In-Depth Survey Report

Control Technology for Crystalline Silica Expousre During Pavement Milling Using a Roadtec Milling Machine Equipped with a Local Exhaust Ventilation System

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

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The report was originally published in July 2013. A new version was published in May 2015 with updated statistics to match the procedures used in NIOSH Publication No. 2015-105. The findings and conclusions remain unchanged.

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

Sites Surveyed:

Site 1: US-31N near Greyhound Pass, Carmel, IN

Site 2: Washington Street and South High School Road, Indianapolis, IN

Site 3: East McCarty Street, Indianapolis, IN

Site 4: South Ford Road, Zionsville, IN

Site 5: I-465 between Allisonville Rd and I-69, Indianapolis, IN

Site 6: US-24, Wabash, IN

Site 7: US-24, Ft. Wayne, IN

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

Survey Dates: Site 1: September 18, Site 2: September 19, Site 3: September 20, Site 4: September 21, Site 5: September 27-29, Site 6: October 4, Site 7: October 10-13, 2012

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Abstract

Between September 18th and October 13th, 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 local exhaust ventilation system (LEV) on a Roadtec RX600e cold milling machine. The tests included ten days of air sampling across seven different highway construction sites in Indiana. At each site, full-shift personal breathing zone samples for respirable crystalline silica were collected from the operator and ground man during the course of normal employee work activities of asphalt pavement milling.

The data were analyzed two ways, assuming the data were either normally distributed or lognormally distributed. For small sample sizes it is difficult to distinguish between the two distributions; therefore, results for both are presented. For each distribution a 95% upper confidence limit for the arithmetic mean respirable crystalline silica exposure for each occupation was calculated. For the normal distribution analysis, the arithmetic mean respirable crystalline silica exposure for the operator was 0.0049 mg/m^3 with an upper 95% confidence limit of 0.0075 mg/m^3. The arithmetic mean respirable crystalline silica exposure for the ground man was 0.011 mg/m^3 with an upper 95% confidence limit of 0.017 mg/m^3. For the lognormal distribution analysis, the geometric mean respirable crystalline silica exposure for the operator was 0.0042 mg/m^3 with an upper 95% confidence limit for the arithmetic mean of 0.012 mg/m^3. The geometric mean respirable crystalline silica exposure for the ground man was 0.009 mg/m^3 with an upper 95% confidence limit for the arithmetic mean of 0.0298 mg/m^3.

All 20 full-shift personal breathing zone samples collected from the operator and ground man were below currently published regulatory and recommended occupational exposure limits for respirable crystalline silica. Based on the results of this study, NIOSH researchers recommend that Roadtec should consider refining their design to prevent clogging of the system before making the LEV system a standard feature on all Roadtec half-lane and larger milling machines. A possible solution to prevent clogging would be to further increase the open area at the intake so that the air velocity at the slots is lower without reducing the total volumetric flow-rate of air through the system. A lower intake air velocity should reduce the number of particles larger than the respirable size range of 10 µm from being drawn into the LEV system while keeping the drum housing and primary conveyor under negative pressure.

With these modifications, Roadtec should then make the LEV system a standard feature on all of their half-lane and larger milling machines. NIOSH researchers also recommend that other manufacturers of half-lane and larger cold milling machines should consider implementing dust controls that include 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 pavement 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 Roadtec RX600e with a 2185 mm (86 inch) wide cutter drum. Most 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 Roadtec RX600e cold-milling machine also had a local exhaust ventilation (LEV) system to capture dust generated in the cutter drum housing and remove the dust from worker locations.

This field study evaluated the performance of the LEV system using full-shift, time-weighted average personal breathing zone sampling for respirable dust and respirable crystalline silica exposures of the milling machine operator and ground man during multiple days at each of four sites. The study was conducted during the course of normal employee work activities on typical highway construction milling jobs.

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 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 exposure concentrations 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 time-weighted average (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

Personal breathing zone air samples for respirable dust and respirable crystalline silica were collected from the milling machine operator and ground man 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 (Gilian model GilAir® Plus, Sensidyne®, Clearwater, FL) 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 0.83%, 0.83%, and 1.7%, respectively.

Statistical Methodology

The statistical criterion used here for effective performance of the control system is that the upper 95% confidence limit for the arithmetic mean of each worker's exposure should be less than the recommended exposure limit (REL) for respirable crystalline silica of 0.05 mg/m^3. Thus, the confidence limit is one-tailed, and the values excluded have no more than 5% probability. Although the required 95% upper confidence limits are computed more easily for the assumption of normal distribution, exposure data are usually treated as lognormal [Rappaport and Kupper

2008]. Also, in small data sets it is difficult to distinguish between the two distributions. Thus, results are given here for both scales. For the lognormal analysis we use the methodology of the *Best Practice Engineering Control Guidelines to Control Worker Exposure to Respirable Crystalline Silica during Asphalt Pavement Milling* [NIOSH 2015].

There were measurements on two workers (one operator and one ground man) for each day at each site. Although the resulting PBZ air sampling data have three variance components (between-sites, between days at sites, and within days at sites), the lognormal methodology used here is intended for analysis of each occupation separately. The result is that the between-days at site and the within days at sites variance components are combined. The separate analyses by occupation are done for both scales – normal and lognormal. See the Statistical Appendix for a fuller discussion.

Description of Evaluated Sites

NIOSH researchers conducted full-shift personal breathing zone sampling for respirable crystalline silica from the operator and ground man of a Roadtec RX600e milling machine. The sampling was conducted over a total of ten days across seven different highway construction sites during the course of normal employee work activities of milling asphalt pavement. The following is a description of what was evaluated at each site.

<u>Site 1: US-31N near Greyhound Pass, Carmel, IN</u>

The milling machine removed between 6-inches and 11-inches of asphalt on each pass until the concrete base was exposed. Milling was conducted heading south in the north bound lane and tramming back to the starting point after each pass. Multiple other dust generating sources were present on the same construction site including a broom machine up-wind and a soil stabilization operation down-wind. The broom machine swept dust from the road surface creating a visible cloud of dust that occasionally blew across the milling crew. Dump truck traffic from the soil stabilization operation passed back and forth next to the milling operation all shift in addition to dump truck traffic serving the milling machine. A concrete breaking machine was operating near the milling machine for approximately half of the shift.

<u>Site 2: Washington Street and South High School Road, Indianapolis, IN</u>

The milling machine removed approximately 11-inches of asphalt each pass. Milling was conducted heading east on Washington Street in the morning and north on High School Road in the afternoon. Another milling crew was milling pavement on another section of Washington Street on the other side of High School Road. It is possible that some cross-contamination occurred since the wind was blowing from the direction of the other milling machine toward the evaluated milling machine during most of the day.

<u>Site 3: East McCarty Street, Indianapolis, IN</u>

The milling machine removed approximately 1-inch of asphalt pavement at an average speed of about 12 feet per minute (fpm). The shift lasted from approximately 8:30 am to 2:45 pm with 45-minute delays in between loading each truck up with recycled asphalt pavement. This was not considered to be a typical day of asphalt milling, and the personal breathing zone air sampling results from this site were not used in the statistical analysis.

Site 4: South Ford Road, Zionsville, IN

The milling machine removed approximately 1.5-inches of asphalt pavement at an average speed of 80 fpm. The milling crew milled heading south in the morning and north in the afternoon.

Site 5: I-465 between Allisonville Rd and I-69, Indianapolis, IN

For most of the shift, the milling machine removed approximately 8-9 inches of asphalt pavement and averaged about 20 fpm for the full depth removal. At times, the milling machine removed as much as 11 inches of asphalt pavement. The milling activities occurred at night in between two barrier walls with live freeway traffic which also generated visible dust at times.

Site 6: US-24, Wabash, IN

The milling machine removed approximately 1.5 inches of asphalt pavement heading west on US-24 but only milled a strip of the shoulder that was about 4-feet wide.

Site 7: US-24, Ft. Wayne, IN

The milling machine removed approximately 1.5 inches of asphalt pavement at night.

Control Technology

Description of tested dust-emission control configuration

The equipment evaluated during this study shown in Figure 1 was a Roadtec RX600e cold milling machine with an 86-inch cutter drum and a diesel engine that provides 620 HP at 1850 rpm. The Roadtec RX600e was fitted with an LEV system consisting of a hydraulic powered 7-horsepower (hp) Ilmeg fan connected to a 6-inch diameter duct leading to a manifold that split the flow into two 4-inch diameter ducts that exhausted air at the top of the secondary conveyor. The LEV system was designed to create negative pressure in the primary conveyor area and to exhaust the air away from any workers.

Results

Full-shift personal breathing zone silica exposures during the ten days of sampling across seven sites for the operator and ground man are shown in Table 1 along with the silica content in the bulk and filter samples for each day. Table 1 also shows the full-shift personal breathing zone respirable dust exposures for the operator and the ground man. At the sites studied, the percent bulk silica content varied between 5 and 12%, with the average less than 8%. Silica content in the PBZ filter air samples for the operator and ground man ranged from below the limit of detection to 9%. The same worker did the operator job for all sites; the same worker did the ground man job except for the three days at the seventh site, at which a second worker served as ground man. See the Statistical Appendix for a discussion of how between-worker variability is treated.

The 20 full-shift PBZ air sampling results for the operator and ground man using the Manufacturer B milling machine generally ranged from below the limit of detection to 0.013 mg/m^3 with the exception of one day where the PBZ air sample for the ground man was 0.024 mg/m^3. The third site sampling results (one day) were below the limit of detection but because it was not a typical sampling day, the results were not used in the statistical analysis. Thus, data were used from six sites.

Because the log of the geometric standard deviation (GSD) is comparable to the relative standard deviation (RSD), it makes sense to compare these quantities as shown in Table 2. We call the RSD derived from the GSD the "GSD-based RSD." The between-sites GSD-based RSD is 69% for the ground man, compared to 61% for the RSD. The between-sites GSD-based RSD is 57% for the operator compared to 52% for the RSD. The within site GSD-based RSD is 31% for the ground man, compared to 26% for the RSD. The within site GSD-based RSD is 37% for the operator compared to 35% for the RSD. Thus, the precision is similar for the two scales, though the log scale estimates are larger.

From Table 2, for the normal distribution analysis, the arithmetic mean respirable crystalline silica exposure for the operator was 0.0049 mg/m^3 with an upper 95% confidence limit of 0.0075 mg/m^3. The arithmetic mean respirable crystalline silica exposure for the ground man was 0.011 mg/m^3 with an upper 95% confidence limit of 0.017 mg/m^3. For the lognormal distribution analysis, the arithmetic mean respirable crystalline silica exposure for the operator was 0.0042 mg/m^3 with an upper 95% confidence limit of 0.012 mg/m^3. The arithmetic mean respirable crystalline silica exposure for the ground man was 0.009 mg/m^3 with an upper 95% confidence limit of 0.0298 mg/m^3. Thus, all upper confidence limits are less than the REL.

From the results shown in Table 2, with 95% confidence for each occupation, the arithmetic mean for operator and ground man are each less than the REL. The REL may be considered to be met for the population of sites from which those studies come.

Weather Observations

Table 3 through Table 5 show weather observations from the National Oceanic and Atmospheric Administration (NOAA) fixed weather station nearest to each evaluated site. Wind direction is reported as the angle, measured in a clockwise direction, between true north and the direction from which the wind is blowing. Wind speed is reported as the rate of horizontal travel of air past a fixed point in meters per second (m/s). The average wind speed during the evaluation ranged from 0 to 7.2 m/s. Hourly temperatures during testing at the seven evaluated sites ranged from 0°C (32°F) to 24.5°C (76°F). Relative humidity during testing at the seven evaluated sites ranged from 33% to 93%.

Discussion

The air intake slots on the evaluated LEV dust control system became partially clogged during the first few hours of testing on each of the first two days. At the end of the second day, Roadtec service specialists installed a replacement air intake with 50% larger slots and clean-out ports on the sides to remove any clogging that may be introduced over time. The larger slots helped to prevent clogging over a shift, but some rocks still entered the system and restricted air flow through the LEV duct system. Although the LEV dust control system still protected workers from silica exposures, some additional solutions are needed to prevent larger particles from entering the intake to the LEV system.

In addition to clogging, there were also some problems with the durability of the material used for the flex duct in the LEV system. By the fourth day of testing, holes began appearing in the LEV flex duct at the downstream side of the fan, as shown in Figure 2. Dust could be visibly seen escaping the system through the holes in the duct. One possible solution would be to install duct material that is more rigid on the downstream side of the fan and other locations where rocks damaged the flex duct system. Another solution may be to further decrease the system's intake velocity while maintaining the same volumetric flow to reduce the number of particles greater than the respirable size range of 10 µm that enter the system and damage the duct.

The evaluated LEV system captured dust generated in the drum housing and released the dust at the top of the secondary conveyor at a location away from the workers. During the ten days of air sampling, the LEV system was very effective at reducing exposures to concentrations below all regulatory and recommended exposure limits for respirable dust and respirable crystalline silica. However, there were times during the evaluation when the crew was milling into the wind and the dust released at the outlet of the LEV system was blown back toward the operator and ground man. It would be beneficial to equip the LEV system with an option to control dust in situations that may require milling into the wind. One option would be to have a switch to turn off the LEV system when milling into the wind. If configured with this option, the LEV system should automatically switch on after 30 minutes (or other appropriate period) or there should be an alarm that sounds to remind the operator that the LEV system should be turned back on.

Conclusions and Recommendations

The evaluated Roadtec RX600e (with LEV) has the potential to significantly reduce worker exposure to respirable crystalline silica during pavement milling operations. The control protected workers even when the system was partially clogged and after abrasion caused damage to the flex duct. These problems need to be corrected, but show that the system has a margin of safety and can still protect workers at a reduced air flow rate. At times, the air flow was reduced by as much as 40% by the end of the shift.

All 20 full-shift personal breathing zone samples collected from the operator and ground man using the evaluated Roadtec RX600e (with LEV) were below currently published regulatory and recommended occupational exposure limits for respirable crystalline silica. Based on the results of this study, NIOSH researchers recommend that Roadtec should further refine their design to resolve the clogging issues and to ensure the system has more durable duct work. A possible solution to prevent clogging would be to further increase the open area at the intake so that the air velocity at the slots is lower without reducing the total volumetric flow-rate of air through the system. A lower intake air velocity should reduce the number of particles larger than the respirable size range of 10 µm from being drawn into the LEV system while keeping the drum housing and primary conveyor under negative pressure.

With these modifications, Roadtec should then make the LEV system a standard feature on all of their half-lane and larger milling machines. NIOSH researchers also recommend that other manufacturers of half-lane and larger cold milling machines should implement dust controls that include local exhaust ventilation as a control for silica exposures.

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Table 1: Full-shift personal breathing zone respirable dust and silica exposures for the operator and ground man in mg/m³

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 5	Site 6	Site 7	Site 7	Site 7
Respirable Dust (mg/m³)	18-Sep	19-Sep	20-Sep	21-Sep	27-Sep	28-Sep	4-Oct	10-Oct	11-Oct	12-Oct
Operator	0.08	0.16	0.05	0.18	0.09	0.07	0.13	0.25	0.15	0.11
Groundman	0.13	0.43	0.08	0.16	0.13	0.15	0.13	0.24	0.38	0.17
Silica (mg/m³)	18-Sep	19-Sep	20-Sep	21-Sep	27-Sep	28-Sep	4-Oct	10-Oct	11-Oct	12-Oct
Operator	0.004	0.005	ND*	0.011	0.002	0.002	0.002	0.007	0.006	0.003
Groundman	0.012	0.024	ND	0.012	0.004	0.005	0.004	0.006	0.013	0.008
% silica bulk	5.0%	5.4%, 12%**	7.2%	11.4%	5.5%	6.3%	5.8%	8.1%	8.9%	9.1%
% silica operator	6%	4%	ND	6%	2%	3%	2%	3%	4%	3%
% silica groundman	9%	6%	ND	8%	3%	3%	3%	3%	3%	5%
Operator ID	1	1	1	1	1	1	1	1	1	1
Ground man ID	2	2	2	2	2	2	2	3	3	3

*ND=non-detect (there was no quartz detected in the filter samples on June 26)
**12% silica content on Washington Street and 5.4% silica content on High School Road

Field limit of detection or Minimum Detectable Concentration (MDC) = (LOD of 0.005 mg/sample)/(volume in cubic meters)

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 5	Site 6	Site 7	Site 7	Site 7
Operator MDC	0.0025	0.0020	0.0035	0.0022	0.0019	0.0018	0.0018	0.0022	0.0021	0.0023
Sample time (min)	484	611	338	540	612	678	676	533	559	519
Groundman MDC	0.0025	0.0019	0.0032	0.0022	0.0019	0.0018	0.0017	0.0022	0.0021	0.0023
Sample time (min)	482	614	370	539	620	677	685	533	556	519

Table 2: Personal Breathing zone sample statistics in mg/m³

Occupation	AM (mg/m³) Normal	GM (mg/m³) Lognormal	Between-Site RSD Normal	Between-Site GSD Lognormal	*GSD-Based RSD	Within-Site RSD Normal	Within-Site GSD Lognormal	*GSD-Based RSD	Upper 95% Confidence Limits (AM) for each Occupation Normally Distributed (mg/m³)	Upper 95% Confidence Limits (AM) for each Occupation Lognormally distributed (mg/m³)
Operator	0.0049	0.0042	52%	1.70	57%	35%	1.43	37%	0.0075	0.0118
Ground man	0.0108	0.0090	61%	1.86	69%	26%	1.35	31%	0.0167	0.0298

***The GSD-based RSD value is given by the formula $\{\exp[\ln(GSD) \times \ln(GSD)] - 1\}^{0.5}$ [Rappaport and Kupper 2008].**

Table 3: Wind speed and direction near Sites 1-4 from September 18 (Indianapolis, IN)

Time (HrMn)	700	800	900	1000	1100	1200	1300	1400	1600	1700
Wind direction (°)	280	330	330	320	330	310	320	320	330	310
Wind Speed (m/s)	2.6	4.1	5.7	5.7	4.6	4.1	6.2	5.1	5.1	5.1
Temperature (°C)	19	18	17	16	15	14	14	14	16	16
Relative Humidity %	88	88	88	82	82	87	82	76	63	59

Wind speed and direction near Sites 1-4 from September 19 (Indianapolis, IN)

Time (HrMn)	754	854	954	1054	1154	1254	1354	1454	1554	1654	1754
Wind direction (°)	250	250	210	210	250	220	220	210	200	230	200
Wind Speed (m/s)	2.1	2.6	2.1	1.5	1.5	1.5	2.6	3.6	4.1	4.6	3.6
Temperature (°C)	7.2	6.7	6.7	6.1	6.1	8.3	12.2	15	17.2	18.3	18.3
Relative Humidity %	82	82	85	85	85	83	64	55	42	38	36

Wind speed and direction near Sites 1-4 from September 20 (Indianapolis, IN)

Time (HrMn)	754	854	954	1054	1154	1254	1354	1454
Wind direction (°)	170	170	180	200	190	210	200	220
Wind Speed (m/s)	4.1	3.1	4.6	6.2	4.1	4.6	6.2	7.2
Temperature (°C)	11.7	11.7	11.7	12.8	13.3	14.4	13.9	17.2
Relative Humidity %	66	66	68	61	61	61	63	60

Wind speed and direction near Sites 1-4 from September 21 (Indianapolis, IN)

Time (HrMn)	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800
Wind direction (°)	---	---	---	---	---	---	---	200	190	200	160
Wind Speed (m/s)	0	0	0	0	0	0	0	1.5	2.1	2.1	4.1
Temperature (°C)	7	6	5	6	6	9	14	16	17	17	19
Relative Humidity %	87	93	93	86	93	87	67	55	45	51	39

Table 4: Wind speed and direction near Site 5 at I-465 on September 27 night (Indianapolis, IN)

Time (HrMn)	1900	2000	2100	2200	2300	0	100	200	300	400	500	600
Wind direction (°)	100	90	110	120	---	---	---	---	---	10	---	110
Wind Speed (m/s)	1.5	1.5	2.1	2.6	0	0	0	0	0	2.6	0	1.5
Temperature (°C)	22	22	22	22	21	18	17	18	17	17	17	17
Relative Humidity %	64	64	64	64	68	82	88	88	88	88	82	82

Wind speed and direction near Site 5 at I-465 on September 28 night (Indianapolis, IN)

Time (HrMn)	1900	2000	2100	2200	2300	0	100	200	300	400	500	600
Wind direction (°)	270	330	310	350	290	310	---	---	---	20	20	20
Wind Speed (m/s)	1.5	1.5	1.5	1.5	1.5	2.1	0	0	0	1.5	2.1	2.6
Temperature (°C)	21	21	21	21	19	16	16	14	12	12	12	11
Relative Humidity %	40	43	43	40	48	59	63	71	81	87	87	87

Table 5: Wind speed and direction near site 6 on October 4, on US-24 (Wabash, IN)

Time (HrMn)	755	855	955	1055	1155	1255	1355	1455	1555	1655	1755
Wind direction (°)	220	230	210	---	200	200	220	220	230	220	240
Wind Speed (m/s)	4.6	3.1	3.1	0	3.1	3.6	4.6	4.1	5.1	7.2	5.7
Temperature (°C)	14.4	12.2	11.1	12.1	13.1	13.9	15.9	18.6	21.1	22.8	24.5
Relative Humidity %	79	89	93	92	89	87	80	71	63	56	51

Wind speed and direction near site 7 on October 10 on US-24 (Ft Wayne, IN)

Time (HrMn)	2054	2154	2254	2354	54	154	254	354	454	554
Wind direction (°)	290	310	290	280	220	240	210	220	230	230
Wind Speed (m/s)	6.2	6.2	3.1	2.1	2.1	2.1	3.6	2.6	2.6	2.1
Temperature (°C)	10	9.4	8.3	6.1	3.9	1.1	1.1	1.1	0	0.6
Relative Humidity %	40	40	41	50	64	78	78	78	85	84

Wind speed and direction near site 7 on October 11 on US-24 (Ft Wayne, IN)

Time (HrMn)	2054	2154	2254	2354	54	154	254	354	454	554
Wind direction (°)	230	250	230	230	220	210	220	230	290	340
Wind Speed (m/s)	6.7	6.7	4.6	3.1	3.6	4.1	4.1	4.1	2.6	3.6
Temperature (°C)	15.6	15.6	13.3	10.6	10.6	10	10.6	11.7	11.1	10.6
Relative Humidity %	33	33	40	54	56	60	58	52	56	63

Wind speed and direction near site 7 on October 12 on US-24 (Ft Wayne, IN)

Time (HrMn)	2154	2254	2354	54	154	254	354	454	554
Wind Speed (m/s)	3.1	2.6	1.5	1.5	0	3.1	4.1	3.1	2.6
Relative Humidity %	34	45	50	57	57	64	69	72	78

Figure 1: Evaluated milling machine with local exhaust ventilation system

Figure 2: Tape over duct work near the fan outlet

Statistical Appendix

Description of Statistical Methods

The statistical criterion used here for effective performance of the control system is that the upper 95% confidence limit for the arithmetic mean of workers' exposures should be less than the NIOSH recommended exposure limit (REL) for respirable crystalline silica of 0.05 mg/m^3. Thus, the confidence limit is one-tailed, and the values excluded have no more than 5% probability.

Industrial hygiene data are usually considered to be lognormally distributed, but for small samples sizes it can be difficult to differentiate between the two distributions. For either distribution an upper confidence limit for the arithmetic mean is required. Thus, results are given here for both distributions in Table 2.

For the study considered here, there were measurements on two workers (one operator and one ground man) for each day at each site. The model used for computation of upper confidence limits for the arithmetic means treats each occupation's data separately. This model on the natural log scale for each occupation's exposures is a one-way random effects model, expressed here as:

$$x_{sd} = \mu + a_s + e_{sd}, \qquad \text{(A-1)}$$

where "s" indexes the sites, "sd" indexes the days at the sites, x_{sd} is the actual sampling result when data are analyzed on the original scale or the natural logarithm of the actual sampling result. μ is the mean on either the original scale or the natural log scale(i.e., the natural log of the geometric mean (GM) for the occupation). Site is treated as a random effect (a_s) which is normally distributed with mean 0 and between-site variance σ^2_s. The residual effect, e_{sd}, is also treated as random and normally distributed with mean 0 and variance σ^2_{sd}. Note that because there is just one measurement for each day, the variance σ^2_{sd} includes both between days at sites and within days at sites variability. The two random effects are treated as statistically independent.

a) Normal theory model

For the original scale analysis, the x_{sd} is the measurement at site s on day d. The two variances are defined as they were above. The 95% upper confidence limit for each occupation arithmetic mean on the normal scale uses the standard formula:

$$UCL = \bar{x} + t_{df,\,0.95} \times (s_{\bar{x}})$$

where

UCL = upper confidence limit,

$\bar{x}$ = estimated occupational mean,

$t_{df,,0.95}$ = the 95th percentile of the Student's t distribution with the degrees of freedom df, based on the dfm=kr option in SAS Proc Mixed [SAS Institute 2004] and [Littell et. al. 2006], which is recommended for repeated measures. The degrees of freedom for this study was between 4.5 and 4.8 for the two occupations.

$s_{\bar{x}}$ = standard error of occupation mean estimate.

For operator data, $\bar{x}$=0.004942 and the standard error=0.001248, and $t_{df,0.95}$=2.062 for df=4.53. The upper confidence limit is 0.004942 + 2.062x0.001248=0.0075.

For ground man data, $\bar{x}$=0.01079 and the standard error=0.002896, and $t_{df,0.95}$=2.035 for df=4.79. The upper confidence limit is

0.01079 + 2.035x0.002896=0.0167.

These results appear in Table 2. The "Rsd Normal" estimates in Table 3 are relative to the above $\bar{x}$ values.

b) Lognormal theory model

There are no exact confidence limits for the arithmetic mean for lognormal data, unless the data are a random sample. The method proposed is applicable for data from a one-way random effects model, such as equation (A-1). In that equation x_{sd} is the natural log of the sampling result. The arithmetic mean associated with model (A-1) is given by $\exp(\mu + 0.5(\sigma^2_s + \sigma^2_{d(s)}))$ for which the following 95% upper confidence limit (A-2) is given for the arithmetic mean. The sample variance of the natural log scale site means is denoted by $s^2_{\bar{x}_s}$. The pooled within-site variance is denoted by $astd^2_{ws}$, for which the within site variances are weighted by their degrees of freedom, summed, and divided by the sum of the degrees of freedom. $\bar{\bar{x}}$ is the mean of the log scale site means. (In Table 2, the geometric mean is $e^{\bar{\bar{x}}}$.) n_{sites} is the number of sites. df1= n_{sites} -1; df2 = (number of measurements-number of sites). nbar is the average of the reciprocals of the number of days at the sites. Thus, if there were n days at each site, nbar=1/n. (For the studies considered here, however, the number of days at each site is not the same.) Also, t(0.95,df1) denotes the 95th percentile of the t distribution with df1 degrees of freedom; chisq(0.05,df1) denotes the 5th percentile of the chi square distribution with df1 degrees of freedom; and chisq(1-0.05,df2) denotes the 95th percentile of the chi square distribution with df2 degrees of freedom.

UCL2= $\bar{\bar{x}} + 0.5 s^2_{\bar{x}_s} + 0.5(1-nbar)astd^2_{ws} +$ (A-2)

$$\sqrt{((s\_(\bar{x}\_s)\ \ (t(0.95,df1))/\sqrt{(n\_sites)})^2 + [[[[0.5]]^2 s]]\_(\bar{x}\_s)^4\ (df1/chisq(0.05,df1)\ -1)^2 + (0.5\ (1-nbar))^2\ [[[[astd]]\_ws^4\ (df2/chisq(1-0.05,df2)\ -1)]]^2\ )}$$

where Term1 = $(\bar{\bar{x}} + 0.5s_{\bar{x}_s}^2 + 0.5(1 - nbar)astd_{ws}^2)$, Term2 = $(s\_(\bar{x}\_s)\ (t(0.95, df1))/\sqrt{(n\_sites)})^2$, Term3 = $[[0.5]^2\ s]\_(\bar{x}\_s)^4\ (df1/chisq(0.05, df1)\ - 1)^2$, and Term4 = $(0.5\ (1 - nbar))^2\ [[astd]\_ws^4\ (df2/chisq(1 - 0.05, df2)\ - 1)]^2$.

UCL$_o$ = e^{UCL2} is the required upper confidence limit for the arithmetic mean of occupation o. More detailed discussion of the above confidence limit is given in *Best Practice Engineering Control Guidelines to Control Worker Exposure to Respirable Crystalline Silica during Asphalt Pavement Milling* [NIOSH 2015]. Note that the above methodology is intended to be applied to each occupation's data separately. Although exact confidence limits are available for the arithmetic mean of lognormal data based on a simple random sample, only approximate limits are available for more complicated designs, such as the designs used in the studies described here [NIOSH 2015].

For the data studied here, there are four sites with 1 measurement per site, one site with two measurements, and another site with three measurements, when the two occupations are considered separately. Thus,

nbar= 1/6 * (4*1 + 1/2 + 1/3)=0.8056

For ground man, Term1 = $(\bar{\bar{x}} + 0.5s_{\bar{x}_s}^2 + 0.5(1 - nbar)astd_{ws}^2)$ = -4.7105 + 0.5 * 0.4611 + 0.5 * (1-.8056)*0.0918 = -4.471;

Term2 = $(s\_(\bar{x}\_s)\ (t(0.95, df1))/\sqrt{(n\_sites)})^2$ = $(\text{sqrt}(0.4611) * 2.015/\text{sqrt}(6))^2$ = 0.3120 where df1 = 5 and 2.015 is the 95th percentile of the t distribution with 5 degrees of freedom.

Term3 = $[[0.5]^2\ s]\_(\bar{x}\_s)^4\ (df1/chisq(0.05, df1)\ - 1)^2$ = 0.25 * 0.4622^2*$(5/1.1455-1)^2$ = 0.6019, where 1.1455 is the 5th percentile of the chi square distribution with 5 degrees of freedom.

Term4 = $(0.5\ (1 - nbar))^2\ [[astd]\_ws^4\ (df2/chisq(1 - 0.05, df2)\ - 1)]^2$ = $(0.5 * (1-0.8056))^2$*0.09182^2*$(3/7.8147 -1)^2$ = 0.0000302, for df2 = 3 and where 7.8147 is the 95th percentile of the chi square distribution with 3 degrees of freedom.

Term1 + sqrt(Term2 + Term3 + Term4) = -4.471 + sqrt(0.312 + 0.6019 + 0.0000302) = -3.515

Exponentiation, $e^{-3.515}$ = 0.02975, yields the upper confidence limit.

At the NIOSH website http://www.cdc.gov/niosh/docs/2015-105/ there is a spreadsheet which works when there are multiple measurements at (some) sites. However, the maximum number of sites is 5. If the site means for sites 5 and 7 (the only sites with multiple days) are used in place of the individual values, then all six sites can be treated as one measurement per site. (Recall that because site 3 data were omitted, there are just six sites used in the statistical analysis.) If these values are entered in the "Blank Strategy 2" worksheet of the spreadsheet then similar upper confidence limits are obtained for the two occupations as those shown here. It is not appropriate to use this averaging approach in general, but it works here because there is little variability of between day measurements at the sites.

Model Fitting

There were several workers who did the occupations. One individual served as operator for the entire study. For ground man, the same worker did the occupation at sites 1 to 6. At site 7, a different individual did the ground man occupation. These individuals are identified by id numbers in Table 1. No individual does both occupations.

To test for variability between workers within occupation, the data from the two occupations was used in one statistical model. The discussion below is for the lognormal model, but a similar discussion would apply to the normal model.

Rewrite equation (A-1), to allow for a model for both occupations with four (statistically independent) variance components:

$$x_{sd,o} = \beta_o + \beta_1(o = op) + a_s + b_{sd} + w(o) + e_{osd}. \qquad \text{(A-3)}$$

Note that because there are two measurements per day, the day random effect(b_{sd}) can be separated from the residual random effect (e_{osd}). β_o is the log scale mean for the ground man occupation. The notation $\beta_1(o = op)$ indicates that β_1 only is present for the operator data. Thus, the operator occupation log scale mean is $\beta_o + \beta_1$. Thus, both $\beta_o and\ \beta_1$ are fixed effects. The other new term in eq (A-3) is w(o), which denotes the particular worker doing the occupation, and is treated as a random effect with variance component representing between-worker variance. Thus, this model allows for between-worker variability for each occupation. Thus, the single worker who did the operator occupation is denoted by the number "1". For the ground man occupation, the two individuals who did the ground man occupation are denoted by "2" and "3", as shown in Table 1. The question here is whether the model (A-3) can be replaced by the model (A-4):

$$x_{sd,o} = \beta_o + \beta_1(o = op) + a_s + b_{sd} + e_{osd} \ , \qquad \text{(A-4)}$$

in which the term w(o) term has been removed, and, thus, the between-worker variance is treated as 0.

The statistical significance of the w(o) term can be tested, using SAS Proc Mixed. Littell et al. recommends the use of a Type3 F test, to test the statistical significance of variance components [Littell et al. 2006]. The p-value of the w(o) term greater than 0.4 for this study's data. Alternatively, the log–likelihood using restricted maximum likelihood estimation is the same with or without inclusion of the w(o) term for the two ground man workers, which supports lack of statistical significance.

Therefore, we delete the w(o) term from the model (A-3) and use the model (A-4), which treats the between-worker variance as 0. Estimates from model (A-4) are shown in Table A-2. The data from model (A-4), when considered separately by occupation, have two variance components (site and residual), as required by equations (A-1) and (A-2). The results are shown in Table 2.

The procedure described here is somewhat indirect, because the method that is available to us for the computation of the upper confidence limits on the log scale works only for one occupation at a time.

Table A-1: Estimates for Upper Confidence Limit Equations (A-2)

Symbol	**Ground man**	**Operator**	**Description**
$\bar{\bar{x}}$	-4.71046	-5.46515	Mean of site means, on natural log scale*
$s\_(\bar{x}\_s)\verb|^|2$	0.461138	0.384668	Variance of site mean, on natural log scale*
df1	5	5	Degrees of freedom for sites*
$astd^2_{ws}$	0.091819	0.126675	Weighted average of within-site variances*
df2	3	3	Degrees of freedom for days at sites*
	0.387173	0.282624	Between-site variance
	-4.47096	-5.2605	Term1**
	0.312069	0.260319	Term2**
	0.601964	0.418872	Term3**
	3.02E-05	5.76E-05	Term4**
UCL2	-3.51489	-4.43633	Natural logarithm of upper confidence limit
$\boldsymbol{UCL_O}$	0.029751	0.011839	Upper confidence limit

Table A-2: Model (A-4) Covariance Parameter Estimates

Cov Parm	Estimate*
Between-Sites	0.322
day(site)	0
Residual**	0.110

*The estimated between-sites variance, 0.322, is close to the average of the two site variances given in Table A-1: 0.5(0.387 + 0.283) ~ 0.335

**The residual variance component, 0.11, is close the two within site variances in Table A-1: 0.5(0.092 + 0.127)=0.1095.

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