In-Depth Survey Report

DUST-CONTROL TECHNOLOGY FOR ASPHALT-PAVEMENT MILLING Controlled-site testing at State Highway 47, Bonduel, Wisconsin

Conducted with assistance from the Silica/Milling-Machines Partnership, affiliated with and coordinated through The National Asphalt Pavement Association (NAPA)

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Division of Applied Research and Technology
Engineering and Physical Hazards Branch
EPHB Report No. 282-18a

December 2011

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Site Surveyed: State Highway 47, Bonduel, Wisconsin

NAICS Code: 237310 (Highway, Street, and Bridge Construction)

Survey Dates: August 9 -18, 2010

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Acknowledgments

The authors thank the members of the Silica/Milling-Machines Partnership, especially the National Asphalt Pavement Association, the participating manufacturers including the manufacturers of the milling machines tested during this field study, Partnership Chair Tony Bodway and his company, Payne and Dolan, Northeast Asphalt, the Association of Equipment Manufacturers (AEM), the International Union of Operating Engineers (IOUE), and the Laborers' International Union of North America (LIUNA), for their efforts on behalf of this study and for their assistance in arranging and conducting this field study.

Table of Contents

Abstract

In 2010, NIOSH researchers and the Silica/Milling-Machines Partnership coordinated by the National Asphalt Pavement Association (NAPA), evaluated dust emission-control systems for five pavement-milling machines on State Highway 47 south of Bonduel, Wisconsin. To suppress dust, water spray controls were installed on all five milling machines and a local exhaust ventilation control was installed on one machine. The tests consisted of numerous, replicate short-term milling trials (nominally about 6 minutes each in duration). During a trial, a test milling machine removed approximately 3 inches of depth of the asphalt surface while operating either its existing production water-spray system (the “baseline configuration”), or one of its modified test emission-control configurations. During the trials, respirable-dust concentrations were measured at ten selected locations around each mill using continuous real-time data-logging dust monitors. The results from six key monitoring locations (from among the ten) together are considered to best represent dust-emission rates, because they surround the low-to-the-ground dust-generating areas of the machine where the modified emission controls are located. Trial-mean concentrations from these “lower-six” locations were averaged together to obtain a single lower-six-location average for that trial. The average lower-six result for the baseline dust-control configuration in a set was compared with that for each of the modified test configurations in that set. Dust-emission reductions were computed for each test configuration versus the baseline in that set. Average reductions across all sets for that machine were computed, along with their statistical confidence intervals.

For the lower six sampling locations, statistically significant reduction in mean respirable dust concentrations of 81% and 69% occurred during testing of configurations D21 and D3 which were local exhaust ventilation configurations at medium and low fan speeds of approximately 1500 actual cubic feet per minute (acfm) and 1000 acfm of air. The reductions in mean respirable dust concentrations at the lower-six sampling locations were not statistically significant for any of the evaluated water spray configurations. For the operator bridge sampling location, statistically significant reductions in mean respirable dust concentrations of 77%, 65%, 59%, and 44% were measured during testing of configurations D21, D3, E23, and E22, respectively. No other evaluated configurations resulted in statistically significant reductions at the operator bridge. Based on the results from this and previous studies, the NIOSH researchers recommend additional testing of the wet drum design and optimization of local exhaust ventilation systems as the primary control method for reducing respirable crystalline silica during asphalt pavement milling.

Introduction

Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC) 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 technology 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

NIOSH is conducting a research study of the effectiveness of dust-emission control measures during asphalt pavement-milling operations. The initial aim of this project is to determine if the dust emission-control systems installed on new pavement-milling machines and operated according to the manufacturers' recommendations are adequate to control worker exposures to respirable dust, especially that containing crystalline silica, a long-recognized occupational respiratory hazard. Chronic over-exposures to such dust may result in silicosis, a chronic progressive lung disease that eventually may be disabling or even fatal, and an increased risk of lung cancer [NIOSH 2002]. The long term goal of this project is to adequately control worker exposures to respirable dust and crystalline silica by providing data to support the development of a set of best practice guidelines for the equipment if the engineering controls are adequate, or to develop a set of recommendations to improve the performance of controls if they are not adequate.

Many construction tasks have been associated with overexposure to crystalline silica [Rappaport et al. 2003]. Among these tasks are tuck pointing, concrete sawing, concrete grinding, and abrasive blasting [NIOSH 2000; Thorpe et al. 1999; Akbar-Kanzadeh and Brillhart 2002; Glindmeyer and Hammad 1988]. Road milling has also been shown to result in overexposures to respirable crystalline silica [Linch 2002; Rappaport et al. 2003; Valiante et al. 2004]. However, all three of those road-milling studies are limited because they do not provide enough information about the operating parameters and engineering controls present on the milling machines to determine if the overexposures were due to a lack of effective controls or poor work practices. This study is helping to fill that knowledge gap.

A variety of machinery and work practices are employed in asphalt pavement recycling, including cold-planers, heater planers, cold-millers, and heater-scarifiers [Public Works 1995]. Cold-milling, which uses a toothed, rotating drum to grind and remove the pavement to be recycled, is primarily used to remove surface deterioration on both petroleum-asphalt aggregate and Portland-cement concrete road surfaces [Public Works 1995]. The milling machines used in cold-milling are the focus of this investigation.

This field research evaluated and compared the performance of several milling machines' existing and modified prototype systems for the control of emissions of respirable dust. Numerous short-term milling trials were conducted at a closed, controlled test site, using each dust emission-control system, and respirable-dust concentrations in the air surrounding the test mills were measured and compared.

This study is facilitated by the Silica/Milling-Machines Partnership, which is affiliated with and coordinated through the National Asphalt Pavement Association (NAPA). The partnership includes NAPA itself, the Association of Equipment Manufacturers, the manufacturers of almost all pavement-milling machines sold in the U.S., numerous construction contractors, employee representatives, NIOSH, and other interested parties.

Previous Silica/Milling Machines Studies

NIOSH researchers collaborated with the Silica/Milling-Machines Partnership to conduct field research on respirable-dust and crystalline-silica exposures and exposure controls from 2003 through 2008. With the assistance of the Partnership in identifying pavement-milling job sites appropriate for study and in arranging for the field work, NIOSH researchers completed a pilot field survey [Echt et al. 2004], four in-depth field surveys from 2004 to 2006 [Echt et al. 2007; Blade et al. 2009a; Blade et al. 2009b; Blade et al. 2009c], and a large study of four milling machines in 2008 [Blade et al. 2011]. However, the road-milling job evaluated during the pilot study was not considered representative of typical jobs. It was a "full-depth removal" job, which is relatively uncommon, and therefore the subsequent field surveys evaluated so-called "mill-and-fill" jobs, which are perhaps the most common. Therefore, the data developed from the pilot survey is not judged to be appropriate for inclusion among the overall study findings.

The following conclusions are based on the research conducted on controls from five different manufacturers from 2003 to 2008:

(1) During the first four studies, NIOSH researchers collected personal breathing zone samples by hanging personal sampling pumps and sampling media on operators and ground crew from multiple manufacturers of cold-milling machines with water-flow dust suppression controls operated at normal and maximum water flow rates. When using water-flow dust suppression, personal breathing zone sampling results for respirable crystalline silica varied dramatically by manufacturer, by study site, and within study site. Between 2004 and 2006, 56 personal breathing zone samples of respirable crystalline silica exposures were collected at four different highway sites from four different milling machines. Three of the 12 personal breathing zone samples from the 2004 study in Wisconsin were below the limit of detection and the remaining nine ranged from 0.04 to 0.17 milligrams (mg) of respirable crystalline silica per cubic meter (m^3) of air [Echt et al. 2007]. Five of the 12 personal breathing zone samples from the 2006 study in Minnesota were below the limit of detection while the remaining 7 samples ranged from 0.02 to 0.06 mg/m^3 [Blade et al. 2006a]. All 22 personal breathing zone samples from the 2006 testing in South Dakota were below the limit of detection [Blade et al. 2009b]. The 10 personal breathing zone samples from the 2006 study in New York ranged from 0.016 to 0.36 mg/m^3 [Blade et al. 2009c].

(2) In addition to evaluating worker exposures using personal breathing zone sampling, controls were evaluated by measuring the reduction in respirable dust in area samples mounted to the cold-milling machines of five manufacturers. Between 2003 and 2008, testing of water-spray dust suppression controls indicated that raising the water flow rate of the milling-machine water-spray systems from the "normal" rate to the maximum rate did not consistently reduce respirable dust concentrations by an appreciable and statistically significant amount. The data revealed appreciable reductions in some cases but not in others.

(3) The local exhaust ventilation control tested in 2008 resulted in the largest reduction in respirable dust concentrations of approximately 60% when compared to the baseline respirable dust concentration on the same machine [Blade et al. 2011].

After the 2008 testing at the Marquette, MI airport runway [Blade et al. 2011], the Silica/Milling-Machines Partnership members decided to conduct another large study in 2010 to further optimize controls to reduce emissions of respirable dust and crystalline silica. The 2010 study included participation from five major manufacturers representing the majority of the U.S. market share for asphalt pavement milling and the results are summarized in this report.

Occupational Exposure Limits and Health Effects

As a guide to the evaluation of the hazards posed by workplace exposures, NIOSH investigators use mandatory and recommended OELs when evaluating chemical, physical, and biological agents in the workplace. Generally, OELs suggest levels of exposure to which most workers may be exposed up to 10 hours per day, 40 hours per week for a working lifetime without experiencing adverse health effects. It is, however, important to note that not all workers will be protected from adverse health effects even though their exposures are maintained below these levels. A small percentage may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or hypersensitivity (allergy). In addition, some hazardous substances may act in combination with other workplace exposures, the general environment, or with medications or personal habits of the worker to produce health effects even if the occupational exposures are controlled at the level set by the exposure limit. Combined effects are often not considered in the OEL. Also, some substances are absorbed by direct contact with the skin and mucous membranes, and thus can increase the overall exposure. Finally, OELs may change over the years as new information on the toxic effects of an agent become available.

Most OELs are expressed as a TWA exposure. A TWA exposure refers to the average airborne concentration of a substance during a normal 8- to 10-hour workday. Some substances have recommended STEL or ceiling values which are intended to supplement the TWA where there are recognized toxic effects from higher exposures over the short-term.

In the U.S., OELs have been established by Federal agencies, professional organizations, state and local governments, and other entities. The U.S. Department of Labor OSHA Permissible Exposure Limits (PELs) [29 CFR 1910.1000] are occupational exposure limits that are legally enforceable in covered workplaces under the Occupational Safety and Health Act. NIOSH recommendations are based on a critical review of the scientific and technical information available on the prevalence of health effects, the existence of safety and health risks, and the adequacy of methods to identify and control hazards [NIOSH 1992]. They have been developed using a weight of evidence approach and formal peer review process. Other OELs that are commonly used and cited in the U.S. include the Threshold Limit Values (TLVs®) recommended by American Conference of Governmental Industrial Hygienists (ACGIH®), a professional organization [ACGIH® 2010]. ACGIH® TLVs® are considered voluntary guidelines for use by industrial hygienists and others trained in this discipline “to assist in the control of health hazards.” Workplace Environmental Exposure Limits (WEELs) are recommended OELs developed by the American Industrial Hygiene Association (AIHA), another professional organization. WEELs have been established for some chemicals “when no other legal or authoritative limits exist.” [AIHA 2007].

OSHA requires an employer to furnish employees a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious physical harm [Occupational Safety and Health Act of 1970, Public Law 91–596, sec. 5(a)(1)]. Thus, employers are required to comply with OSHA PELs. Some hazardous agents do not have PELs, however, and for others, the PELs do not reflect the most current health-based information. Thus, NIOSH investigators encourage employers to consider the other OELs in making risk assessment and risk management decisions to best protect the health of their employees. NIOSH investigators also encourage the use of the traditional hierarchy of controls approach to eliminating or minimizing identified workplace hazards. This includes, in preferential order, the use of: (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation) (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection).

Occupational Exposure to Crystalline Silica

Silicosis is an occupational respiratory disease caused by inhaling respirable crystalline-silica dust. 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. Exposure to respirable crystalline silica dust occurs in many occupations, including construction. Crystalline silica refers to a group of minerals composed of chemical compounds containing the elements silicon and oxygen; a crystalline structure is one in which the molecules 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 refers to that portion of airborne crystalline silica 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].

When proper practices are not followed or controls are inadequate or not maintained, respirable crystalline silica exposures can exceed the NIOSH Recommended Exposure Limit (REL), the OSHA PEL, or the ACGIH® TLV® [NIOSH 2002; 29 CFR 1910.1000 and 29 CFR 1926.55; ACGIH® 2009]. The NIOSH REL is 0.05 mg/m^3, for a full-workshift time-weighted average exposure, for up to a 10-hour workday during a 40-hour workweek. This level is intended to minimize exposed workers' risks of developing silicosis, lung cancer, and other adverse health effects.

The OSHA general-industry PEL for airborne respirable dust containing 1% or more crystalline silica is expressed as an equation. For quartz, the following equation applies [29 CFR 1910.1000]:

$$\text{Respirable PEL} = \frac{10\ \text{mg/m3}}{\%\ \text{Silica} + 2}$$

If, for example, the dust contains no crystalline silica, the PEL for an 8-hour time-weighted average exposure is 5 mg/m^3; if the dust is 100% crystalline silica, the PEL is 0.1 mg/m^3. For cristobalite and tridymite, the PELs are each one half the value obtained with the above equation [29 CFR 1910.1000]. When more than one of these three forms of crystalline silica are present, the additive mixture formula in 29 CFR 1900.1000 must be applied to the individually determined PELs.

In contrast to the general-industry PEL, the construction-industry PEL for airborne respirable dust which contains crystalline silica is based upon measurements made with impinger sampling and particle counting, and is expressed in millions of particles per cubic foot (mppcf) of air in accordance with the following formula [29 CFR 1926.55]:

$$\text{Respirable PEL} = \frac{250\ \text{mppcf}}{\%\ \text{Silica} + 5}$$

The “Mineral Dusts” table in 29 CFR 1926.55 specifies the above equation to determine the PEL for 8-hour time-weighted average exposures to quartz. No limits are specified in the table for other forms of crystalline silica such as cristobalite or tridymite. Since the PELs were adopted, impinger sampling and particle-counting methodology has been rendered obsolete by respirable size-selective sampling and gravimetric analysis such as that used to determine compliance with the general-industry PEL for silica, and the latter is the only methodology currently available to OSHA compliance personnel [OSHA 2008]. To allow for comparison of gravimetric results reported in mg/m^3 with the mppcf PEL in 29 CFR 1926.55, OSHA has further specified that a conversion factor of 0.1 mg/m^3 per 1 mppcf should be applied to the results of gravimetric respirable-dust samples [OSHA 2008].

The ACGIH® TLV® for airborne respirable crystalline silica, including both quartz and cristobalite, is 0.025 mg/m^3 for an 8-hour time-weighted average exposure [ACGIH® 2009].

Methodology

Performance testing of the prototype dust-emission controls was conducted in August 2010 for five manufacturers’ milling machines on a closed road, State Highway 47, Bonduel, Wisconsin. Each manufacturer modified a large, new or late-model milling machine to allow testing of multiple dust-suppression and emission-control systems on a single machine. The emission-controls systems tested included a “baseline” or existing production configuration and at least one and as many as six modified, prototype “test” configurations, depending on the milling machine manufacturer.

Ten real time, data-logging optical particle counters (pDR instruments) were mounted at fixed locations on each machine. Six key locations were chosen that best represented the areas where dust was generated; these areas were the focus of the dust emission-control measures and included the cutter housing and the primary-to-secondary material-conveyor transition point. The six key monitoring locations were four locations around the cutter housing and two locations on either side of the primary-to-secondary material-conveyor transition point. The other four monitoring locations include both sides of the operator's bridge and both sides of the top of the conveyor. Data from these four locations supplement the data from the six key locations.

Multiple sets or blocks of trials, with each set testing the baseline and each modified configuration in randomized order, were conducted and the average concentration at each location during each trial was determined. A typical trial was about 6 minutes in duration. The mean of these six key location average concentrations (referred to as the "lower-six source location" mean concentration) for each modified configuration tested within a set was compared with the mean for the baseline configuration tested within that set. Ratios of modified-to-baseline values were calculated. The reduction in mean "lower-six source location" concentration is used as a surrogate for reduction in respirable dust-emission rate from the primary source areas. Ratios were also computed for modified-to-baseline values for the operator bridge and conveyor top sampling locations.

Water flow and pressure

Water flow rates were measured using digital water-flow meters (GPI Electronic Digital Meter, Model S10N, Great Plains Industries, Wichita, KS) with a range of 5 to 50 gallons per minute (gpm) installed in the main water-supply lines on the mills. Water pressure was measured using a standard analog pressure gauge attached to "tee" fittings also installed in the main water lines. The readings on these devices were observed and recorded during each milling trial.

Depth and width of cut, wind speed and direction, temperature, vehicle speed

Depth of cut was measured during each set using a tape measure held at the edge of the cut pavement. The width of the cut was measured as well. Ambient air temperature, wind speed, and direction were continuously monitored and recorded using weather-station instruments (Model 26800, R.M. Young Co., Traverse City, MI) operating in the real-time monitoring mode, with data logging for subsequent computer download. Each device's sensors were mounted atop a pole attached to the operator-bridge railing of one of the test milling machines. Speed was also recorded during both days of milling by a NIOSH researcher recording the speed reading on the instrument panel of the mill during each set.

Respirable-dust and crystalline-silica air-sampling measurements

During all milling trials, area air samples for respirable dust and crystalline silica were collected at ten locations on the milling machine, using an array of instruments mounted on a metal frame at each location. The locations were on the railings on both sides of the operator's platform, near the front and the rear of the cutter-drum housing on both sides of the mill, on both sides near the transition from the primary conveyor to the secondary conveyor, and on both sides at the top of the secondary-conveyor boom near the discharge of the secondary conveyor into the trucks. These locations are shown in Figure 1. The sampling instruments in each array included a light-scattering aerosol photometer (pDR, Model 1000, MIE, Inc., Bedford, MA) operated in the passive-sampling, real-time monitoring mode, with data logging at 10-second-intervals for subsequent computer download.

Also included in each sampling array at each of the ten sampling locations were two air-sampling assemblies for the collection of time-integrated respirable-dust samples. Each sampler assembly consisted of a battery-operated sampling pump (Escort Elf Pump, Mine Safety Appliances Company, Pittsburgh, PA) connected through flexible tubing to a sampling head consisting of a standard 10-mm, nylon, respirable size-selective cyclone followed by a pre-weighed, 37-mm diameter, 5 micron (µm) pore-size polyvinyl chloride filter supported by a backup pad in a two-piece filter cassette sealed with a cellulose shrink band, in accordance with NIOSH Methods 0600 and 7500 [NIOSH 1994]. Each sampling pump drew air at a nominal air-flow rate of 1.7 liters per minute (L/min) through the cyclone and filter assembly. Actual air-flow rates were measured before and after each day of testing, and flow rates adjusted to the nominal rate as needed. The primary purpose of these area samples was to measure the time-integrated respirable-dust concentration and the quartz content of the respirable dust for each sampling location for each entire day. The mean of the resulting two respirable-dust concentrations was used to establish the corrected mean for all respirable-dust concentration measurements on that day from the pDR instrument at that location. This allowed a correction factor to be determined that was then applied to each respirable-dust concentration measurement from that instrument on that day. The secondary purpose of these samples is to determine the crystalline-silica content of the airborne respirable dust at each location for each full day.

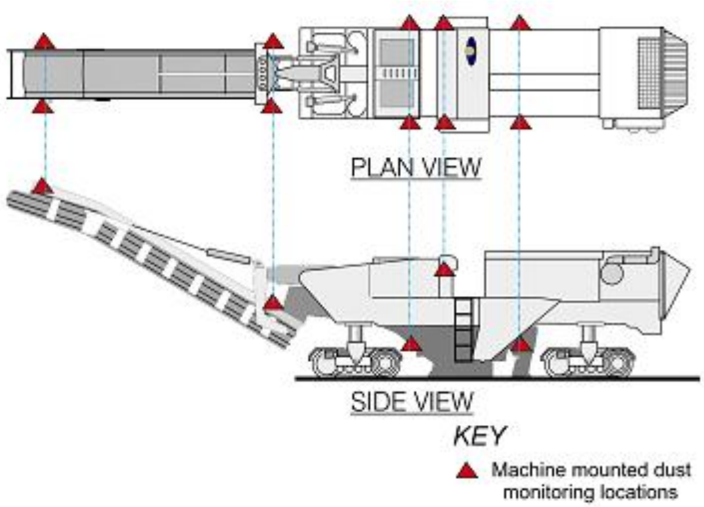

Figure 1. Diagram of typical pavement-milling machine showing 10 area air-sampling locations. (Front of machine is to the left)

Gravimetric analysis of each filter for respirable particulate was carried out the NIOSH Office of Mine Safety and Health Research (OMSHR) in accordance with NIOSH Method 0600. After this analysis was completed, crystalline silica analysis of each filter was performed Bureau Veritas North America using X-ray diffraction in accordance with NIOSH Method 7500. The samples were analyzed for quartz, cristobalite, and tridymite.

Bulk-material sampling and analysis for crystalline-silica

Bulk-material samples of asphalt-pavement material milled during this study were collected in screw-cap glass vials for crystalline-silica analysis. Analysis of each sample was performed by Bureau Veritas North America using X-ray diffraction in accordance with NIOSH Method 7500. The samples were analyzed for quartz, cristobalite, and tridymite.

Experimental design and methodology

This testing was performed on new or late-model highway-class milling machines with the latest production water-spray configurations. Each machine was modified with additional dust emission-control elements to allow replicate sequential testing of the production dust emission-control configuration (baseline) and multiple modified, prototype dust-control configurations using the same machine. During the testing, milling parameters such as depth and forward speed were chosen to mimic “mill-and-fill” highway resurfacing jobs, since these are the most commonly encountered milling jobs.

This field study consisted of a series of 6 minute trials, to test the respirable-dust emission-control performance of pavement-milling machines equipped with prototype emission-control systems. The decision to use six minute trials was based on the results of the 12 minute trials used during the 2008 study [Blade et al

2011]. Analysis of the results from the 2008 study indicated that when the ratio (test configuration /baseline) for a 12-minute trial was small (less than 0.4), there was a similarly small ratio for the first six minutes of that trial.

During each trial, one of the emission-control systems was operated while the machine milled a section of asphalt pavement, and respirable-dust concentrations were measured at ten locations (described above in the measurement methods description) around the machine being tested. Five milling machines were evaluated from Manufacturers A, B, C, D and E during the study which was conducted in August of 2010. Tests conducted with a given machine were grouped into sets, each of which included one trial to evaluate each configuration, conducted in randomized order within the set.

Control Technology

Description of tested dust-emission control configurations

All production milling machines are equipped with water-spray systems to cool the cutting teeth and suppress dust, and most of the modified test configurations involved additional spray nozzles and/or variations in water pressures and flows. Manufacturer D also tested a prototype local exhaust-ventilation system to produce negative static pressure in the cutter housing and the discharge area from the housing to the primary conveyor. The mill from Manufacturer A was tested with the mill’s existing, baseline configuration and one modified test configuration. The mills from Manufacturers B and D were each tested with the mill’s baseline configuration plus five modified configurations. The mill from Manufacturer C was tested with the mill’s baseline configuration plus six modified configurations. The mill from Manufacturer E was tested with the mill’s baseline configuration plus three modified configurations. Tables 1 through 5 summarizes each manufacturer’s modified test configurations and how they differed from their standard-production, or baseline, configurations. Table 6 summarizes cutting speed, depth, width, removal rate, water flow rate, and percent water to asphalt removed by weight during each configuration for all five evaluated milling machines.

Table 1: Manufacturer A spray configurations

Location	Number of Nozzles	Nozzle Model	Spray Type	Spray Angle	Flow per Nozzle	Total Flow
Configuration A1 (Baseline configuration)						
Drum Housing	20	UniJet* PU-11003-SS	flat	123° @ 200 psi	0.91 GPM @ 362 PSI	18.2 GPM @ 362 PSI
Primary Transition	2	UniJet TPU-11003-SS	flat	123° @ 200 psi	0.91 GPM @ 362 PSI	1.82 GPM @ 362 PSI
Secondary Transition	2	UniJet TPU-11003-SS	flat	123° @ 200 psi	0.91 GPM @ 362 PSI	1.82 GPM @ 362 PSI
Configuration A21						
Drum Housing	10	UniJet TG-SS-10SQ	square	66° @ 20 PSI	1.5 GPM @ 23 PSI	15 GPM @ 23 PSI
Primary Transition	2	UniJet TG-SS-14W	wide angle cone	120° @ 10 PSI	2 GPM @ 23 PSI	4 GPM @ 23 PSI
Secondary Transition	2	UniJet TG-SS-14W	wide angle cone	120° @ 10 PSI	2 GPM @ 23 PSI	4 GPM @ 23 PSI

*Spraying Systems Co. manufacturers UniJet model nozzles

Table 2: Manufacturer B spray configurations

Location	# of Sprays	Nozzle Model*	Spray Type	Spray Angle	Flow per Nozzle	System status for each configuration					
						B1	B2	B21	B22	B23	B24
Rear Drum Housing	11	QHA-10SQ	square	67° @ 20 psi	1.5 GPM @ 23 psi	On	On	On	On	On	On
Front Drum Housing	5	QHA-10	solid cone	67° @ 20 psi	1.5 GPM @ 23 psi	On	-	-	-	-	-
*Primary Transition	2	QHA-14W	solid cone	120° @ 10 PSI	2 GPM @ 24 PSI	On	On	On	On	-	On
Primary Conveyor (middle)	4	QHA-10SQ	square	67° @ 20 psi	1.5 GPM @ 23 psi	-	-	-	On	-	-
Primary Conveyor (upper)	2	1/4GGA-14W	wide angle cone	120° @ 10 PSI	2 GPM @ 23 PSI	-	On	On	On	On	On
Primary Conveyor (top)	1	QHA-14W	solid cone	120° @ 10 PSI	2 GPM @ 24 PSI	-	-	On	On	On	On

*The two nozzles at the primary transition were replaced for every B1 (baseline configuration) test with two model QHA-10 solid cone nozzles with a spray angle of 67° @ 20 psi and a flow per nozzle of 1.5 GPM @ 23 psi.
**Spraying Systems Co. manufacturers QHA and GGA model number nozzles.

Table 3: Manufacturer C spray configurations

Location	# of Sprays	Nozzle Model*	Spray Type	Spray Angle	Flow per Nozzle	System status for each configuration						
						C20	C21	C22	C23	C24	C25	C26
Drum Housing A	18	QVVA-6503	flat	72° @ 80 psi	0.42 gpm @ 80 psi	On	-	On	-	-	On	On
Drum Housing B	33	QVVA-6503	flat	72° @ 80 psi	0.42 gpm @ 80 psi	-	On	-	On	On	-	-
Primary Conveyor	2	1/4LN-14	cone	88° @ 80 psi	0.30 gpm @ 80 psi	-	On	-	On	-	-	On
Primary Transition	2	QVVA-50015	flat	58° @ 80 psi	0.21 gpm @ 80 psi	-	On	-	On	On	On	-
Secondary Transition	4	QVVA-50015	flat	58° @ 80 psi	0.21 gpm @ 80 psi	-	On	On	On	On	On	On

*Spraying Systems Co. manufactures all QVVA and LN model number nozzles

Table 4: Manufacturer D spray configurations

Location	# of Sprays	Nozzle Model*	Spray Type	Spray Angle	Flow per Nozzle	System status for each configuration					
						D1	D3	D21	D22	D23	D24
Drum Housing A	12	TG-SS10W	full cone	103° @ 80 PSI	2.2 gpm @ 60 psi	On	On	On	-	-	-
Drum Housing B	12	TG-SS10W	full cone	103° @ 80 PSI	2.4 gpm @ 75 psi	-	-	-	On	On	On
Primary Transition A	2	1/8GG2.8W	full cone	102° @ 80 PSI	0.66 gpm @ 70 psi	-	-	-	On	-	-
Primary Transition B	2	1/8GG2.8W	full cone	102° @ 80 PSI	0.45 gpm @ 30 psi	-	-	-	-	On	On
Secondary Transition A	1	1/8GG2.8W	full cone	102° @ 80 PSI	0.66 gpm @ 70 psi	-	-	-	On	-	-
Secondary Transition B	1	1/8GG2.8W	full cone	102° @ 80 PSI	0.45 gpm @ 30 psi	-	-	-	-	On	On
LEV low setting					1000 ACFM	-	On	-	-	-	-
LEV medium setting					1500 ACFM	-	-	On	-	-	-

*Spraying Systems Co. manufactured all nozzle model numbers listed in this table

Table 5: Manufacturer E spray configurations

Location	Number of Nozzles	Nozzle Model*	Spray Type	Spray Angle	Flow per Nozzle	Total Flow
Configuration E1 (baseline configuration)						
Drum Housing	12	QVVA-8008	Flat Fan	80° @ 40 psi	0.84 GPM @ 45 PSI	10 GPM @ 45 PSI
Transition	4	30 HCX8 Grey (Hypro)	Hollow Cone	80° @ 40 psi	0.156 GPM @ 55 PSI	0.62 GPM @ 55 PSI
Primary Conveyor	4	30-05F80LB (Hypro)	Flat Fan	80° @ 40 psi	0.46 GPM @ 35 PSI	1.84 GPM @ 35 PSI
Secondary Conveyor	4	30 HCX8 Grey (Hypro)	Hollow Cone	80° @ 40 psi	0.34 GPM @ 10 PSI	1.36 GPM @ 10 PSI
Configuration E21						
Wet Drum	-	-	Wet Drum	-	7.9 GPM @ 70 PSI	7.9 GPM @ 70 PSI
Transition	4	30 HCX8 Grey (Hypro)	Hollow Cone	80° @ 40 psi	0.149 GPM @ 50 PSI	0.596 GPM @ 50 PSI
Primary Conveyor	4	30-05F80LB (Hypro)	Flat Fan	80° @ 40 psi	0.43 GPM @ 30 PSI	1.72 GPM @ 30 PSI
Secondary Conveyor	4	30 HCX8 Grey (Hypro)	Hollow Cone	80° @ 40 psi	0.34 GPM @ 10 PSI	1.36 GPM @ 10 PSI
Configuration E22						
Wet Drum	-	-	Wet Drum	-	8 GPM @ 70 PSI	8 GPM @ 70 PSI
Primary Conveyor	4	30-05F80LB (Hypro)	Flat Fan	80° @ 40 psi	0.43 GPM @ 30 PSI	1.72 GPM @ 30 PSI
Secondary Conveyor	4	30 HCX8 Grey (Hypro)	Hollow Cone	80° @ 40 psi	0.34 GPM @ 10 PSI	1.36 GPM @ 10 PSI
Configuration E23						
Wet Drum	-	-	Wet Drum	-	10.95 GPM @ 70 PSI	10.95 GPM @ 70 PSI

*Spraying Systems Co. manufactured all nozzle model numbers listed in this table

Table 6: Percent water to asphalt removed during each test configurations

Configuration	Cutting Speed (ft/min)	Cutting Depth (ft)	Cutting Width (ft)	Volume removal rate (ft^3/min)	Asphalt Density (lbs/ft^3)	Asphalt removal rate (lb/min)	Volumetric Flow Rate (gpm)	Mass flow rate of water (lb/min)	Percent water to asphalt
A1	70	0.25	7.22	126	153	19332	19.2	160	0.83%
A21	70	0.25	7.22	126	153	19332	21.3	178	0.92%
B1	60	0.25	8.17	123	153	18743	21.3	178	0.95%
B2	60	0.25	8.17	123	153	18743	19.2	160	0.86%
B21	60	0.25	8.17	123	153	18743	20.3	169	0.90%
B22	60	0.25	8.17	123	153	18743	23.3	194	1.04%
B23	60	0.25	8.17	123	153	18743	18.7	156	0.83%
B24	60	0.25	8.17	123	153	18743	20.3	169	0.90%
C20	50	0.25	6.56	82	153	12546	7.5	62	0.50%
C21	50	0.25	6.56	82	153	12546	12.5	104	0.83%
C22	50	0.25	6.56	82	153	12546	8.3	69	0.55%
C23	50	0.25	6.56	82	153	12546	12.4	104	0.83%
C24	50	0.25	6.56	82	153	12546	11.8	99	0.79%
C25	50	0.25	6.56	82	153	12546	8.5	71	0.57%
C26	50	0.25	6.56	82	153	12546	8.7	73	0.58%
D1	75	0.25	7.17	134	153	20560	26.40	220	1.07%
D3	75	0.25	7.17	134	153	20560	26.40	220	1.07%
D21	75	0.25	7.17	134	153	20560	26.40	220	1.07%
D22	75	0.25	7.17	134	153	20560	30.78	257	1.25%
D23	75	0.25	7.17	134	153	20560	30.15	252	1.22%
D24	75	0.25	7.17	134	153	20560	20.55	172	0.83%
E1	70	0.25	6.5	114	153	17404	7.32	61	0.35%
E21	70	0.25	6.5	114	153	17404	11.61	97	0.56%
E22	70	0.25	6.5	114	153	17404	11.08	93	0.53%
E23	70	0.25	6.5	114	153	17404	10.95	91	0.53%

Results

The individual 10 second-interval measurements of airborne respirable-dust concentrations from a given location during a given trial are averaged together to provide the location trial-mean concentration. The results from the ten respirable-dust sampling locations are separated into the following groups: (1) the "lower-six source locations" that include the cutter-drum rear sampling locations (right and left), the cutter-drum front locations (right and left), and the lower conveyor locations (right and left); (2) the "conveyor top locations," on either side of the secondary conveyor boom, near the point where milled asphalt material is discharged into dump trucks moving ahead of the machine; and, (3) the "operator-bridge locations," two locations on the right and left sides of the operator bridge.

Group trial-mean concentrations of respirable dust for each trial were determined by calculating the arithmetic means of the location trial-means for all the locations in a given group such as "lower-six". The group trial-mean respirable dust concentration for the each modified test configuration divided by the group trial-mean for the baseline configuration represents the ratio for each trial. The mean of the trial ratios for each modified to baseline configuration are presented in Table 7.

The group trial-mean respirable dust concentrations (mg/m^3) for each individual trial are presented in Tables A1 through A5 of Appendix A.

Table 7: Group mean ratios of respirable dust concentrations for modified to baseline configurations, and lower and upper 95% confidence limits for the true ratio.

	Lower6	Lower 95%CL	Upper 95%CL	Operator bridge	Lower 95%CL	Upper 95%CL	Conveyor top	Lower 95%CL	Upper 95%CL
A21/A1	1.56	1.14	1.95	0.95	0.66	1.14	1.39	0.93	1.59
B2/B1	1.07	0.61	1.58	1.05	0.56	1.46	1.15	0.63	1.68
B21/B1	1.05	0.59	1.54	0.90	0.48	1.25	0.85	0.47	1.26
B22/B1	1.10	0.63	1.62	0.93	0.54	1.40	1.07	0.51	1.36
B23/B1	1.35	0.77	2.01	1.36	0.75	1.93	1.31	0.62	1.67
B24/B1	1.50	0.84	2.17	1.46	0.78	2.01	1.73	0.96	2.58
C21/C20	1.02	0.66	1.43	1.00	0.62	1.34	0.73	0.46	1.00
C22/C20	0.95	0.63	1.36	0.98	0.60	1.29	0.98	0.60	1.31
C23/C20	0.92	0.61	1.31	0.95	0.58	1.26	0.79	0.46	1.00
C24/C20	1.03	0.66	1.43	0.92	0.56	1.22	0.84	0.47	1.02
C25/C20	1.19	0.76	1.65	0.89	0.56	1.21	0.81	0.41	0.89
C26/C20	1.05	0.69	1.49	0.97	0.63	1.36	0.82	0.52	1.12
D3/D1	0.31	0.20	0.47	0.35	0.20	0.49	2.86	1.64	3.91
D21/D1	0.19	0.10	0.25	0.23	0.12	0.30	1.84	0.90	2.14
D22/D1	0.87	0.53	1.26	1.28	0.58	1.43	1.06	0.57	1.35
D23/D1	0.93	0.58	1.38	1.02	0.56	1.36	0.98	0.57	1.36
D24/D1	0.97	0.61	1.45	1.15	0.61	1.49	1.05	0.57	1.36
E21/E1	0.98	0.57	1.64	0.99	0.51	1.57	0.88	0.38	1.08
E22/E1	0.72	0.42	1.20	0.56	0.29	0.90	1.27	0.51	1.50
E23/E1	0.68	0.39	1.11	0.41	0.22	0.67	1.29*	0.42	1.22

*Mean ratios are not always in between the lower and upper limits because the confidence limits are based on transformation of the data to the natural log scale; also, the "mean ratio" will differ depending on how the "mean" is calculated.

For the lower-six sampling locations, the local exhaust ventilation control resulted in the largest control to baseline reduction (reduction =1 – mean ratio, from Table 7) in mean respirable dust concentrations of any evaluated control configuration tested across all machines. The largest mean reduction in mean respirable dust concentrations was 81% when comparing configuration D21 to configuration D1. Configuration D21 used a local exhaust ventilation control at a medium fan speed exhausting approximately 1500 acfm of air to capture dust and the baseline D1 configuration used water to cool the cutting teeth without any additional controls to suppress dust. The second largest reduction in respirable dust for the lower-six sampling location was 69% and was measured during testing of configuration D3 compared to the D1 baseline configuration. The D3 configuration was the same local exhaust ventilation control as D21 operated at a low fan speed exhausting approximately 1000 acfm of air. The reductions for the D21 and D3 compared to the baseline D1 were statistically significant and showed less variability in individual respirable dust concentrations than all other evaluated configurations. The reductions in respirable dust concentrations at the lower-six sampling locations were not statistically significant for any of the evaluated water spray configurations.

For the operator bridge sampling location, the largest control to baseline reductions (reduction =1 – mean ratio, from Table 7) in mean respirable dust concentrations of 77%, 65%, and 59% were statistically significant and occurred from the medium (D21) and low (D3) fan speed local exhaust ventilation configurations and the E23 wet drum configuration when compared to their baseline configurations, respectively. No other evaluated configurations resulted in statistically significant reductions at the operator bridge with the exception of the E22 configuration, which yielded a reduction of 44% when compared to the baseline E1 configuration.

The highest increase in mean respirable dust concentrations of any control to baseline configurations were 286% (D3/D1) and 184% (D21/D1) configurations at the conveyor top sampling locations. The local exhaust ventilation configurations exhausted air at the top of the secondary conveyor at the location where the asphalt is transferred into the back of a truck away from any worker locations.

Bulk-material samples analyzed for crystalline silica

Five bulk-material samples of asphalt-pavement material milled during this study were collected for crystalline-silica analysis. These bulk-material samples contained 8.6%, 7.6%, 4.8%, 4.3%, and 1.8% quartz. All crystalline silica detected in the bulk-material samples was quartz; the samples were scanned for cristobalite and tridymite at the primary diffraction angle and none was detected. The established instrument limit of detection was 0.5% for each of the crystalline forms, quartz, cristobalite, and tridymite.

Estimated crystalline-silica content of airborne respirable dust

Table 8 summarizes the mean crystalline-silica percentages measured in respirable dust samples by machine manufacturer. No tridymite was detected in any of the samples. All results for each manufacturer are included, and for each crystalline-silica sample-mass result reported as "less than the LOD" – indicating a non-detectable (ND) concentration of crystalline silica – an estimated concentration was substituted using the method of Hornung and Reed [1990]. This method suggests using an estimated sample mass equal to the LOD divided by the square root of 2 ($LOD/\sqrt{2}$). These criteria also state that that if the number of results reported as ND exceeds 50% of the total within a group of samples, then it is best not to compute averages for that group.

Table 8: Mean crystalline-silica percentages in respirable dust

Manufacturer	% Quartz*	% Cristobalite**	% Crystalline Silica	Number of samples with Quartz	Number of samples with Cristobalite	number of samples
A	2.3%	0%	2.3%	17	0	20
B	2.5%	0.1%	2.6%	53	6	60
C	2.5%	0.3%	2.8%	45	16	59
D	2.1%	0.1%	2.2%	33	8	40
E	2.5%	0.1%	2.6%	34	6	40

*The mean % quartz was calculated using the method of Hornung and Reed [1990]
**The mean % cristobalite was calculated using zero for each "ND" result instead of Hornung and Reed

Table 9: Wind speed and direction by milling trial

	Trial Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Wind speed in mph over wind direction in degrees															
A1	0 0	3 185	4 160	4 160	6 168	6 168	5 199	5 199	6 144	6 144	7 177	7 177	7 167	6 146	6 146	7 137
A21	0 0	3 185	3 185	4 160	6 168	6 168	5 199	5 199	5 149	6 144	7 177	7 177	6 146	6 146	6 146	7 137
B1	13 190	6 171	5 181	3 238	2 313	3 307	4 265	4 250	5 201	4 231	8 305	10 297	4 233	5 232	7 217	9 267
B2	11 189	4 144	5 106	3 182	3 319	4 313	2 276	3 241	5 209	3 238	6 299	5 281	6 287	10 307	5 197	9 250
B21	10 177	3 139	4 70	2 164	4 303	4 318	3 255	4 231	5 241	5 233	9 311	8 312	7 269	9 299	4 198	7 248
B22	11 173	4 184	3 80	3 36	4 300	4 312	5 309	3 222	6 250	5 236	10 320	8 310	7 289	9 308	9 242	7 246
B23	9 178	3 190	3 179	3 179	4 296	3 310	5 316	4 223	6 235	6 247	10 306	6 301	9 293	10 312	10 248	8 251
B24	8 182	4 175	3 165	3 165	4 306	4 310	5 306	4 209	5 243	5 212	7 307	8 304	3 199	4 210	11 255	2 195
C20	2 205	4 77	3 107	5 101	3 103	3 71	2 64	1 194	1 179	2 215	2 244	2 153	1 137	2 204	3 227	4 311
C21	2 129	6 60	5 85	4 80	4 127	2 69	2 70	1 160	2 219	2 148	2 241	1 254	1 187	2 101	3 216	2 304
C22	3 45	5 52	5 88	4 112	2 182	2 80	2 156	2 219	2 168	2 194	2 84	2 304	1 131	3 73	3 231	2 179
C23	2 107	2 128	5 90	4 80	3 145	1 220	2 136	1 164	1 134	2 261	2 259	1 297	1 186	2 235	5 247	4 276
C24	4 33	5 82	5 98	4 96	2 148	2 63	2 69	1 134	1 156	4 61	2 286	2 231	4 241	2 74	1 184	3 291
C25	5 29	5 72	3 128	5 91	3 135	3 62	2 70	2 183	2 213	3 80	2 289	2 251	1 196	2 108	1 197	3 253
C26	2 215	4 93	5 88	4 75	3 156	2 77	2 88	1 121	1 179	2 204	2 246	2 240	1 162	2 294	3 242	2 220
D1	3 48	4 29	4 36	4 36	4 172	4 203	0 0	7 28	7 34	5 69	7 44	8 210	7 216	7 211	9 195	9 34
D3	3 48	4 29	4 36	4 138	4 182	4 203	7 28	7 28	7 34	5 69	7 44	8 210	7 213	7 211	9 209	9 195
D21	0 0	4 29	4 36	4 138	4 172	3 210	0 0	7 28	7 34	5 69	7 44	8 210	7 216	7 211	9 195	9 88
D22	3 48	4 29	4 36	4 138	4 172	4 203	0 0	7 28	6 50	5 63	7 44	7 216	7 216	7 210	9 195	9 34
D23	3 48	4 29	4 36	4 138	4 172	4 203	0 0	7 34	6 50	6 69	7 44	7 216	7 216	7 211	9 195	9 195
D24	0 0	4 36	4 36	4 138	4 172	4 203	0 0	7 28	7 34	5 69	7 44	8 210	7 211	7 211	9 195	9 34
E1	No wind data were collected for the first 8 trials of manufacturer E testing								1 58	2 116	3 87	3 72	2 44	2 28	3 339	2 257
E21									2 116	2 116	3 72	3 196	2 44	2 28	3 339	2 257
E22									2 116	2 116	3 72	3 196	2 28	2 28	3 339	2 257
E23									2 116	2 116	3 72	3 196	2 28	3 339	3 339	2 7

Conclusions and Recommendations

A total of 18 water spray and two local exhaust ventilation control configurations were tested among five milling-machine manufacturers during the August 2010 testing. Only two of the 18 water spray configurations showed statistically significant reductions in respirable dust concentrations compared to the baseline (E1) on the same machine. These were the E22 and E23 configurations which resulted in mean reductions of 44% and 59%, respectively. The test results for the B1 water spray configuration did not result in any statistically significant reductions in respirable dust concentrations during this study even though the same B1 configuration yielded an estimated, statistically significant 55% reduction in respirable-dust concentrations at the lower-six locations compared to those for the baseline configuration on the same mill during similar testing in Marquette, Michigan in 2008 [Blade et al. 2011].

Local exhaust ventilation controls resulted in larger reductions in respirable dust concentrations than any evaluated water spray control during both the 2008 and 2010 studies. Local exhaust ventilation controls resulted in reductions of about 60% during the 2008 testing, and 81% and 69% during the 2010 testing. Based on the results from this and previous studies, the NIOSH researchers recommend optimization of local exhaust ventilation systems as the primary control method for reducing respirable crystalline silica during asphalt pavement milling. Additional testing of the wet drum design is also recommended.

When designing a local exhaust ventilation system, designers should consider the level of enclosure, the hood design, and the airflow capacity. The ideal approach is to maximize the level of enclosure to isolate and contain the release of dust. Equipment manufacturers are strongly encouraged to identify and incorporate the maximum feasible level of enclosure in their engineering control designs. During the current evaluation of the local exhaust ventilation system, higher airflow settings resulted in rocks being sucked into the local exhaust ventilation system. When designing hoods to transition between the duct and point of capture, larger dimensions of the openings can slow capture velocity to prevent rocks from being drawn into the duct while maintaining the designed flow rate. Based on this evaluation, manufacturers should consider starting at approximately 1500 acfm and higher for ventilation designs which will depend on the level of enclosure.

Once manufacturers have developed the local exhaust ventilation designs, these systems should be tested and optimized for capture efficiency in a factory/laboratory setting using smoke and tracer gas. Following the smoke and tracer gas testing, field testing using respirable dust measurements should be conducted to verify field performance.

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Appendixes

Appendix A

Table A1: Manufacturer A mean respirable dust concentrations (mg/m^3)

	A1			A21		
Trial	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top
1	2.65	1.78	1.24	3.28	1.55	1.66
2	2.07	1.28	2.21	3.24	1.30	2.47
3	2.26	1.23	0.72	3.11	2.28	2.38
4	1.82	1.30	2.22	2.19	1.15	1.11
5	1.47	1.51	0.57	1.54	0.88	1.06
6	0.89	1.34	0.67	1.53	0.59	0.60
7	1.26	1.46	0.39	1.39	0.59	0.54
8	0.96	0.87	0.40	1.63	0.94	0.90
9	0.97	0.50	0.38	1.90	0.76	1.01
10	0.74	0.49	0.53	1.64	0.49	0.57
11	1.03	0.69	0.80	1.19	0.52	0.59
12	0.37	0.41	0.42	0.96	0.34	0.34
13	0.56	0.57	0.46	0.97	0.61	0.32
14	0.76	0.75	0.40	0.86	0.38	0.50
15	0.61	0.70	0.39	0.63	0.58	0.26
16	0.98	0.81	0.47	2.13	1.29	0.79

Table A2: Manufacturer B mean respirable dust concentrations (mg/m^3)

	B1			B2			B21			B22			B23			B24		
Trial	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top
1	1.76	1.02	0.33	1.75	0.94	0.44	4.73	0.98	0.29	3.90	1.00	1.51	4.31	1.27	0.91	3.79	1.56	1.28
2	2.92	1.10	0.40	2.30	0.98	0.50	1.45	0.57	0.22	4.44	1.88	0.41	6.85	2.10	0.52	4.89	1.49	1.11
3	3.24	2.12	0.14	3.06	1.68	0.16	4.50	1.16	1.84	5.53	1.20	2.95	5.66	2.25	2.72	8.96	5.23	4.63
4	6.63	3.63	2.40	6.81	3.77	3.53	7.17	2.08	3.71	6.31	2.58	2.63	5.07	2.56	2.79	4.33	2.61	2.64
5	3.53	1.27	1.77	4.16	1.28	2.34	2.92	0.88	1.49	2.69	1.52	2.10	3.94	1.53	2.40	6.10	2.33	2.74
6	4.07	1.38	2.15	3.48	1.52	2.37	3.48	1.98	2.71	3.08	1.44	3.01	5.12	2.52	3.23	3.40	2.33	2.76
7	3.14	0.77	1.64	2.73	0.84	1.85	3.01	0.98	2.52	6.57	1.21	2.36	4.37	2.25	2.96	3.85	1.67	2.32
8	2.96	1.18	1.17	3.45	1.03	0.84	2.36	1.69	1.36	3.31	1.36	1.17	3.88	2.87	2.07	5.10	2.23	2.08
9	1.86	1.14	0.63	3.14	1.28	1.47	2.36	0.55	0.27	2.59	0.84	0.76	3.48	2.02	1.96	2.40	1.54	1.67
10	1.41	1.58	0.84	2.72	0.99	1.34	3.32	0.98	1.27	1.61	0.65	0.68	1.24	0.94	0.92	1.32	0.48	0.59
11	0.46	0.11	0.22	0.84	0.20	0.41	0.45	0.10	0.10	0.62	0.08	0.14	1.08	0.13	0.31	1.44	0.33	0.74
12	1.39	0.42	1.10	1.69	0.87	1.44	1.12	0.28	0.75	0.93	0.37	0.84	2.31	0.72	1.74	0.90	0.18	0.69
13	3.07	0.74	2.09	2.00	1.20	1.57	1.39	1.64	1.84	1.33	0.87	0.97	2.03	0.69	0.67	7.55	1.56	5.22
14	2.86	1.41	2.10	1.37	0.34	0.59	1.09	0.99	0.98	0.88	1.05	0.68	1.36	0.72	0.43	3.32	1.24	2.06
15	2.61	0.52	1.55	2.68	0.61	0.99	2.23	0.50	0.44	1.60	0.45	0.15	1.48	0.52	0.16	1.37	0.37	0.24
16	3.55	1.30	1.98	1.48	0.31	0.43	2.33	0.36	0.60	1.61	0.49	0.17	2.50	0.83	0.46	3.76	1.12	2.57

Table A3: Manufacturer C mean respirable dust concentrations (mg/m^3)

	C20			C21			C22			C23			C24			C25			C26		
Trial	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top
1	1.59	0.46	2.01	2.02	0.40	2.12	1.76	0.23	3.59	1.9	0.27	1.83	1.71	0.16	3.92	1.98	0.17	5.44	1.38	0.31	1.62
2	2.05	0.48	5.95	2.55	0.19	5.12	1.35	0.14	6.33	1.94	0.17	1.30	1.9	0.15	2.92	1.5	0.17	3.85	2.89	0.15	1.62
3	2.07	0.25	2.48	2.04	0.16	1.18	2.79	0.16	2.35	2.46	0.12	1.56	2.92	0.12	2.60	1.93	0.19	0.76	2.96	0.19	1.41
4	3.25	0.11	3.17	2.14	0.13	1.57	1.99	0.11	5.40	2	0.15	2.45	2.78	0.12	2.79	4.11	0.12	2.27	2.47	0.14	2.67
5	0.87	0.11	0.85	0.94	0.10	0.36	0.75	0.15	0.50	0.85	0.14	0.64	1.01	0.12	0.50	1.45	0.11	0.42	1.03	0.13	0.50
6	1.78	0.34	3.03	2.58	0.29	2.24	2.04	0.19	2.86	2.3	0.53	1.26	2.26	0.56	3.75	3.17	0.28	3.37	2.34	0.40	3.00
7	2.05	0.26	3.16	2.21	0.56	3.97	1.66	0.38	2.97	1.6	0.50	3.87	3.01	0.37	3.79	3.23	0.41	2.16	2.25	0.28	2.66
8	2.92	0.44	3.05	2.2	0.42	1.71	3.01	0.29	3.73	2.15	0.31	1.25	2.23	0.52	2.78	2.04	0.35	0.92	1.64	0.41	1.64
9	1.69	0.30	1.81	2.3	0.24	1.56	1.86	0.36	1.10	1.78	0.36	2.04	2.13	0.39	1.78	3.29	0.36	1.04	1.95	0.35	1.51
10	1.01	0.41	2.03	1.07	0.39	1.40	1.1	0.33	1.83	1.2	0.26	1.39	1.15	0.34	1.86	1.06	0.25	2.48	1.2	0.37	1.74
11	1.03	0.37	1.90	1.03	0.33	1.42	0.89	0.40	1.35	0.79	0.26	0.77	0.84	0.25	1.19	0.9	0.26	1.59	1.28	0.39	1.87
12	2.14	0.42	3.51	2.49	0.18	1.89	1.54	0.24	2.37	2.13	0.24	3.51	2.27	0.32	2.19	1.89	0.28	3.54	1.7	0.24	3.65
13	2.15	0.28	1.76	2.08	0.47	1.58	2.02	0.27	1.98	1.79	0.40	2.06	1.23	0.21	1.13	1.76	0.34	1.24	2.2	0.35	1.36
14	1.09	0.17	1.16	1.24	0.26	1.35	1.17	0.33	1.82	0.87	0.11	0.94	0.76	0.18	0.06	1.18	0.24	0.06	0.96	0.16	1.82
15	0.99	0.35	0.05	0.54	0.38	0.02	1.05	0.57	0.02	0.68	0.41	0.05	1.27	0.39	0.03	1.6	0.23	0.06	0.78	0.39	0.05
16	0.75	0.10	3.87	0.41	0.09	1.88	0.62	0.12	1.40	0.54	0.07	4.14	0.5	0.07	2.77	0.7	0.10	1.40	0.83	0.12	2.30

Table A4: Manufacturer D mean respirable dust concentrations (mg/m^3)

	D1			D3			D21			D22			D23			D24		
Trial	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top
1	5.02	0.14	0.24	1.88	0.08	1.46	0.81	0.06	0.36	7.94	0.88	1.01	5.42	0.30	0.24	6.27	0.45	0.80
2	8.31	0.36	1.00	1.71	0.14	1.04	1.03	0.15	1.56	5.65	0.58	0.62	6.81	0.80	0.89	7.63	0.63	1.54
3	11.55	0.83	1.86	3.86	0.28	2.39	1.19	0.07	0.94	6.03	0.30	0.73	7.75	0.58	0.74	7.73	0.38	0.74
4	5.65	1.56	0.75	1.34	0.31	3.25	0.96	0.31	2.49	6.71	0.76	0.67	6.99	1.26	0.88	7.41	1.06	0.75
5	5.68	0.95	0.43	1.82	0.25	1.38	0.92	0.14	0.83	4.43	0.41	0.36	3.63	0.64	0.39	4.76	0.57	0.17
6	6.23	1.08	0.40	2.26	0.20	1.52	1.06	0.15	0.72	3.70	0.80	0.59	4.92	0.82	0.31	4.55	0.75	0.38
7	3.48	0.13	0.30	1.00	0.05	0.52	0.23	0.01	0.17	2.79	0.10	0.23	2.86	0.02	0.19	2.26	0.07	0.12
8	3.10	0.24	0.54	1.17	0.06	1.09	0.40	0.04	0.26	4.51	0.23	0.43	3.76	0.18	0.45	4.21	0.28	0.38
9	4.97	0.39	0.42	1.61	0.11	1.64	1.28	0.08	1.38	6.99	0.62	0.71	8.24	0.77	0.71	7.35	0.62	0.90
10	6.72	0.26	0.73	1.84	0.21	1.82	1.06	0.08	1.19	4.48	0.29	0.41	7.56	0.41	0.71	4.61	0.28	0.45
11	7.26	0.64	0.20	2.24	0.11	0.74	4.99	0.29	0.24	3.82	0.30	0.22	5.53	0.31	0.41	6.46	0.44	0.18
12	4.56	0.52	0.15	1.38	0.21	0.86	0.71	0.10	1.12	5.02	0.47	0.21	2.59	0.17	0.13	2.87	0.26	0.10
13	4.44	0.37	0.36	1.13	0.09	0.50	0.68	0.05	0.27	2.94	0.26	0.10	3.21	0.36	0.19	4.23	0.40	0.22
14	3.79	0.21	0.22	1.43	0.11	0.43	0.52	0.06	0.35	2.33	0.31	0.16	2.88	0.17	0.12	4.56	0.43	0.35
15	4.21	*	0.28	1.58	*	0.39	0.79	*	0.18	3.70	*	0.23	4.03	*	0.39	4.49	*	0.25
16	7.53	*	1.01	1.71	*	1.56	1.36	*	0.95	3.90	*	0.34	8.42	*	1.02	7.23	*	0.65

*A sampling pump stopped during trials 15 and 16 at the operator location; therefore data are not reported for those trials.

Table A5: Manufacturer E mean respirable dust concentrations (mg/m^3)

	E1			E21			E22			E23		
Trial	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top	Lower 6	Operator Area	Conveyor Top
1	1.44	0.17	0.57	1.97	0.17	0.38	1.16	0.18	0.93	0.84	0.17	0.94
2	2.07	0.29	0.79	1.20	0.23	0.65	1.47	0.36	1.60	1.03	0.20	1.54
3	2.45	0.54	1.94	4.15	1.15	2.77	1.64	0.22	1.69	1.09	0.13	0.63
4	1.60	0.42	0.70	2.04	0.55	0.73	1.16	0.23	1.49	1.33	0.32	1.78
5	1.30	0.16	0.57	1.62	0.33	0.88	0.72	0.15	1.48	0.68	0.10	0.25
6	0.56	*	0.52	0.73	*	1.48	0.57	*	0.47	0.49	*	1.41
7	0.49	*	0.74	0.51	*	0.58	0.60	*	2.04	0.61	*	1.90
8	3.72	3.78	1.63	3.91	3.45	0.98	2.97	1.02	1.06	3.94	1.37	2.86
9	7.67	3.87	1.33	4.48	1.37	0.11	2.04	0.54	0.09	2.99	0.64	0.05
10	4.28	3.96	0.95	6.12	0.69	0.25	2.34	0.75	1.71	3.34	0.70	3.04
11	5.72	2.49	0.76	3.34	2.03	0.33	2.50	1.03	2.06	2.03	0.54	0.76
12	3.89	2.20	1.85	2.99	1.51	3.05	2.52	0.68	1.78	2.10	0.41	1.25
13	3.11	0.47	5.43	2.49	0.22	6.14	1.93	0.27	4.11	2.46	0.29	5.96
14	1.70	0.22	19.78	0.98	0.19	2.56	2.09	0.22	0.11	0.90	0.05	4.25
15	1.90	0.43	3.15	1.30	0.79	0.61	0.89	0.12	0.20	1.92	0.11	0.18
16	1.62	0.98	4.91	1.16	0.37	2.53	1.27	0.45	2.12	0.61	0.18	1.67

*A sampling pump stopped working during trials 6 and 7 at the operator location; therefore data are not reported for those trials.

Appendix B (Statistical Appendix)

Examination of the data indicates that manufacturer D had the highest baseline respirable dust concentrations compared to the other four manufacturers. Manufacturer D also had the largest reductions in respirable dust concentrations using the local exhaust ventilation control. Further statistical analysis was performed to determine whether the large reductions measured for manufacturer D were due to the higher baseline respirable dust concentrations.

The minimum baseline lower six respirable dust concentration for manufacturer D was 3.1 mg/m^3. There were seven sets each for manufacturers B and E for which the baseline lower six average exceeded 3.1 mg/m^3 as shown in Table B1. For Manufacturer D, the most effective configuration had a mean ratio of 0.19 relative to the baseline respirable dust concentration, compared to 0.55 for manufacturer E's most effective configuration and 0.85 for manufacturer B's most effective configuration. In addition, if manufacturer D baseline measurements are limited to the range 3.1-5 mg/m^3 (seven measurements), the ratio of D21 to baseline is 0.16. Therefore, there is no evidence that the presence of relatively high baseline respirable dust measurements were the reason for the larger reductions in respirable dust concentrations.

Table B1: Comparison of reductions at higher baseline respirable dust levels

Manufacturer	Number of samples	Baseline values mg/m^3		Mean ratio to baseline for most effective configuration
		average	(min, max)	
D, all data	16	5.78	(3.1,11.6)	0.19
D , $3.1 mg/m^3 < \text{baseline mean} < 5 mg/m^3$	7	4.1	(3.1,4.97)	0.16
B, baseline mean $>3.1 mg/m^3$	7	3.9	(3.1,6.63)	0.85
E	6	4.7	(3.1,7.7)	0.55

There is also interest in comparing the reductions by dividing the lower-six locations into two groups: the two sampling locations near the transition between the primary and secondary conveyor versus the four locations surrounding the drum housing. In Table B2 below the averages for the baseline are shown for these two groups. The values in Table B2 show the large difference between the two baseline means for manufacturer D: 14.8 mg/m^3 for the conveyor transition average respirable dust concentration versus 1.3 mg/m^3 for the drum housing average respirable dust concentration. Higher respirable dust concentration at the conveyor transition locations contributed to the higher lower-six average baseline respirable dust concentrations measured for manufacturer D. However, the ratios of the best configurations to baseline do not change sufficiently to alter any conclusions. Only D21 (and D3) have average ratios less than 0.5 and D21's ratio differs very little between conveyor and drum housing within the lower-six. Also manufacturer D has the lowest average at the four drum housing sample locations (1.3 mg/m^3), again supporting the idea that small ratios associated with D21 and D3 are independent of baseline dust concentration levels.

Table B2: Baseline lower-six average by conveyor transition and drum housing grouping

Manufacturer	Average Conveyor Transition, mg/m^3	Average Drum Housing mg/m^3	Conveyor data: ratio to baseline for best configuration	Drum Housing data: ratio to baseline for best configuration	Average ratio of best configuration for combined data
A	0.8	1.4	1.1(A2)	1.7(A2)	1.6(A21)
B	1.8	3.4	1.3(B21)	0.9(B21)	1.1(B21)
C	2.1	1.6	0.8(C22)	0.8(C23)	0.9(C23), 1.0(C22)
D	14.8	1.3	0.2(D21)	0.2(D21)	0.2(D21)
E	1.4	3.4	1.3(E23)	0.6(E23)	0.7 (E23)

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