In-Depth Survey Report

Evaluation of a Volvo Milling Machine Equipped with a Wet Drum Designed to Reduce Respirable Crystalline Silica Exposure During Pavement Milling

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

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Site Surveyed:

Larchmont Drive and Tenny Avenue in Waukesha, WI

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

Survey Dates: August 17-18, 2012

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Abstract

From August 17-18, 2012, National Institute for Occupational Safety and Health (NIOSH) researchers and the Silica/Milling-Machines Partnership coordinated by the National Asphalt Pavement Association (NAPA) conducted field testing of a Volvo MT-2000 cold milling machine equipped with a wet drum designed to reduce respirable crystalline silica concentrations. The wet drum design uses gravity to release water from inside the drum through nozzles to the cutting surface to suppress dust. The effectiveness of the dust controls examined in this study was evaluated by measuring the reduction in the respirable dust and respirable quartz concentrations in area samples collected during a typical milling job.

The test consisted of replicate short-term milling trials (nominally about 10 minutes each in duration). During a trial, the milling machine removed approximately 2-inches of depth of the asphalt surface while operating either its existing production water-spray system (the “baseline configuration”), or its wet drum configuration. Respirable-dust concentrations were measured at ten selected locations around the milling machine 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. Average dust-emission reductions, along with their statistical confidence intervals, were computed for the wet drum configuration versus the baseline. In addition, average dust-emission reductions were also computed for the operator bridge and conveyor top. Full-shift personal breathing zone sampling for respirable dust and respirable crystalline silica was also conducted for the operator and groundman each day. The personal breathing zone samples collected during this study do not provide a direct measure of the control efficiency since the samples include periods of operation of both control configurations.

A total of 19 short-term trials were conducted to compare reductions in respirable dust concentrations between the wet drum and baseline water configurations on a Volvo MT-2000 cold milling machine. The results showed a geometric mean reduction in respirable dust concentrations of 37% at the lower-six source locations and 27% at the operator locations. However, these results were not statistically significant at the 95% confidence level. The personal breathing zone sampling results for respirable crystalline silica

for the operator were 0.085 mg/m^3 on day 1 and 0.028 mg/m^3 on day 2. The personal breathing zone sampling results for respirable crystalline silica for the ground man were 0.040 mg/m^3 on day 1 and 0.043 mg/m^3 on day 2.

The results of this study showed that while the wet drum provided an increased level of control over the baseline configuration, there was no statistically significant difference between the two designs. In addition, the magnitude of the exposure reduction does not appear to be sufficient to protect workers from excessive crystalline silica exposures. Based on the results of this study and previous studies, NIOSH researchers recommend that manufacturers of half-lane and larger cold milling machines use local exhaust ventilation as a control for silica exposures.

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 studying the effectiveness of dust-emission controls during asphalt pavement-milling operations. Pavement-milling is the process of removing the road surface for recycling. The 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 below occupational exposure limits for 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 best practice guidelines for engineering controls on asphalt milling machines.

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-Khanzadeh 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].

A variety of machinery 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 cutter 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 study.

The large cold-milling machine evaluated during this study was a Volvo MT2000 with a 2000 mm (79-inch) wide cutter drum. Half-lane cold-milling machines have a spinning cutter drum with teeth to remove pavement from the road surface and transfer it onto a primary conveyor. From the primary conveyor, the reclaimed pavement is transferred to a secondary conveyor and into a dump truck. All production milling machines are also equipped with water-spray systems to cool the cutting teeth and suppress dust. The evaluated Volvo MT2000 cold-milling machine also had a wet drum system designed to suppress dust generated in the cutter drum housing and prevent worker exposure to respirable crystalline silica.

This field study evaluated the performance of the wet drum by measuring the reduction in the respirable dust and respirable quartz concentrations in area samples collected during a typical milling job. Time-weighted average personal breathing zone samples for respirable crystalline silica exposures were also collected for the milling machine operator and groundman during each day. The study was conducted during the course of normal employee work activities on a typical highway construction milling job.

This study was facilitated by the Silica/Milling-Machines Partnership, which is affiliated with and coordinated through the National Asphalt Pavement Association (NAPA). The partnership includes NAPA, the Association of Equipment Manufacturers (AEM), the manufacturers of almost all pavement-milling machines sold in the U.S., numerous construction contractors, the International Union of Operating Engineers (IOUE), the Laborers' International Union of North America (LIUNA), NIOSH, and other interested parties.

Occupational Exposure Limits and Health Effects

As a guide to the evaluation of the hazardous workplace exposures, NIOSH investigators use mandatory and recommended Occupational Exposure Limits (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 a recommended Short Term Exposure Limit (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 2003a] 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 Levels™ (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).

Crystalline Silica Exposure Limits

NIOSH recommends an exposure limit for respirable crystalline silica of 0.05 mg/m^3 as a TWA determined during a full-shift sample for up to a 10-hr workday during a 40-hr workweek to reduce the risk of developing silicosis, lung cancer, and other adverse health effects [NIOSH 2002]. In cases of simultaneous exposure to more than one form of crystalline silica, the concentration of free silica in air can be expressed as micrograms of free silica per cubic meter of air sampled (µg/m^3) [NIOSH 1975].

$$\frac{\mu g SiO_2}{m^3} = \frac{\mu g Q + \mu g C + \mu g T + \mu g P}{V} \qquad (1)$$

Where Q is quartz, C is cristobalite, T is tridymite, P is “other polymorphs” and V is volume of air sampled in cubic meters.

The current OSHA PEL for respirable dust containing crystalline silica for the construction industry is measured by impinger sampling. In the construction industry, the PELs for cristobalite and quartz are the same. The PELs are expressed in millions of particles per cubic foot (mppcf) and calculated using the following formula [29 CFR 1926.55 2003b]:

$$Respirable\ PEL = \frac{250\ mppcf}{\%\ Silica + 5} \qquad (2)$$

Since the PELs were adopted, the impinger sampling method has been rendered obsolete by gravimetric sampling [OSHA 1996]. OSHA currently instructs its compliance officers to apply a conversion factor of 0.1 mg/m^3 per mppcf when converting between gravimetric sampling and the particle count standard when characterizing construction operation exposures [OSHA 2008].

The ACGIH® TLV® for α-quartz and cristobalite (respirable fraction) is 0.025 mg/m^3 [ACGIH® 2010a].

Methodology

Area respirable-dust and crystalline-silica air-sampling

Area air samples for respirable dust and respirable 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.

Gravimetric analysis of each area sample filter for respirable particulate was carried out by Bureau Veritas North America in accordance with NIOSH Method 0600. After this analysis was completed, crystalline silica analysis of each filter 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.

Based on past asphalt milling studies using ten area sampling locations, six key locations were chosen that best represented the areas where dust was generated. These locations include four near the cutter housing and two locations on either side of the primary-to-secondary material-conveyor transition point. Nineteen sets of trials, with each set testing the baseline and the wet drum configuration in randomized order, were conducted and the average concentration at each location during each trial was determined. A typical trial was about 10-minutes in duration. The arithmetic mean of these six key location average concentrations (referred to as the “lower-six source location” mean concentration) for the wet drum configuration within a set was compared with the corresponding 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 was used as a surrogate for reduction in respirable dust-emission rate from the primary source areas. Ratios were also computed for modified-to-baseline arithmetic means for the operator bridge and conveyor top sampling locations. Thus, the comparison of wet drum concentrations to baseline is made for each of the three location groups: lower six, operator bridge, and conveyor top.

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.

Personal-Breathing Zone Air Samples

The personal breathing zone samples collected during this study do not provide a direct measure of the control efficiency since the samples include periods of operation of both control configurations. Personal breathing zone air samples for respirable dust and respirable crystalline silica were collected from the milling machine operator and groundman using respirable dust cyclones (model GK2.69, BGI Inc., Waltham, MA) at a flow rate of 4.2 liters/minute (L/min) with battery-operated sampling pumps (Aircheck Sampler model 224, SKC, Inc., Eighty Four, PA) calibrated before and after each day’s use. A sampling pump was clipped to each sampled employee’s belt worn at their waist. The pump was connected via Tygon® tubing and a tapered Leur-type fitting to a pre-weighed, 37-mm diameter, 5-micron (µm) pore-size polyvinyl chloride filter supported by a backup pad in a three-piece 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 a respirable dust cyclone.

The filter samples were analyzed for respirable particulates in accordance with NIOSH Method 0600 [NIOSH 1998]. The limit of detection (LOD) was 30 µg/sample. The limit of quantitation (LOQ) was 110 µg/sample. The results were blank corrected with the average of the media blanks.

Crystalline silica analysis of filter samples was performed using X-ray diffraction in accordance with NIOSH Method 7500 [NIOSH 2003]. The LODs for quartz, cristobalite and tridymite are 5 µg/sample, 10 µg/sample, and 10 µg/sample, respectively. The LOQs for quartz, cristobalite, and tridymite are 17 µg/sample, 33 µg/sample, and 33 µg/sample, respectively.

Bulk samples were analyzed in accordance with NIOSH Method 7500. The LODs for quartz, cristobalite, and tridymite in bulk samples are 0.3%, 0.3%, and 0.5%, respectively. The LOQs for quartz, cristobalite, and tridymite in bulk samples are 1.1%, 0.95%, and 1.7%, respectively.

Water flow

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 milling machine.

Temperature, wind speed, and direction

The NIOSH researchers used a data-logging weather station (Kestrel 4500, Nielsen-Kellerman, Boothwyn, PA) mounted on top of a tripod to assess weather conditions at the site. The weather station was approximately 0.75 m (30 in) off the ground. On both days, the tripod was placed in the grass median between north and south lanes of Tenny Avenue. The weather station was programmed to record data every 5 minutes.

Control Technology

Description of tested dust-emission control configuration

The equipment evaluated during this study was a Volvo MT2000 with a Cummins QSX-15, 6 cylinder diesel engine that produces 455 kilowatt (kW) (610 horsepower (HP)) at 1900 rpm and has a 2000 mm (79-inch) wide cutter drum. All production milling machines are equipped with water-spray systems to cool the cutting teeth and suppress dust. The evaluated Volvo MT2000 had a baseline water spray system that consisted of spray nozzles to suppress dust along the primary and secondary conveyors in addition to the water used to cool the cutting teeth. The evaluated machine was also equipped with a wet drum designed to suppress dust at the point of generation in the drum housing of the machine instead of suppressing dust with the baseline water spray nozzles along the conveyors. The wet drum design uses gravity to release water from inside the drum through nozzles to the cutting surface to suppress dust. The wet drum was set to a flow water at a rate of 10 gallons per minute. The focus of this study was to determine if the wet drum dust control was effective at reducing respirable dust and respirable crystalline silica concentrations compared to the baseline water configuration. The testing occurred during the course of normal employee work activities on a typical highway construction milling job.

Results

A total of 19 short-term trials were conducted to compare reductions in respirable dust concentrations between the wet drum and baseline water configurations for each of the three location groups on a Volvo MT-2000 cold milling machine. For the statistical model, done in Proc Mixed in SAS [SAS Institute, Inc. 2004], the natural logs of the group means are used as the dependent variable. There were 19 randomized pairs (baseline design, test design) and 3 groups for each trial. This results in 19 x 2 x 3 = 114 means. The statistical model gives geometric means for date, group, control type, and their interactions, also allowing for multiple sources of variability-- pair, control types over pairs, groups over pairs, and the residual. Examination of residuals indicates that the log transformation follows approximately a normal distribution. The statistical model is used to obtain the confidence limits, which uses standard errors for the estimates from the statistical model. The lognormal distribution is typical of occupational exposure data [Rappaport and Kupper, 2008]. The conclusions from the model used here apply to the machine that was used, at the specific site and days on which the work was done.

Table 1 shows the ratios of the wet drum to baseline respirable dust concentrations at the lower six source locations, the operator locations and the conveyor top locations. Average ratios are computed and displayed at the bottom of the table. Because the data are normal on the log scale and because the main aim is comparison of the wet drum averages to the baseline averages, the most appropriate summary measure to use is the geometric mean. The equation [(1-ratio)x100%] was used to convert the ratios in Table 1 to a percent reduction. The results showed a geometric mean reduction in respirable dust concentrations of 37% at the lower-six source locations and 27% at the operator locations. Table 2 shows the geometric mean and 95% confidence limits for the lower six source locations, the operator locations and the conveyor top locations. The upper confidence limits all exceeded 1, and there were no statistically significant reductions in respirable dust concentrations.

Personal breathing zone samples were also collected during the two days of sampling for the operator and the ground man. Statistical analysis was not performed for the personal breathing zone samples since there were only two air samples collected for the operator and two for the ground man (one sample each day for each worker). The personal breathing zone sampling results for the operator were 0.085 mg/m^3 on day 1 and 0.028 mg/m^3 on day 2. The personal breathing zone sampling results for the ground man were 0.040 mg/m^3 on day 1 and 0.043 mg/m^3 on day 2. These personal breathing zone samples do not provide a direct measure of the control efficiency since the samples include periods of operation of both control configurations.

One bulk silica sample was collected and contained 14% quartz and 0.51% cristobalite.

Wind speed, wind direction, temperature, and relative humidity during each trial are shown in Table 3. The wind was relatively light during both days of sampling. The highest wind speeds occurred during the first three trials on the first day of sampling, and the highest average wind speed during a trial never exceeded 3.5 meters per second.

Discussion

The Volvo MT-2000 milling machine with the wet drum design evaluated during this study was the same machine and wet drum tested in Wisconsin during the 2010 silica/milling machines partnership study [Hammond et al. 2011]. In 2010, the wet-drum control resulted in a statistically significant 59% reduction in respirable dust concentrations measured at the operator location. In 2012, because the 95% upper confidence limits all exceeded 1, there were no statistically significant reductions in respirable dust concentrations at the same locations evaluated in 2010. The purpose of testing the wet drum design again in 2012 was to see if the 2010 results could be repeated or improved since other water spray dust control configurations evaluated in 2008 and 2010 showed reductions in respirable dust concentrations in some cases but not in others [Blade et al. 2011, Hammond et al. 2011].

Figure 2 shows plots of the 2010 and 2012 wet drum to baseline ratios for the lower 6, operator, and conveyor top locations. All three locations indicate that there is a decrease in ratio as baseline values increase, for both studies. Whereas in the 2010 study the 95% confidence interval for the ratio of the wet drum design to the baseline means at the operator location was (0.22, 0.67), in the present study it is (0.46, 1.18). In 2012 there was less reduction at the operator location than in

2010. Figure 2 also indicates that there is not much difference between the results from 2010 and 2012 for the lower 6 locations (wet drum to baseline 95% confidence intervals, respectively for 2010 and 2012, (0.39, 1.11) and (0.39, 1.01)), even though the 2012 results had somewhat larger baseline average. Figure 2 also indicates that the 2012 baseline levels are larger for the conveyor top, but the ratios themselves are somewhat larger (wet drum to baseline 95% confidence intervals for 2010 and 2012, respectively, (0.42, 1.22) and (0.72, 1.86)). As in the 2010 study, the conveyor top concentrations had mean values comparable to the lower-six source means.

Conclusions and Recommendations

A total of 19 short-term trials were conducted to compare reductions in respirable dust concentrations between the wet drum and baseline water configurations on a Volvo MT-2000 cold milling machine. The results showed a geometric mean reduction in respirable dust concentrations of 37% at the lower-six source locations and 27% at the operator locations. However, these results were not statistically significant at the 95% confidence level. The results of this study showed that while the wet drum provided an increased level of control over the baseline configuration, there was no statistically significant difference between the two designs. In addition, the magnitude of the exposure reduction does not appear to be sufficient to protect workers from excessive crystalline silica exposures.

During both the 2010 and 2012 evaluations of the wet drum, water was applied through the drum evenly to the entire milled strip when milling on level ground. However, approximately half of the milled strip was dry when the road was not perfectly level from side-to-side, which occurred during a substantial portion of both the 2010 and 2012 evaluations of the wet drum control. It is possible that improved dust suppression with the wet drum could be achieved with a more even distribution of water.

The results from this study did not show statistically significant reductions in respriable dust when using the wet drum. Previous studies have shown larger and more consistent reductions in respirable dust concentrations using ventilation [Blade et al. 2011; Hammond et al. 2011]. Based on the results of this study and previous studies, NIOSH researchers recommend that manufacturers of half-lane and larger cold milling machines use local exhaust ventilation as a control for silica exposures.

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Table 1: Ratios of the wet drum to baseline respirable dust concentrations

	Baseline Water Configuration (Mean Respirable Dust Concentrations mg/m³)			Wet drum water configuration (Mean Respirable Dust Concentrations mg/m³)				Ratio: wet drum / baseline		
set	Lower 6	Operator	Conveyor top	Lower 6	Operator	Conveyor top		Lower 6	Operator	Conveyor top
1	3.51	0.22	2.00	1.81	0.34	5.28		0.51	1.52	2.64
2	4.13	0.76	3.20	3.32	1.53	9.82		0.80	2.01	3.07
3	3.02	0.62	4.61	2.19	0.57	5.00		0.73	0.92	1.09
4	4.48	0.71	4.65	2.31	0.25	8.08		0.52	0.35	1.74
5	3.62	1.56	3.83	2.27	1.30	5.51		0.63	0.83	1.44
6	2.31	0.66	3.24	2.65	1.15	4.15		1.15	1.74	1.28
7	1.79	0.61	3.28	2.38	0.91	5.09		1.33	1.48	1.55
8	1.98	1.22	3.70	1.74	1.38	6.39		0.88	1.13	1.73
9	2.08	0.99	2.93	1.22	0.73	3.53		0.59	0.74	1.20
10	2.84	0.99	2.61	1.51	1.44	5.54		0.53	1.46	2.12
11	4.14	2.27	4.51	1.17	0.65	3.29		0.28	0.28	0.73
12	3.55	0.04	0.38	2.59	0.12	0.85		0.73	3.28	2.23
13	4.01	0.03	0.36	2.36	0.03	0.86		0.59	1.03	2.36
14	4.00	0.21	1.99	2.95	0.25	3.08		0.74	1.20	1.54
15	4.81	0.48	3.45	1.80	0.02	0.46		0.37	0.05	0.13
16	4.59	0.96	2.16	2.86	0.36	3.52		0.62	0.38	1.63
17	7.75	1.21	5.19	4.61	0.84	1.83		0.59	0.69	0.35
18	4.07	0.89	3.07	2.25	0.81	3.47		0.55	0.91	1.13
19	4.74	0.70	3.88	2.48	0.05	0.59		0.52	0.08	0.15
								Summary of ratios:		
AM	3.76	0.80	3.11	2.34	0.67	4.02	AM*	0.67	1.06	1.48
GM	3.54	0.54	2.62	2.22	0.40	3.02	**GM****	**0.63**	**0.73**	**1.15**
							Ratio of AMs***	0.62	0.84	1.29

* Arithmetic mean (AM)
** Geometric mean (GM)—for lognormal data involving comparison of two different control methods. the geometric mean is the most appropriate summary measure.
***Ratio of the overall averages

Table 2: Geometric mean ratios and 95% confidence limits

	Lower 6	Operator	Conveyor Top
Estimated Ratio (GM)	0.63	0.73	1.15
(lower conf limit, upper conf limit)	(0.39,1.01)	(0.46,1.18)	(0.72,1.86)

Table 3: Wind speed, wind direction, temperature and humidity during each trial

Trial #	Condition	Wind direction (°)	Wind Speed (mph)	Temperature °F	Relative Humidity%
Day 1, August 17, 2012					
trial 1*	Baseline	139	6.1	59.6	71.5
trial 1	Wet drum	156	7.8	60.2	69.8
trail 2	Wet drum	142	5	63.2	63.6
trial 2	Baseline	141	6.7	63	61.2
trial 3	Wet drum	143	4.4	64	56.9
trial 3	baseline	160	7.1	66.1	56.5
trial 4	baseline	153	3.2	67.4	55.7
trial 4	Wet drum	146	1.7	69.4	50.2
trial 5**	Wet drum	142	2.6	72.8	41.7
trial 5	baseline	143	2.1	73.3	41.5
trial 6	Wet drum	131	1.5	71.9	42.6
trial 6	baseline	103	4	71.6	41.9
trial 7	Wet drum	74	3.4	71.8	39.4
trial 7	baseline	126	1.2	74.3	38.3
trial 8	Wet drum	107	2.4	73.2	39
trial 8	baseline	141	3.1	73.5	39.4
trial 9	baseline	95	2.5	73.9	37.8
trail 9	Wet drum	123	3.7	71.6	39.3
trail 10	baseline	141	4.1	72.4	39.3
trail 10	Wet drum	119	5.2	73.2	41.3
trial 11	baseline	146	3.9	73.5	37.8
trial 11	Wet drum	119	2.8	76.1	35.3
Day 2, August 18, 2012 ***					
Trial 12	Wet drum	147	1.6	56.6	67.7
trial 12	baseline	145	0	58.6	64.8
trial 13	Wet drum	146	0	65.3	55.6
trial 13	baseline	145	0	69.9	46.4
trial 14	Wet drum	144	0	72.2	42
trial 14	baseline	136	1.9	65.8	55.2
trial 15	Wet drum	125	2.9	66.4	57.7
trial 15	baseline	60	2.1	70.3	49.2
trial 16	Wet drum	31	0	69.1	50
trial 16	baseline	359	2.8	69	46.6
trial 17	Wet drum	0	2.7	72.5	41
trail 17	baseline	8	1.1	72.6	42.9
trial 18	baseline	13	2.2	71.8	38
trial 18	Wet drum	58	1.1	72.3	35.3
trial 19	baseline	6	1.8	77.2	31.9
trial 19	Wet drum	8	2.8	74.8	32.2

*Trials 1-4 were on Larchmont Drive milling east
**Trials 5-11 were on Tenny Avenue milling north
***Trials 12-19 were on Tenny Avenue milling south

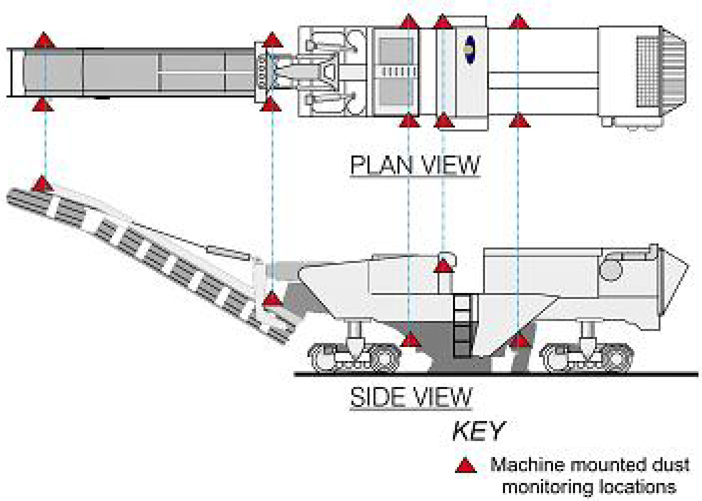

Figure 1: Diagram of typical pavement-milling machine showing 10 area air-sampling locations. (Front of machine is to the left)

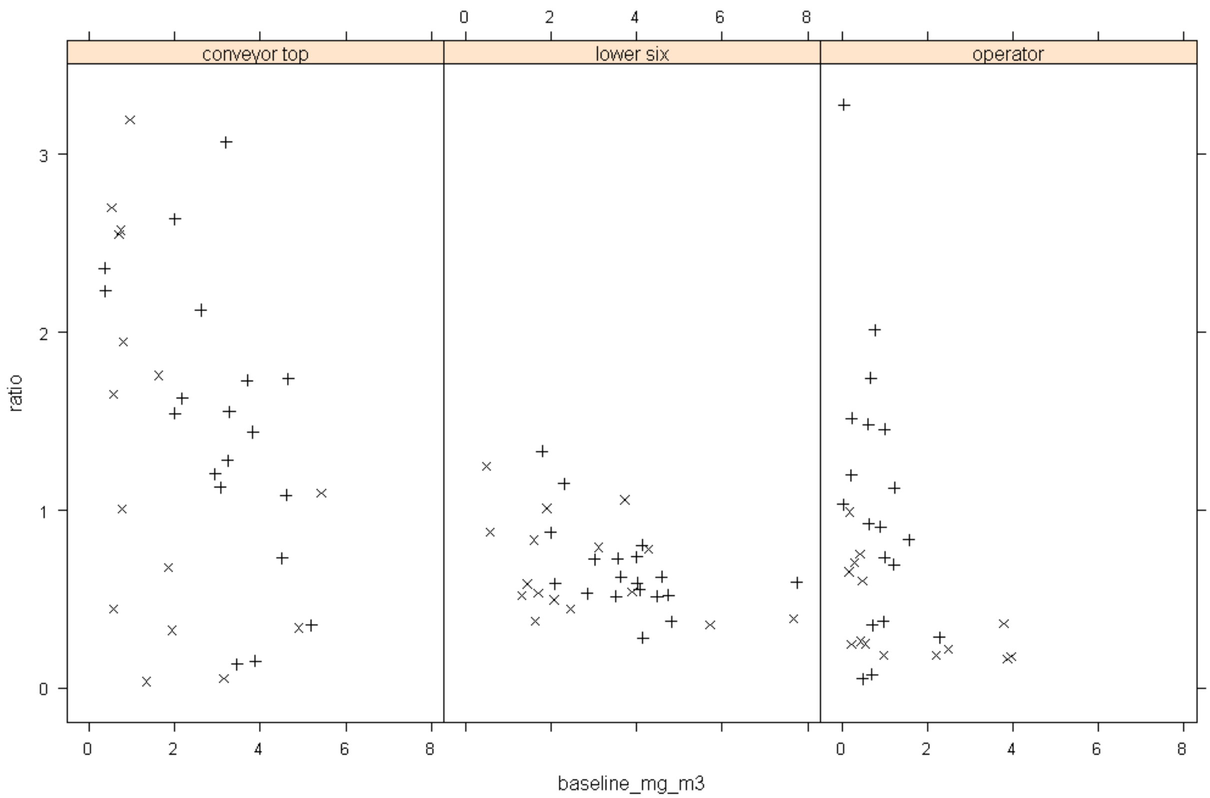

Figure 2: 2010 ("x") and 2012("+") wet drum to baseline ratios at the three locations, plotted versus baseline concentrations in mg/m^3. (One large baseline conveyor top value is not shown.)

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