide range of 1.2% to 9.3%, perhaps due to the varied formulations the four manufacturers used in their respective fiber-cement siding boards that were evaluated in this study.

As mentioned earlier, the MOUDI samples offered an additional insight on the content of crystalline silica in the dust of different sizes by analyzing the amount of crystalline silica in the dust collected on each stage of the MOUDI. This information is shown in Figure 7 for the boards from the four manufacturers. The data for bulk samples and respirable dust samples (lab) shown in Figure 7 were obtained by analyzing the silica content in the bulk samples and the respirable dust samples (the same data presented in Figure 6) collected in the laboratory study. In addition, the fiber-cement siding from CertainTeed and James Hardie were used respectively in one [Qi et al., 2013a] and four [Qi et al., 2013b; 2014a, 2014b, 2014c] field surveys conducted as a part of this study. The averaged silica contents in the respirable dust samples (field) collected in these field surveys were also presented in Figure 7 (a) and (b), and they were found very close to the averaged silica content in the corresponding laboratory respirable dust samples. For all four manufacturers, the silica content in the dust showed the same obvious trend of an increase with the aerodynamic diameter of the dust, approaching to the silica content levels found in their respective bulk samples.

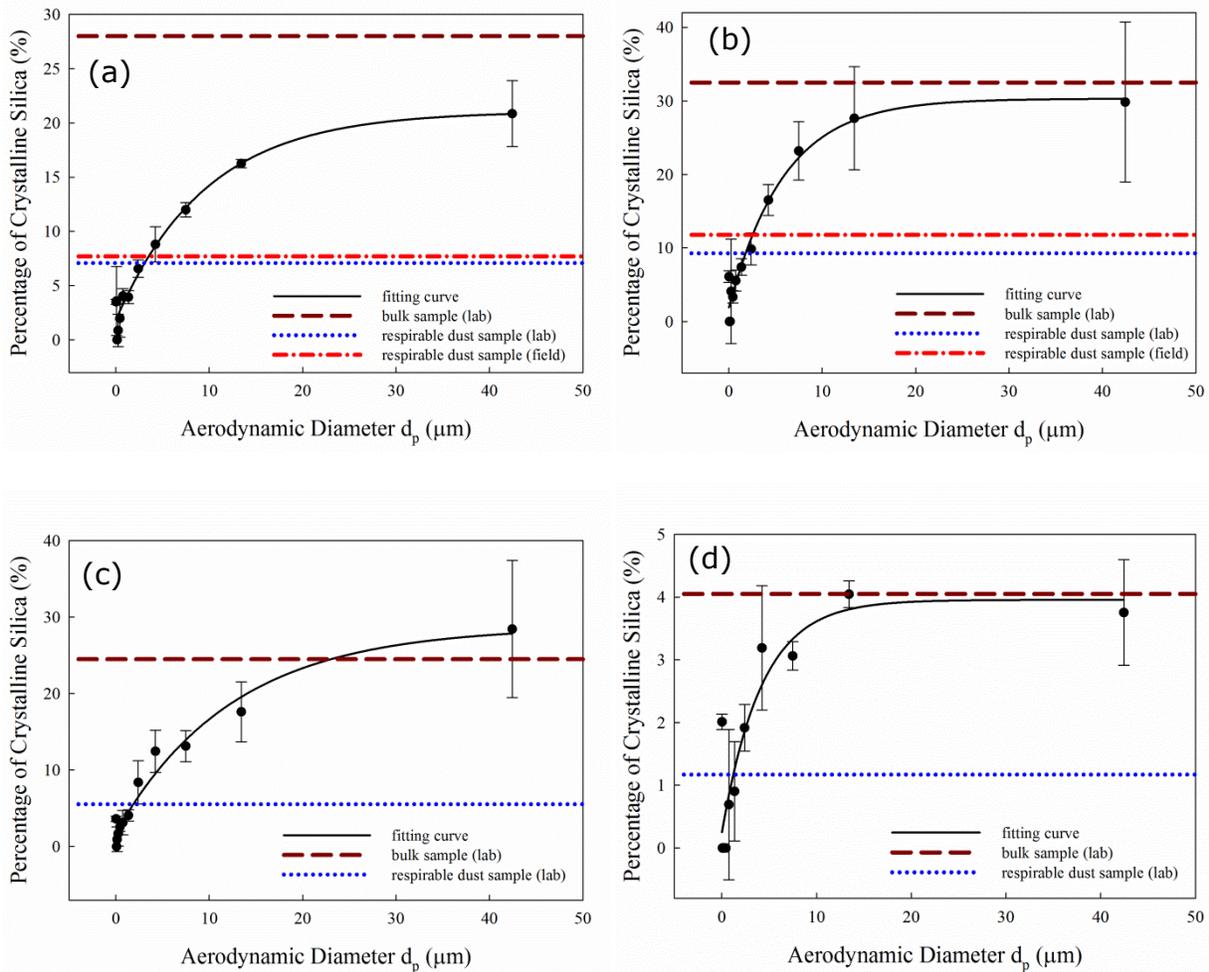


Figure 7. Silica distribution in the dusts of different sizes from cutting fiber-cement siding board of (a) CertainTeed; (b) James Hardie; (c) Maxitile; (d) Nichiha. Power tool: M-H; Blade: Hitachi 18109; Saw cutting feed rate: 2.54 cm/sec.

The MOUDI data, including the dust size distribution and silica distribution in the dust of varying sizes, can also be used to derive the overall silica content in the respirable dust with the knowledge of a respirable fraction based on the convention curve for the aerodynamic diameters of the size channels in MOUDI. Figure 8 compares the silica contents in the respirable dusts derived from the MOUDI data and obtained from the laboratory respirable dust samples. The results from the two methods are reasonably comparable, with those from the MOUDI data consistently lower than those from the laboratory respirable dust samples (ranging from 0.9% to 6.9% compared to ranging from 1.2% to 9.3%). This is possibly due to the low sizing resolution of the MOUDI and the higher fraction of larger dusts with higher contents of silica bouncing off the substrates in the MOUDI.

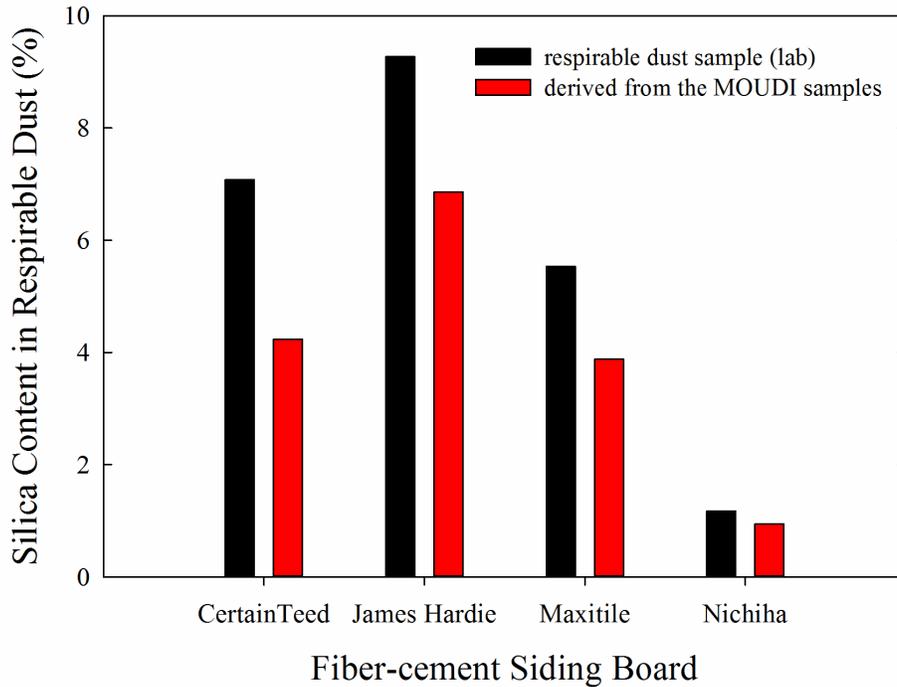


Figure 8. Comparison of the silica content in respirable dust from respirable dust samples and derived from the MOUDI samples. Power tool: M-H; Blade: Hitachi 18109; Saw cutting feed rate: 2.54 cm/sec.

Dust generation from cutting fiber-cement siding using different saw blades

The specifications and respective G_{APS} for the tested saw blades are listed in Table 3. Among the three 7.25-inch diameter blades, the Makita blade with 28 carbide tipped teeth generated significantly more dusts than the other two blades (1.02 g/m vs 0.41 g/m and 0.42 g/m), which have 4 PCD tipped teeth and 6 carbide tipped teeth, respectively. Comparing the two 12-inch diameter blades, the blade with 60 carbide tipped teeth generated 62% more dust than the blade with 8 PCD tipped teeth (0.86 g/m vs 0.53 g/m). The 5-inch diameter Freud blade is the only blade of its size tested in this study and its G_{APS} was the highest among all the blades tested. Specifically, its G_{APS} was 148% higher than the 7.25-inch diameter Freud blade (1.04 g/m vs 0.42 g/m). These two Freud blades both have 6 carbide tipped teeth and a kerf width of 1.7 mm. They were used in two different circular saws with different saw blade diameters (5 inches vs 7.25 inches) and blade rotating speeds (9068 RPM vs 5500 RPM). This resulted in a difference of 13.7% on the linear speed of the blade's tooth cutting through the board (60.3 m/sec vs 53.0 m/sec). Based on the comparisons of these specifications, the higher G_{APS} for the 5-inch diameter blade was likely due to its higher blade rotating speed, as a higher blade rotating speed leads to proportionally more cutting interactions between the blade's teeth and the board during one complete cut, and a higher blade rotating

speed also contributes to a higher linear cutting speed from the blade’s teeth. It should be noted that the blades used in these tests were brand new so the G_{APS} results may be different for aged blades. Since the PCD blades were designed to last much longer than the carbide tipped blade, only the PCD blades were used in the rest of this study if not specified otherwise, except for the C-R saw, which only had the 5-inch diameter Freud blade available for it.

Table 3. Saw blade used in the study and their specifications

Manufacturer	Model #	Blade Diameter (inch)	Number of Tooth	Tooth Type	Kerf Width (mm)	Test Saw	Generation Rate of Respirable Dust G_{APS} (g/m)
Hitachi	18109	12	8	PCD Tipped	2.2	M-M	0.53
Makita	A-93712	12	60	Carbide tipped	2.3	M-M	0.86
Hitachi	18008	7.25	4	PCD Tipped	1.8	C-M	0.41
Makita	A-90451	7.25	28	Carbide tipped	2.0	C-M	1.02
Freud	D0706CH	7.25	6	Carbide tipped	1.7	C-M	0.42
Freud	D0506CH	5	6	Carbide tipped	1.7	C-R	1.04

Dust generation from cutting fiber-cement siding using different power tools

Figure 9 shows the G_{APS} for the four miter saws tested in this study. Both the “chopping and sliding” and “chopping only” modes were tested for these miter saws. It was apparent that all the miter saws generated less dust in the “chopping mode” (ranging from 0.23 to 0.34 g/m compared to ranging from 0.53 to 0.77 g/m in the “chopping and sliding” mode), during which the saws were controlled to chop down at a speed of 2.54 cm/sec. Since the test CertainTeed board is only 0.76 cm thick, it took considerably less time to conduct one cut in the “chopping mode” than in the “chopping and sliding mode”. Thus, there were fewer cutting interactions between the blade’s teeth and the board during one chopping cut, which was likely the reason for a lower dust generation rate. The comparison of the G_{APS} among the four miter saws was consistent for both modes, with the M-H saw having the highest G_{APS} and the M-M saw having the lowest. The differences were likely due to their different specifications, especially the blade rotating speed, which is also presented in Figure 9. Figure 10 plots the G_{APS} against the saws’ blade rotating speed and a linear correlation was found with a R^2 of 0.99 for both modes.

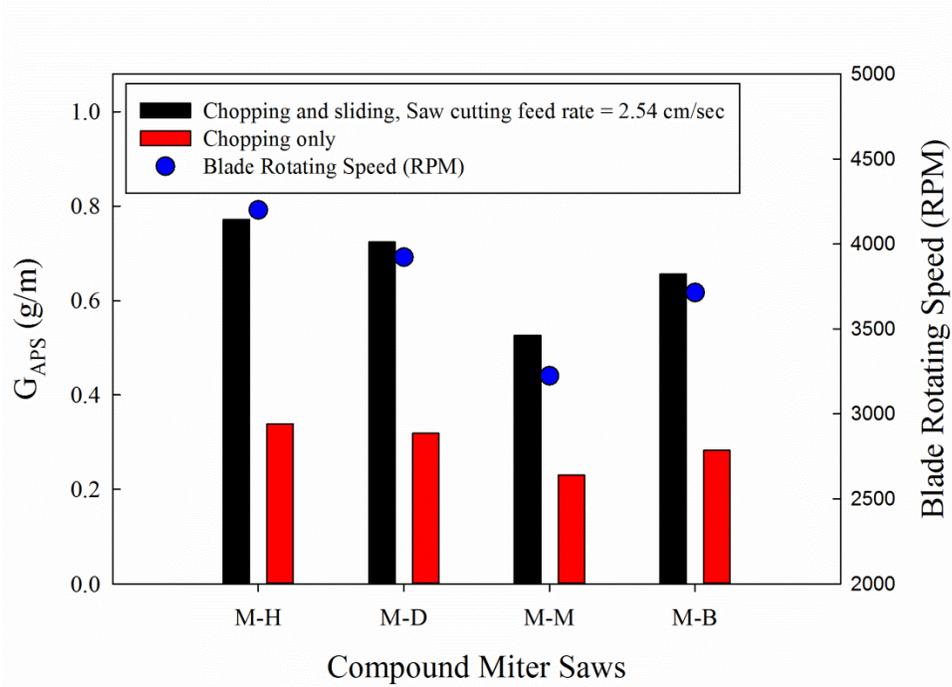


Figure 9. Generation rate of respirable dust for the miter saws. Blade: Hitachi 18109; Siding: CertainTeed.

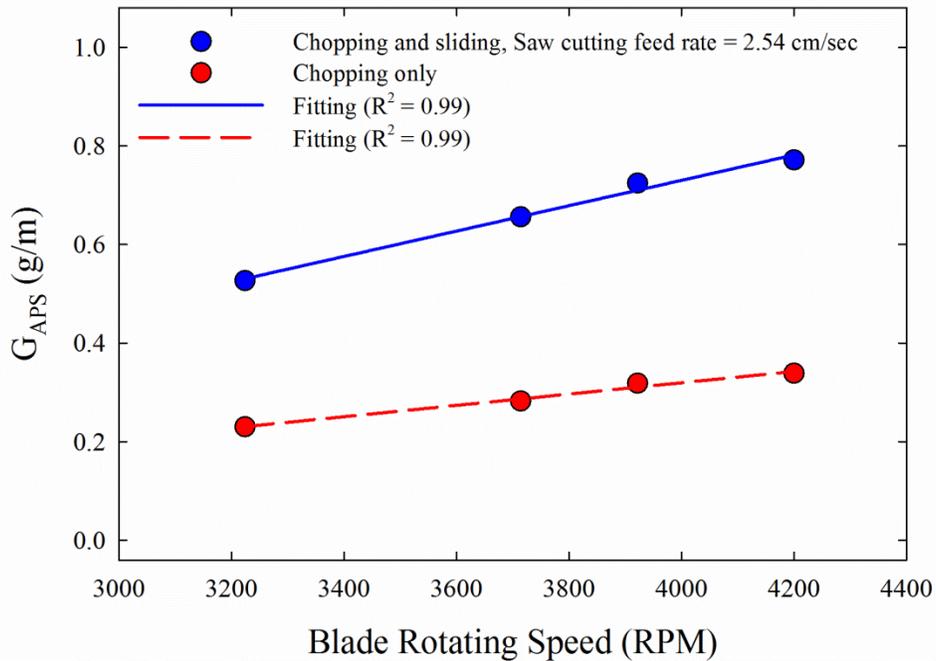


Figure 10. Comparison of the generation rate of respirable dust and the blade rotating speed for the miter saws. Blade: Hitachi 18109; Siding: CertainTeed.

The saw cutting feed rate was varied for the circular saws and miter saws operated under the “chopping and sliding” mode in this study. Figure 11 shows the G_{APS} results for the tested saws under different saw cutting feed rates. It is apparent that the G_{APS} decreased with the saw cutting feed rate for all the tested saws. This was likely due to fewer cutting interactions between the blade’s teeth and the board during one cut when the saw cutting feed rate was higher. The circular saw C-R generated the highest amount of dust when it was used with the 5-inch diameter Freud blade running at a higher blade rotating speed at 9068 RPM. The other circular saws, i.e., C-H and C-M, generated the least amount of dust.

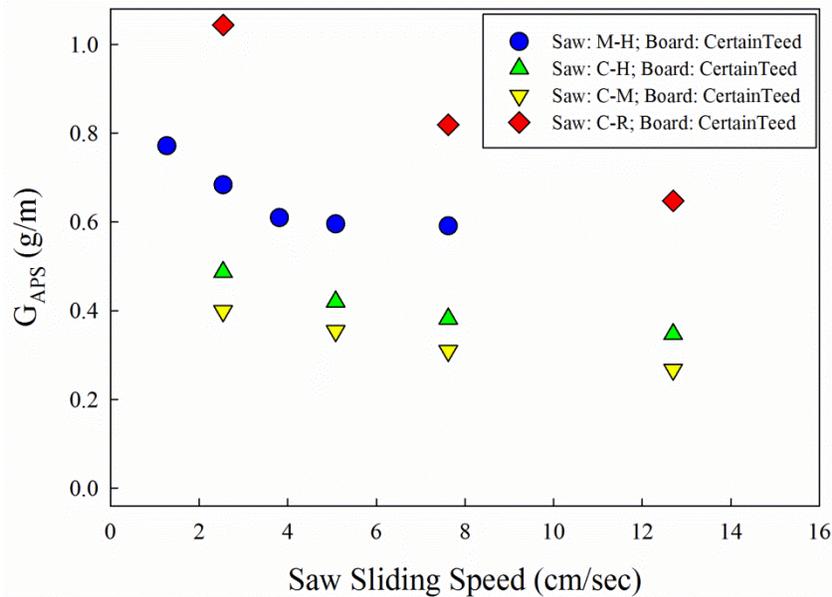


Figure 11. Generation rate of respirable dust at different saw cutting feed rate. Siding: CertainTeed.

Dust generation from cutting different number of fiber-cement siding boards at once

Up to six boards were stacked and cut in this study for the M-B, C-H, and C-M saws, and their G_{APS} results were presented in Figure 12. For all the three saws, the G_{APS} decreased with the number of board in the stack. Since the saw cutting feed rate was fixed at 2.54 cm/sec for these tests, it took about the same amount of time for the same saw to cut the stack of boards no matter how many boards were in the stack. Therefore, fewer cutting interactions occurred between the blade’s teeth and the siding material for a unit linear length of cut when a larger number of boards were in the stack, which likely contributed to the lower G_{APS} , which was defined in Equation (2) as the mass of respirable dust generated per unit linear length of cut.

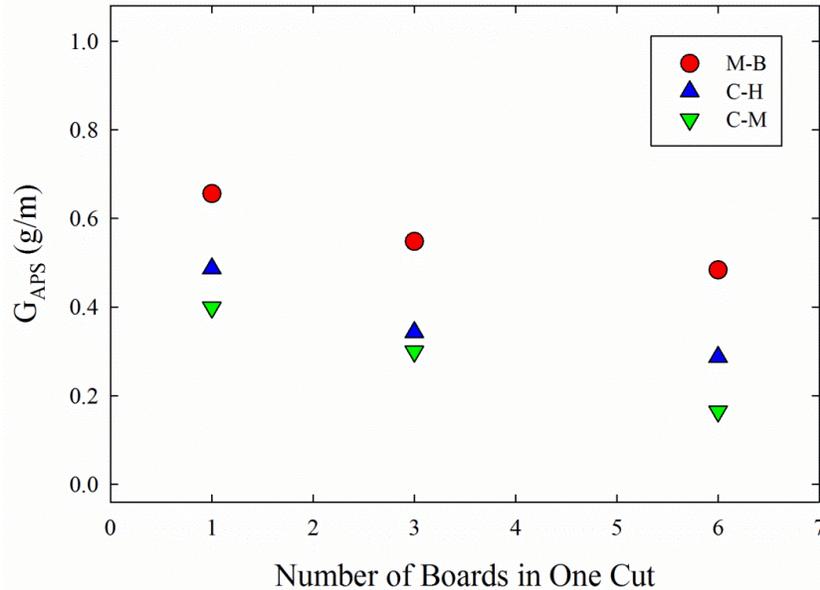


Figure 12. Generation rate of respirable dust when cutting different numbers of siding board in the stack. Saw cutting feed rate 2.54 cm/sec; Siding: CertainTeed.

The effectiveness of the LEV for different power tools

By combining the results of the dust size distribution from the APS data, respirable fraction from the convention curve, and the silica distribution in the dust of different sizes (fitting curves in Figure 7), a size distribution of respirable crystalline silica for the dust from cutting fiber-cement siding can be estimated for the four manufacturers and presented in Figure 13. Since the main objective of this study was to reduce workers' exposure to respirable crystalline silica while cutting fiber-cement siding, the results in Figure 13 are important to consider for choosing and evaluating engineering control measures. As shown in Figure 13, most respirable silica resides in the dust about 2.5 μm in aerodynamic diameter, although the overall concentration level varied among the four manufacturers. These data suggest that if an LEV system can capture the dust larger than about 1.0 μm from where they are generated and remove these dusts by air filtration, about 95% of the respirable silica would be removed. When an LEV system is implemented, it removes the majority of the dust across all the dust sizes with the air flow. This is evident in Figure 14, which shows the number-based size distributions of the generated dust when using the C-M saw with and without an LEV engineering control system. As shown in Figure 14, the dust across the entire size range was removed considerably even at a volumetric flow rate of only 1.18 m^3/min (41.6 CFM). As mentioned earlier, all the power saws tested in this study have a dust collecting feature with an exhaust port that can be connected to an external LEV system. Dust removal efficiency (DRE) defined in Equation (4) was characterized for all the test saws in this study.

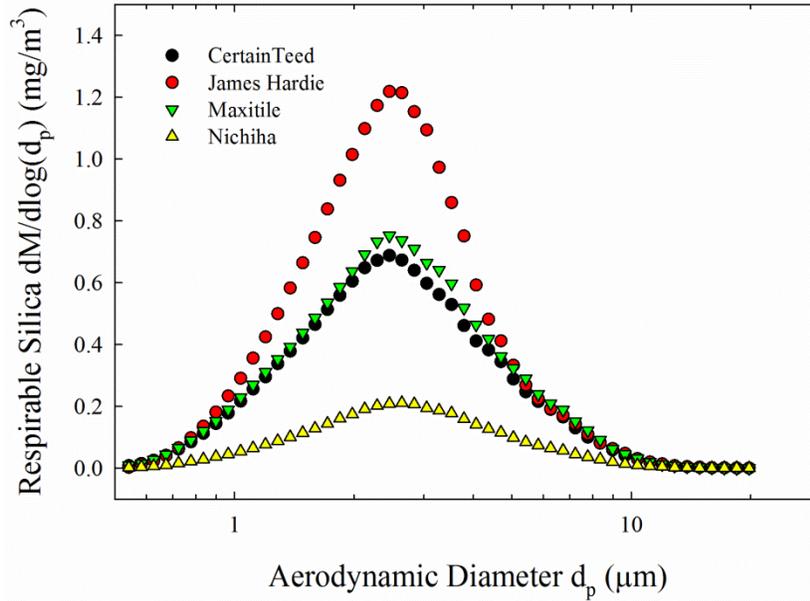


Figure 13. Size distribution of respirable crystalline silica for the dust from cutting fiber-cement siding of different manufacturers.

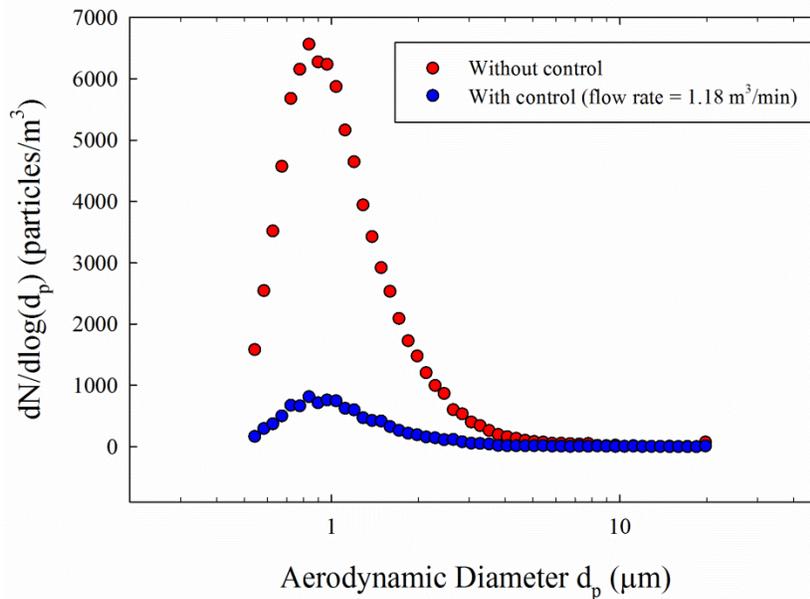
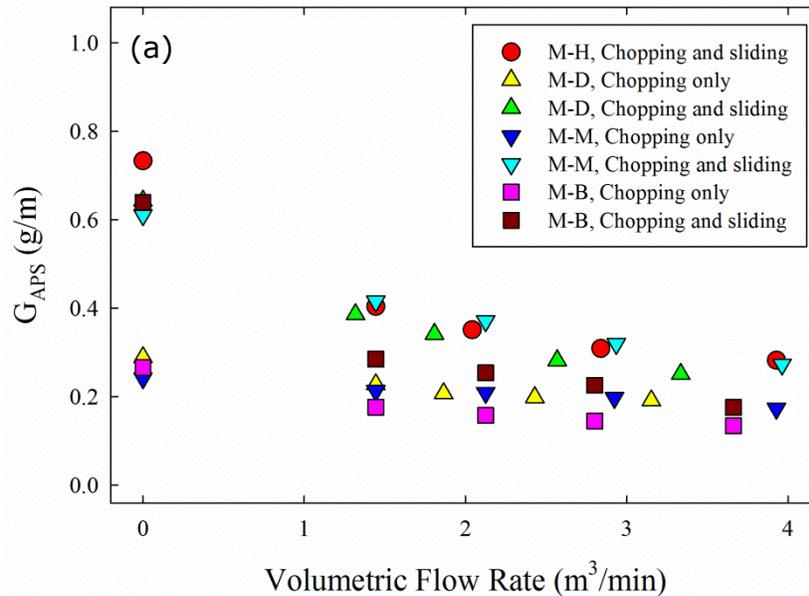


Figure 14. Dust size distributions with and without the LEV control. Power tool: C-M; Blade: Hitachi 18008; Saw cutting feed rate 2.54 cm/sec; Siding: CertainTeed.

Figure 15 illustrates the results of G_{APS} and DRE for the four miter saws under different volumetric flow rates of the LEV. Except for the M-H saw, both the

“chopping and sliding” and “chopping only” modes were tested. The test condition of the volumetric flow rate of zero refers to the case when the LEV system was connected to the test saw without being turned on. The highest tested flow rate was 3.97 m³/min (140 CFM), which was lower than the rating of the Dustcontrol 3700 vacuum cleaner (5.0 m³/min, 175 CFM) due to the extra flow restrictions added by the exhaust port, hose, and connections in the LEV system. As shown in Figure 15, the increased volumetric flow rate of the LEV did lead to a lower G_{APS} and higher DRE, although the increment seemed to diminish with increased flow rate, suggesting that the higher flow rate did not work as efficiently removing the extra amount of dust for these miter saws. This is more apparent in the “chopping only” mode. Similar to the observation in Figure 9, the dust generation in the “chopping only” mode was generally lower than that in the “chopping and sliding” mode when other test conditions were the same. However, the DRE result was higher in the “chopping and sliding” mode. This is possibly because more dust can be captured by the LEV when the blade slides to the far end of the miter saws, where their exhaust ports were located. In most test conditions for the four miter saws, the DRE was about or lower than 65%, even at the highest flow rate of about 3.97 m³/min. Although the M-M saw generated the least amount of dust when the LEV was not connected (Figure 9), the M-B saw demonstrated the lowest G_{APS} and the highest DRE when the LEV was used, possibly due to the design of its exhaust port, which might be able to collect more dust under the same flow rate of the LEV.



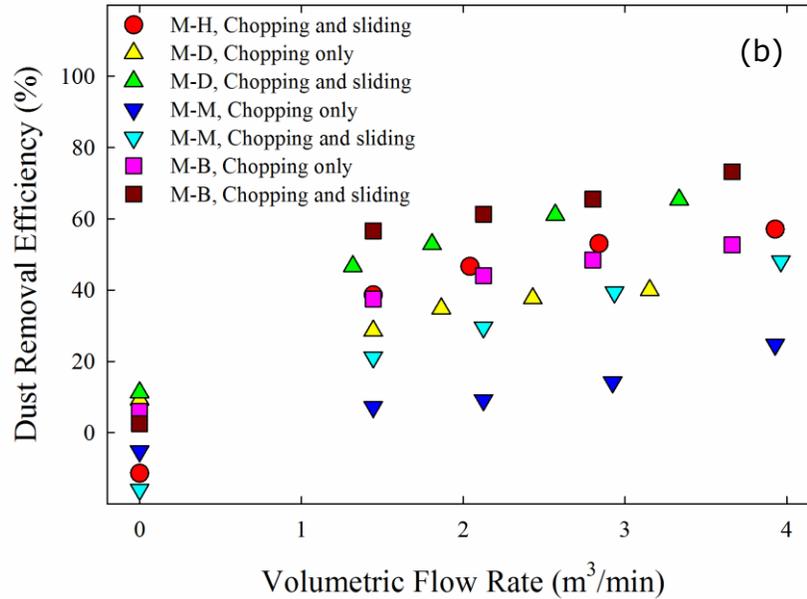


Figure 15. (a) Generation rate of respirable dust; and (b) Dust removal efficiency; for the miter saws cutting one board in the stack under different flow rates of the LEV. Saw cutting feed rate 2.54 cm/sec; Blade: Hitachi 18109; Siding: CertainTeed.

The results of G_{APS} and DRE at different saw cutting feed rate for the C-H saw are shown in Figure 16. Similar to the test of the miter saws, the test condition of the volumetric flow rate of zero refers to the case when the LEV system was connected to the C-H saw without being turned on. The DRE was between about 20% to about 42% even when the flow rate was zero. The C-H saw has a dust-collecting feature with a built-in shroud covering the saw blade and connecting to an exhaust port so that the flow induced by the spinning blade collects in the shroud a large amount of the dust generated while cutting and directs the dust to the exhaust port. When the flow rate of the LEV was zero, the induced flow by the spinning saw blade would still be able to collect and send some dusts into the vacuum cleaner, resulting in the 20% to 40% DRE. The DRE jumped to about 78% when the LEV was turned on, even at a low flow rate of about 1.4 m³/min. However, further increasing the flow rate did not lead to significantly lower G_{APS} and higher DRE as shown in Figure 16. The highest DRE achieved was about 87% at about 2.5 m³/min flow rate. This is possibly limited by the shroud design, whose dust capture efficiency can only reach a certain limit so the increased flow rate would not be able to remove more dust. Figure 16 also shows that a higher saw cutting feed rate in general leads to lower G_{APS} (similar to the observation in Figure 11) and higher DRE when the flow rate was similar. Compared to the DRE results for the miter saws, the DRE for the C-H saw was obviously higher and this higher DRE can be achieved even at low flow rates.

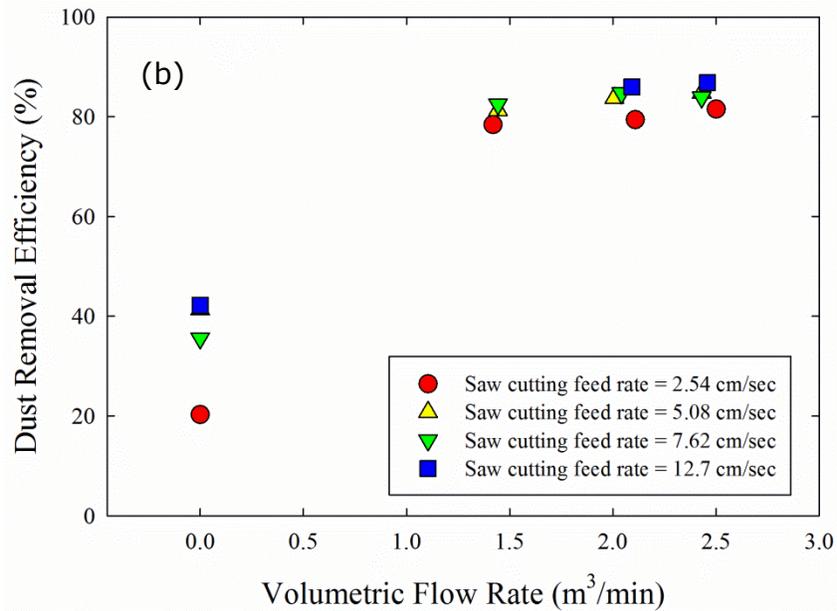
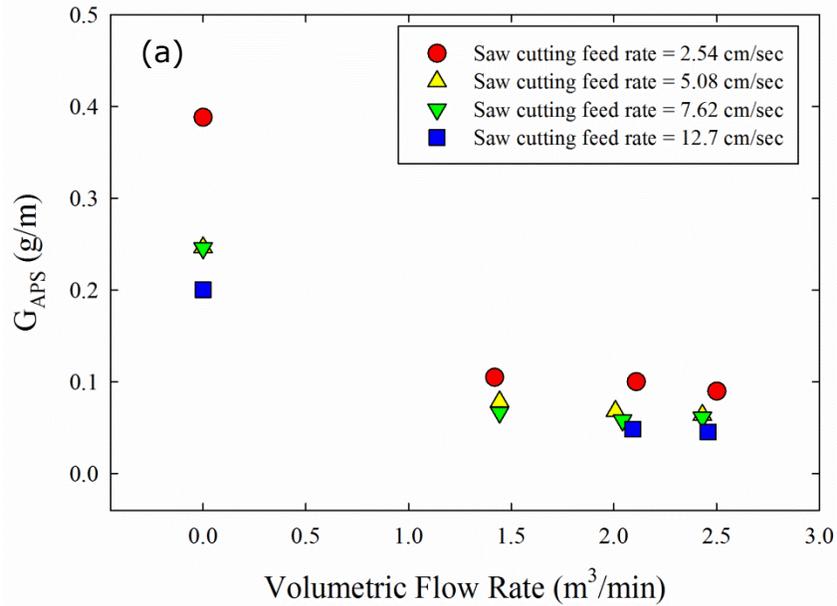
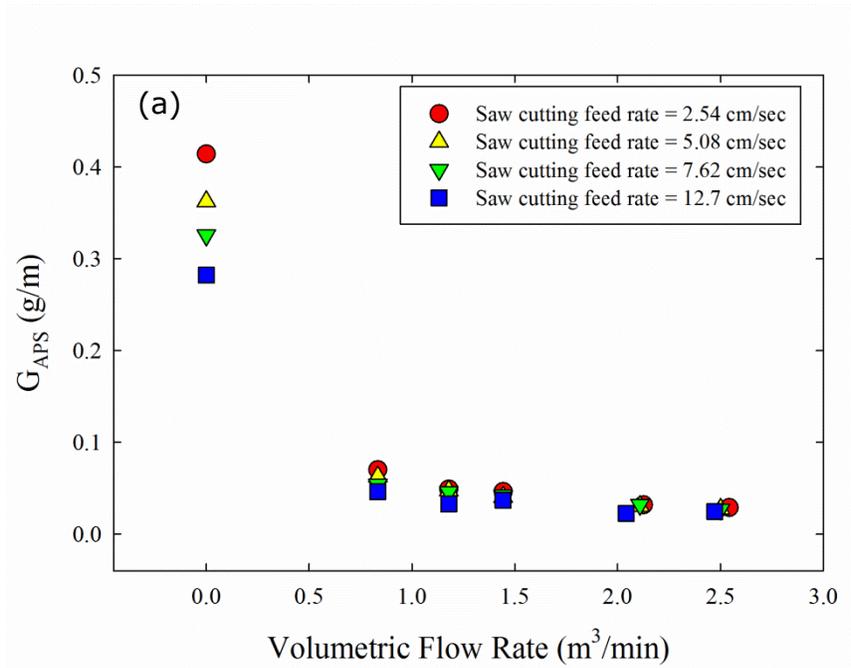


Figure 16. (a) Generation rate of respirable dust; and (b) Dust removal efficiency; for the C-H saw cutting one board in the stack under different flow rates of the LEV. Blade: Hitachi 18008; Siding: CertainTeed.

Unlike the C-H saw, the C-M saw has a removable dust-collecting container, which covers about 69% of the saw blade's surface. Similar to the shroud in the C-H saw, this hood also helps collect dust by the induced flow from the spinning saw blade

and sends the dusts to an exhaust port. The exhaust port can be connected to an external LEV system or capped when it is not in use. The results of G_{APS} and DRE for the C-M saw shown in Figure 17 are largely similar to those shown in Figure 16 for the C-H saw. The DRE jumped to about 82% once the LEV was turned on at a low flow rate of about $0.83 \text{ m}^3/\text{min}$, and the highest DRE achieved was about 93% at a flow rate of about $2.5 \text{ m}^3/\text{min}$. The effect from the saw cutting feed rate is less apparent compared to the observation for the C-H saw. The dust-collecting container of the C-M saw included a cap, which was not available to the C-H and C-R saws, and the test condition of the volumetric flow rate of zero refers to the case when its exhaust port was capped. The capped exhaust port blocked the induced flow so the dust cannot be effectively collected in the container, resulting in an averaged -4% DRE as shown in Figure 17.



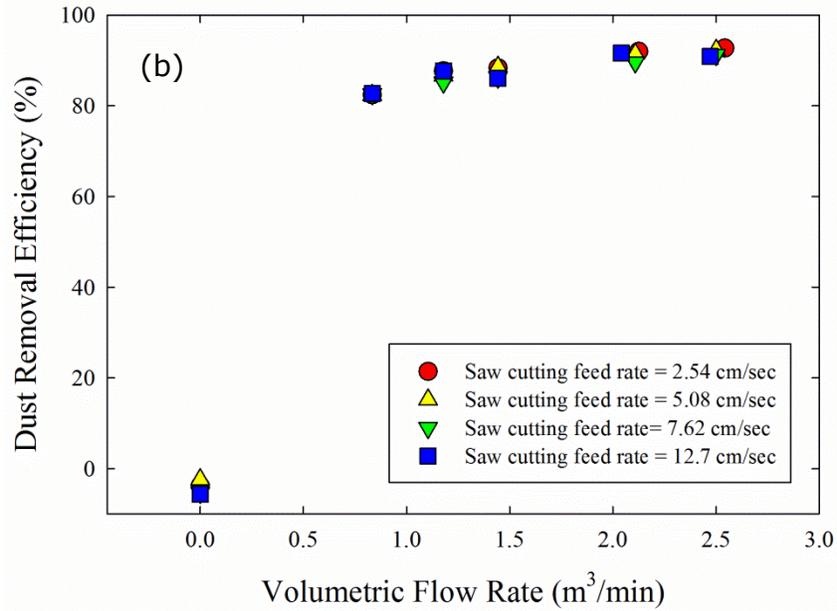


Figure 17. (a) Generation rate of respirable dust; and (b) Dust removal efficiency; for the C-M saw cutting one board in the stack under different flow rates of the LEV. Blade: Hitachi 18008; Siding: CertainTeed.

For both the C-H and C-M saws, tests were conducted with 3 or 6 boards stacked for one cut while the LEV system was activated; the results of G_{APS} and DRE are illustrated in Figure 18. The overall observations in Figure 18 are similar to those in Figure 16 and 17. For the C-H saw, the DRE was about 86% for all the test conditions; and for the C-M saw, the DRE ranged from about 84% to 98%.

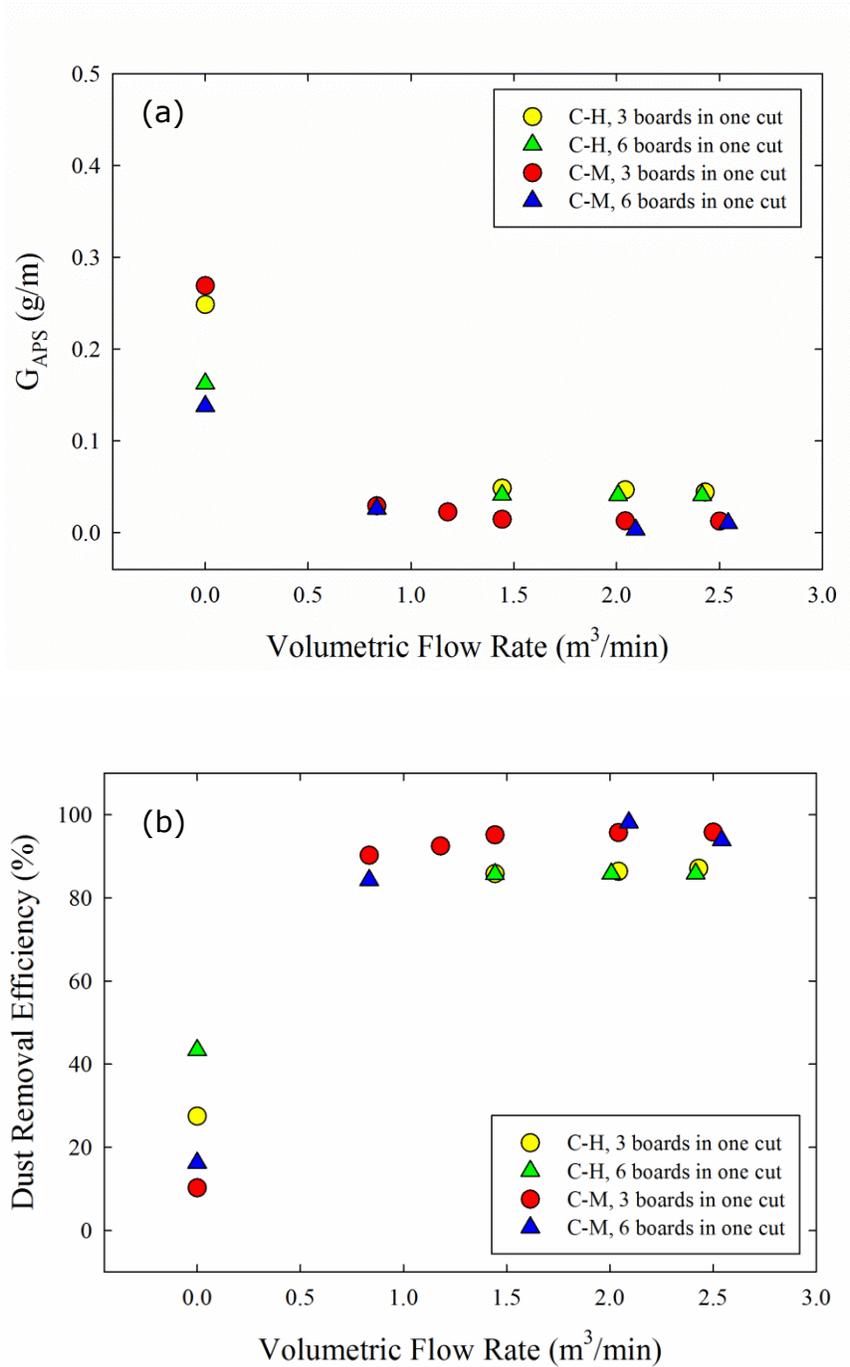


Figure 18. (a) Generation rate of respirable dust; and (b) Dust removal efficiency; for the C-H and C-M saws cutting three or six boards in the stack under different flow rates of the LEV. Saw cutting feed rate 2.54 cm/sec; Blade: Hitachi 18008; Siding: CertainTeed.

As mentioned earlier, the C-R saw has a small built-in blower that pushes air through its exhaust port. Thus, the flow rate of its LEV was about 1.3 m³/min even when the external LEV system was not activated. At this test condition, the DRE

was about 92%. Activating the external LEV and increasing the flow rate led to an increase of the DRE to about 98%.

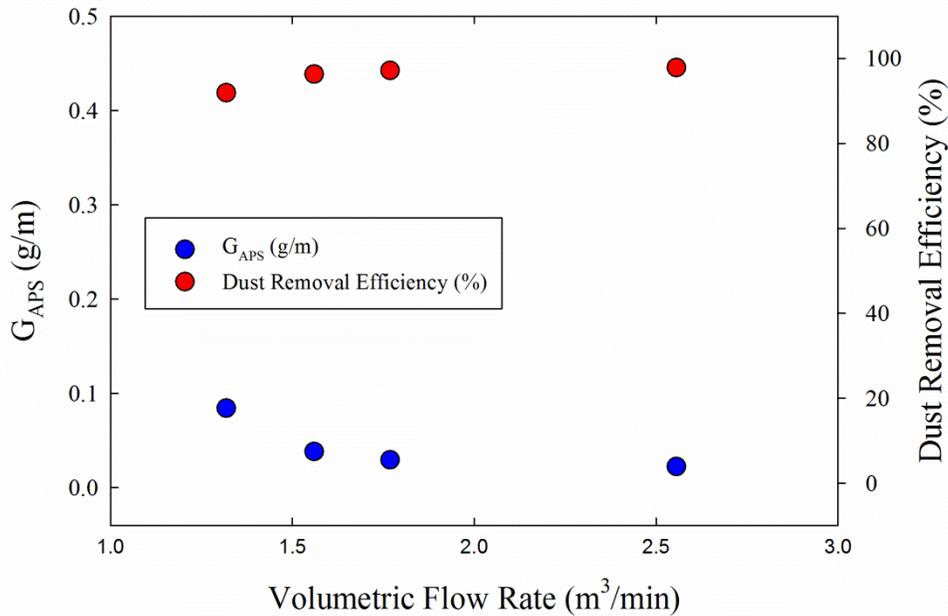


Figure 19. Generation rate of respirable dust and dust removal efficiency for the C-R saw cutting one board in the stack under different flow rates of the LEV. Saw cutting feed rate 2.54 cm/sec; Blade: Freud D0506CH; Siding: CertainTeed.

Discussion of the Laboratory Evaluation

The result of G_{APS} for the power shear was 0.006 g/m at a saw cutting feed rate of 2.54 cm/sec, verifying that it is indeed an almost dust free operation. However, as mentioned earlier, it is limited by slow production rates and low cutting precision.

Under most testing conditions in the laboratory evaluation, the DRE for the four miter saws was about 65% or less, even at the highest tested flow rate of 3.97 m³/min (140 CFM). In addition, increasing the flow rate of the LEV did not lead to an equivalent increase on the DRE. This is mainly due to the design limitations of these miter saws in terms of dust collection. Although all of them were equipped with an exhaust port to be connected to an external LEV system, their exhaust ports were located at a fixed position at the back of the saws and they are not integrated with any other dust collecting apparatus, such as a hood covering the blade to assist in dust collection. Therefore, dusts were scattered from the blade during a cut and the LEV was not able to collect the dust and remove it even at a high flow rate, especially when the cutting point was far away from the exhaust port.

Although all the four miter saws showed a lower dust generation rate in the “chopping only” mode, they cannot complete one crosscut of the lap siding board

used in this study under this mode. In addition, miter saws cannot effectively cut panel siding. Thus, circular saws are the dominant tools used by the siding contractors when cutting fiber-cement siding.

Comparing the four miter saws, all three circular saws had a built-in dust collection container or shroud, which served as a hood and partially enclosed the saw blade. Thus, they were able to collect a considerable amount of dust while cutting and remove it by connecting to an external LEV system even at a low flow rate of 0.83 m³/min (29 CFM). This flow rate can be easily achieved by most basic shop vacuums. The lowest DRE for the three circular saws with an activated LEV was about 78%, demonstrating the effectiveness of the LEV working with these circular saws on removing respirable dust. The C-R saw with a built-in blower has the highest DRE among the three circular saws, providing a 92% DRE even when the LEV system was simply connected but not activated. Activating the LEV increased this DRE to roughly 98%. It should be noted that in the test condition when the LEV was connected but not activated, the air flow induced by the running blade and/or provided by the built-in blower (the C-R saw only) can still capture a certain amount of dust and direct it towards the vacuum cleaner. In practice, if the circular saws were simply connected to a dust bag, which did not have an exhaust, the flow would become blocked and most dust would not be removed, as was the case of the C-M saw when the dust collecting container was capped (Figure 17).

Although the C-R saw demonstrated the highest DRE among the three circular saws, it generated a larger amount of dust when the LEV was not connected (as shown in Table 3), possibly due to its much higher blade rotating speed (9068 RPM compared to 5663 RPM for the C-H saw and 5500 for the C-M saw). So the actual G_{APS} when the LEV was working needs to be compared. At the same saw cutting feed rate of 2.54 cm/sec and cutting one board at a time, the lowest G_{APS} was 0.090 g/m for the C-H saw, 0.029 g/m for the C-M saw, and 0.023 g/m for the C-R saw. The larger blade diameter of the C-H saw and C-M saw (18.4 cm or 7.25 inch, compared to 12.7 cm or 5.0 inch for the C-R saw) make them capable of cutting up to six boards at once. At the saw cutting feed rate of 2.54 cm/sec and cutting six boards at once, the lowest G_{APS} was 0.041 g/m for the C-H saw, and 0.010 g/m for the C-M saw, which was getting close to the G_{APS} of the power shear (0.006 g/m). These results suggest that cutting six boards using the C-M saw with the LEV system results in the lowest generation rate of respirable dust among all the test conditions for power saws in the laboratory evaluation.

Field Validation of the Laboratory Findings

From the two studies by Lofgren et al. [2004] and Qi et al. [2013a], the highest 8-hr TWA exposure to respirable crystalline silica observed without using controls was 0.17 mg/m³. If the DRE for the circular saws equipped with LEV ($\geq 81\%$) obtained in the laboratory evaluation could be translated into the same amount of reduction on workers' exposures, exposures below the NIOSH REL of 0.05 mg/m³ would be achievable. The results from the laboratory evaluation suggested that connecting a dust-collecting circular saw to a basic shop vacuum with built-in air filters, which

normally runs at a higher flow rate than 0.83 m³/min (29 CFM), had the potential to provide a simple and low-cost engineering control for the dust generated from cutting fiber-cement siding. It is referred to as the LEV control in this report. To validate the effectiveness of this engineering control measure, four field surveys were conducted to evaluate workers' exposures at construction sites where it was used to reduce exposure while cutting fiber-cement siding. Detailed information about the four field surveys were published in the survey reports by Qi et al. [2013b, 2014a, 2014b, 2014c].

In the surveys, a 12-gallon shop vacuum (model 586-62-11, Shop-Vac[®] Corporation, Williamsport, PA) was used to provide LEV for the dust-collecting circular saws used by the surveyed cutters. A vacuum hose was used to connect the saw's exhaust port to the shop vacuum. Figure 20 shows C-M saw and its connection to the shop vacuum. The shop vacuum came with a standard disposable filter bag (part number 90662, Shop-Vac[®] Corporation, Williamsport, PA) to trap most of the dust, and a standard Prolong cartridge filter (part number 90304, Shop-Vac[®] Corporation, Williamsport, PA) to capture the dust passing through the filter bag. In order to collect more dust in the filter bag, a high efficiency disposable filter bag (fine filtration bag, part number 90672, Shop-Vac[®] Corporation, Williamsport, PA) was used in this study, replacing the standard disposable filter bag. Since most of the dust was captured in the filter bag rather than in the cartridge filter, the life of the cartridge filter was greatly extended as evidenced in these field surveys [Qi et al., 2013b, 2014a, 2014b, 2014c].

The shop vacuum was rated to provide a 5.66 m³/min (200 CFM) flow rate by the manufacturer, which is sufficient to provide good LEV for the cutting task, based on the laboratory evaluation. However, the actual flow rate can be affected when the shop vacuum is connected to the filters and vacuum hose. More importantly, the flow rate might change due to dust loading on the filter bag and cartridge filter. Thus, a data logging pressure transducer (Smart Reader SRP-004-30G-128K 0-30 PSI-G, ACR Systems, Surrey, BC, Canada) was placed in the tank of the shop vacuum, between the filter bag and the cartridge filter in the flow path, to log the local absolute air pressure. Prior to the field surveys, a laboratory test found that the difference between the absolute air pressure in the shop vacuum tank when the shop vacuum was on and off was linearly correlated with the actual air flow rate, as measured using a Delta tube (model # 307BZ-11-AO, Mid-West Instrument, Sterling Heights, MI). In the laboratory study, the same experimental setup as shown in Figure 3 was used and the gate valves were used to adjust the air flow rate so that the correlation between the actual flow rate read from the Delta tube and the absolute air pressure difference from the data logging pressure transducer in the shop vacuum tank could be obtained. This correlation was used with the pressure data collected from the shop vacuums at the job sites to estimate their actual flow rates during the surveys. The flow rate of the LEV was in the range of 1.95-2.96 m³/min (69-105.8 CFM), which was well above the lowest flow rate tested in the laboratory evaluation of the LEV system. In the field surveys, a battery pack (model # BP-101, ACR Systems, Surrey, BC, Canada) was used

together with the data logging pressure transducer in the shop vacuums in order to obtain the vacuum tank pressure readings every 2 seconds.



Photo by NIOSH

Figure 20. The dust-collecting circular saw and its connection to the shop vacuum used in the field surveys.

In two of these four field surveys, another control measure by using a prototype circular saw with a built-in cyclone dust collector and an air filter was concurrently evaluated [Qi et al., 2014a and 2014b]. This prototype circular saw was developed by James Hardie Industries, and is referred to as the RS saw in this report. The RS saw collects dust in its built-in cyclone dust collector and air filter without using an external shop vacuum. It utilizes a shroud to cover the blade and the flow induced by the spinning blade to direct the dust to a built-in chamber which works as a cyclone dust collector to remove larger dust particles by their inertial effect. The cyclone chamber is inter-connected to another chamber on its side where an air filter is incorporated to remove the residual dust escaping from the cyclone.

Figure 21 shows a surveyed cutter cutting fiber-cement siding on his work bench using the LEV control. Figure 22 shows a picture of the RS saw with its main

components and Figure 23 shows a surveyed cutter cutting fiber-cement siding using the RS saw control.



Photo by NIOSH

Figure 21. A worker (cutter) cutting fiber-cement siding using a dust-collecting circular saw that was connected to a shop vacuum.

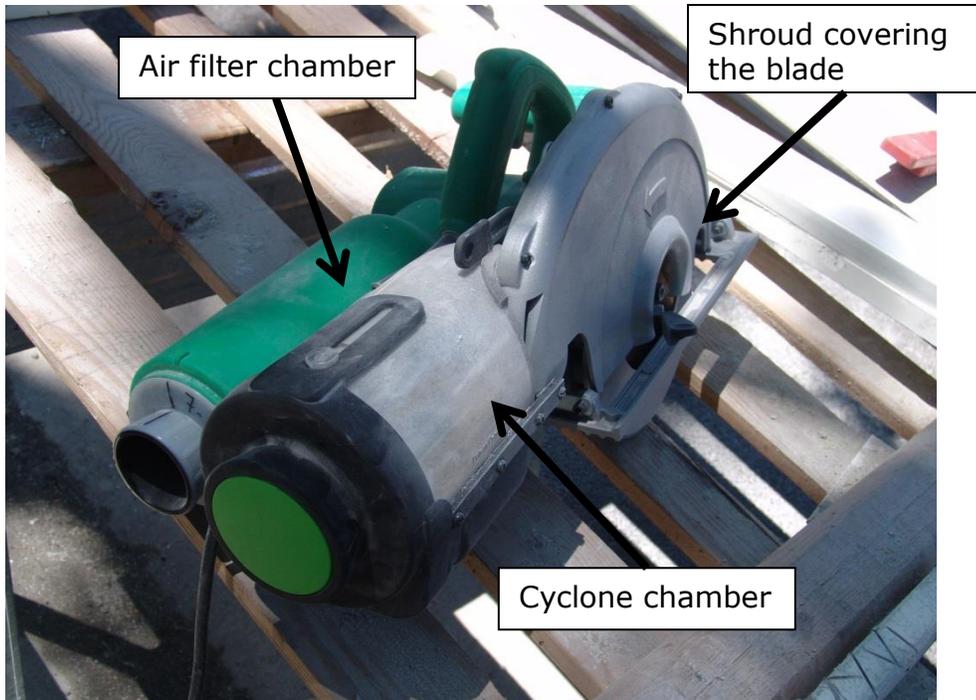


Photo by NIOSH

Figure 22 – The prototype RS saw with its built-in cyclone dust collector and air filter.



Photo by NIOSH

Figure 23 – A worker (cutter) cutting fiber-cement siding using a prototype circular saw with a built-in cyclone dust collector and an air filter (RS saw).

Table 4 provides a summary of the four field surveys. During the surveys, the cutters cut fiber-cement siding using the tested engineering control measures (as shown in Figure 21 and 23), and the installers mainly took the measurements, verbally communicated the size requirement to the cutters, and installed the siding. The fiber-cement siding used in these surveys was from James Hardie.

Table 4. Summary of the field surveys and exposure results

Survey Site	Survey Dates	Power Saw	Number of Cutters Surveyed	Respirable crystalline silica 10-hr/8-hr TWA concentration (mg/m ³) for the surveyed cutter	Number of Installers Surveyed	Respirable crystalline silica 10-hr/8-hr TWA concentration (mg/m ³) for the surveyed installer
Greensboro, GA [Qi et al., 2013b]	06/18/14 to 06/20/14	C-H	2	0.003-0.015/ 0.003-0.018	2	0.001-0.007/ 0.002-0.009
Glenview, IL [Qi et al., 2014a]	07/09/14 to 07/11/14	C-M	2	0.001-0.013/ 0.002-0.016	1	0.004-0.010/ 0.004-0.013
		RS	1	0.024-0.061/ 0.029-0.076		
Woodbury, MN [Qi et al., 2014b]	07/23/14 to 07/25/14	C-M	1	0.013-0.033/ 0.016-0.041	0	n/a
		RS	1	0.016-0.087/ 0.019-0.108		
Huntsville, AL [Qi et al., 2014c]	09/24/14 to 09/26/14	C-M	2	0.007-0.024/ 0.008-0.029	0	n/a

Note: n/a means "not available"

Statistical analyses were performed using SAS v12.1 (SAS Institute Inc.). From the workers participating in the four surveys, we obtained 21 10-hr/8-hr TWA exposure measurements for cutters using the LEV control, 6 measurements for cutters using the RS saw control, and 12 measurements for installers. The exposure data were found to be log-normally distributed (based on the Shapiro-Wilk test) for each group of workers and they were used in the statistical calculation for respirable crystalline silica TWA concentrations. The summary statistics are listed in Table 5.

As listed in Table 5, the exposures for the cutters using the LEV control were well below the NIOSH REL of 0.05 mg/m³ for respirable crystalline silica 10-hr TWA concentration, with the 95% upper confidence limit being only 24% of the NIOSH REL. The 95% upper confidence limit of 8-hr TWA exposures was also only 60% of the ACGIH[®] Threshold Limit Value (TLV[®]) of 0.025 mg/m³. The geometric standard deviation for these cutters' exposure data was 2.06. The exposure level for the installers was about half of that for the cutters using the LEV control, and the

geometric standard deviation for the installers' exposure data was 1.67. However, the exposures for the cutters using the RS saw control were considerably higher, with the geometric mean of the 10-hr TWA concentration being 0.040 mg/m³, which was 5 times of that for the LEV control (0.008 mg/m³). But it was still 20% lower than the NIOSH REL. The 95% lower and higher confidence limits of the 8-hr TWA concentration for these cutters were 0.023 and 0.105 mg/m³, respectively.

Table 5. Summary Statistics for the exposure results from the field surveys

Job Type	Control Type	TWA Type	Number of TWA	Geometric Mean (mg/m ³)	Lower 95% Confidence Limit (mg/m ³)	Upper 95% Confidence Limit (mg/m ³)	Geometric Standard Deviation
cutters	LEV	10-hr TWA	21	0.008	0.006	0.012	2.06
		8-hr TWA	21	0.011	0.008	0.015	2.06
	RS saw	10-hr TWA	6	0.040	0.019	0.084	2.04
		8-hr TWA	6	0.049	0.023	0.105	2.08
installers	n/a	10-hr TWA	12	0.004	0.003	0.006	1.67
		8-hr TWA	12	0.005	0.004	0.007	1.67

Note: n/a means "not available"

In order to statistically validate the effectiveness of the LEV control, further analyses were performed using the combined data set for all the cutters from the above four field surveys as well as from the previous field survey [Qi et al., 2013a], which did not use any control measures. The respirable crystalline silica 10-hr TWA concentrations in the combined data set (31 10-hr TWA exposure measurements) were also log-normally distributed based on the Shapiro-Wilk test. A SAS mixed model procedure followed by the Tukey-Kramer adjusted multiple comparison was used to examine the determinants of exposure. The model set the logarithm of the 10-hr TWA respirable silica concentration as the dependent variable, treated the survey site as a random factor, and included other factors such as control measure, wind speed, wind direction, temperature, relative humidity and workers' productivity as covariance variables. Control measure, as used in the model included three scenarios, i.e., no control, the LEV control, and the RS saw control. During each survey, the NIOSH researchers used a Kestrel model 4500 Weather Meter (Nielsen-Kellerman Co., Boothwyn, PA) to log the wind speed, wind direction, temperature, and relative humidity at the construction site. The averaged data during the sampling period corresponding to each TWA concentration measurement was used in the model. The survey reports [Qi et al., 2013a, 2013b, 2014a, 2014b, and 2014c] described the data processing in detail. The worker's productivity is defined as the mass of crystalline silica in the removed material from cutting fiber-cement siding per unit time during the sampling period corresponding to each TWA concentration measurement. It was measured by using the board density and averaged silica content reported by the siding manufacturers, and counting the

number of cuts, their length, the number of boards stacked and cut, and the thickness of each board cut during each sampling period.

Table 6. The p-value from a mixed model for factors on exposure to respirable crystalline silica 10-hr TWA concentration.

Factor	Control Measure	Wind Speed	Wind Direction	Temperature	Relative Humidity	Worker Productivity
p-value	0.0007	0.0396	0.4094	0.3505	0.3330	0.4163

Table 6 reports the p-value for each factor in the mixed model. Both control measure ($p=0.0007$) and wind speed ($p=0.0396$) were statistically significant in terms of affecting the TWA respirable silica exposure. Since the model treated the survey site as a random factor, the p-value of 0.0007 for control measure confirms that the lower exposure level listed in Table 5 for the workers using the LEV control is statistically significant, and it can be applied to the population of sites from which the random sites were chosen. Therefore, the effectiveness of this control measure is statistically validated. The p-value of 0.0396 for wind speed suggests that wind speed played an important role in reducing worker's exposure to respirable crystalline silica while cutting fiber-cement siding. This is possibly due to the fact that wind could be considered natural ventilation, blowing the dust away from the workers. However, the dust carried away by wind could be a potential hazard for other people working downwind from the source at the construction site. Thus, removing the dust by LEV is preferred. The p-value of the other factors in Table 6 indicates that they did not have a statistically significant effect upon a worker's TWA respirable crystalline silica exposure. This is most likely because the effect from the control measure is so dominant that the effect from these factors becomes insignificant in this particular model.

It should be noted that the respirable dust cyclone sampler used in the field surveys was model GK2.69 from BGI Inc (Waltham, MA) and the sampling flow rate used was 4.2 L/min. Its performance was characterized experimentally in the laboratory by Kenny and Gussman [1997], and more recently by Lee et al. [2010]. At the flow rate of 4.2 L/min, Lee et al. observed a larger sampling efficiency for dust larger than 6 μm comparing to the result from Kenny and Gussman as well as the respirable convention curve. Over sampling of the larger dusts may result in an overestimation of the exposure level. This bias may be particularly apparent for this study as the larger dusts from cutting fiber-cement siding were found containing a larger percentage of silica as shown in Figure 7. Assuming the dust size distribution and the silica distribution in the dust of difference sizes are the same in the laboratory evaluation and the field surveys, we estimated that the bias on the exposure to respirable crystalline silica using the GK2.69 sampler comparing to the exposure level based on the respirable convention curve was +1.5% when using the data from Kenny and Gussman [1997], and +12.3% using the data from Lee et al. [2010].

Limitations of the Control Measure

Both the laboratory evaluation and field surveys suggest that the tested LEV control measure works effectively by removing dust at its source and reducing workers' exposure to respirable crystalline silica while cutting fiber-cement siding. A couple of drawbacks of this engineering control measure were also observed during the field survey. The vacuum hose may collide with the work bench during cutting, especially for long rip cut of lap sidings or cutting panel sidings. Some improvement on this issue may be needed to help workers maintain their productivity while engaging the engineering control measure. Another issue is that the dust-collecting container of the C-M saw often blocks the cutters' view of the blade, which was preferred to be avoided by most workers. The shroud used in the C-H and C-R saws does not have this issue. However, the C-H saw has been discontinued since 2013.

The effectiveness of an air filter is normally rated by its Minimum Efficiency Reporting Value (MERV), which was designed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). However, the manufacturer of the shop vacuum used in the field surveys did not provide such ratings for its filters. The exhaust air of the shop vacuum could potentially still carry some respirable crystalline silica after passing through the filter bag and cartridge filter. If this occurred, it might get inhaled by nearby workers. The exposure levels for the workers using the LEV control in this study included any contributions from this effect. Although evaluating the filtration efficiencies of these air filters and the amount of crystalline silica in the exhaust air of the shop vacuum was beyond the scope of the current study, it is worth noting that using shop vacuums that incorporate filters with lower efficiencies than those used in this study could result in higher exposure levels for the workers.

Conclusions/Recommendations

Controlling exposures to occupational hazards is the fundamental method of protecting workers. Traditionally, a hierarchy of controls has been used as a means of determining how to implement feasible and effective controls. One representation of the hierarchy controls can be summarized as follows:

- Elimination
- Substitution
- Engineering Controls (e.g. ventilation)
- Administrative Controls (e.g. reduced work schedules)
- Personal Protective Equipment (PPE, e.g. respirators)

The idea behind this hierarchy is that the control methods at the top of the list are potentially more effective, protective, and economical (in the long run) than those at the bottom. Following the hierarchy normally leads to the implementation of inherently safer systems, ones where the risk of illness or injury has been substantially reduced.

In the laboratory evaluation of this study, the dust generated by cutting fiber-cement siding from four manufacturers using a variety of power tools was characterized in detail. The overall size distribution and generation rate of respirable dust by cutting fiber-cement siding from the four manufacturers were found very close to each other. The size distribution of the airborne dust showed a bimodal distribution, with a larger mode around 13 μm , and another mode smaller than 5 μm . The overall respirable fraction of the airborne dust from cutting fiber-cement siding of the four manufacturers was estimated to be in the range of 37.8% to 48.8%, and the content of crystalline silica in their respective respirable dusts was estimated to be in the range of 1.2% to 9.3%. Analysis of size-selective samples collected by MOUDI revealed that the dust from cutting fiber-cement siding of the four manufacturers had the same trend of increasing silica content occurring with increases in the aerodynamic diameter of the dust, approaching to the silica content levels found in their respective bulk samples. This result suggested that most crystalline silica distributes in larger dusts, which have less respirable fraction and are likely be well controlled by LEV equipped with regular air filters instead of high-efficiency particulate air (HEPA) filters.

The results from the laboratory test also suggest that the number of teeth on the saw blade and the blade rotating speed in the tested range are likely two dominant factors affecting the dust generation rate for cutting fiber-cement siding, with the saw blade having fewer number of teeth and the saw running at lower blade rotating speed generating considerably less amount of respirable dust. Miter saws evaluated in this study generated less respirable dust when operated under the "chopping only" mode compared to the "chopping and sliding" mode. For miter saws operated under the "chopping and sliding" mode and all the circular saws evaluated in this study, the generation rate of respirable dust, which was defined in Equation (2) as the total mass of respirable dust generated per unit linear length of cut of fiber-cement siding, was lower when the saw cutting feed rate was higher in the tested range. The generation rate of respirable dust was also found lower when stacking more board to cut at one time.

From the laboratory evaluation of the LEV, the DRE for the four miter saws was about 65% or less, even at the highest tested flow rate of 3.97 m^3/min (140 CFM). In addition, increasing the flow rate of the LEV did not lead to an equivalent increase on the DRE. This is mainly due to the design limitations of these miter saws in terms of dust collection. The test for the three dust-collecting circular saws connected to the laboratory LEV system showed that more than 78% of the respirable dust from cutting fiber-cement siding can be removed, even at a low flow rate of 0.83 m^3/min (29 CFM). The lowest generation rate of respirable dust was achieved by using the C-M saw to cut six boards at once in a stack with the LEV implemented. These results suggested that connecting a dust-collecting circular saw to a basic shop vacuum with built-in air filters, which normally runs at a higher flow rate than 0.83 m^3/min (29 CFM), had the potential to provide a simple and low-cost engineering control for the dust generated from cutting fiber-cement siding. Through four field surveys using a basic shop vacuum, which was equipped

with a high efficiency disposable filter bag and a filter cartridge, to provide the LEV and remove the dust while cutting fiber-cement siding, the effectiveness of this engineering control measure was validated. The statistics from the field survey results showed that the 95% upper confidence limit for 10-hr TWA exposure to respirable crystalline silica was only 24% of the NIOSH REL of 0.05 mg/m³. These results indicate that this engineering control measure effectively controlled the dust emissions, reduced the workers' exposures, and provided an effective, simple and low cost solution for workers cutting fiber-cement siding. The use of this type of engineering control technology for the dust-collecting circular saws is a preferred solution and adheres to the hierarchy of controls.

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