IN-DEPTH FIELD EVALUATION…

DUST-CONTROL TECHNOLOGY
FOR ASPHALT PAVEMENT MILLING

at

New York State Thruway (Interstate Highway 90) resurfacing project
Donegal Construction, contractor
Hamburg, New York, September 25 and 26, 2006

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

REPORT WRITTEN BY:
Leo Michael Blade, C.I.H.
Stanley A. Shulman, Ph.D.
Alberto Garcia
David A. Marlow

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U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Division of Applied Research and Technology
Engineering and Physical Hazards Branch
4676 Columbia Parkway, Mail Stop R-5
Cincinnati, Ohio 45226-1998

SITE SURVEYED:	New York State Thruway (Interstate Highway 90) resurfacing project Donegal Construction, contractor Hamburg, New York
SIC CODE:	1611 (Highway and Street Construction)
SURVEY DATE:	September 25 and 26, 2006
SURVEY CONDUCTED BY:	Leo Michael Blade, NIOSH/DART Alberto Garcia, NIOSH/DART Stanley A. Shulman, NIOSH/DART David A. Marlow, NIOSH/DART
EMPLOYER REPRESENTATIVES CONTACTED:	Tim Lamantia, Donegal Construction

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The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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ABSTRACT

As part of an ongoing study to evaluate the effectiveness of dust-control systems on pavement-milling machines, a field survey was performed during milling of asphalt on a rural, limited-access, four-lane divided toll highway. The objective of this survey was to estimate the reduction in respirable dust emissions and workers' exposures that could be achieved through the use of higher water-flow rates through the milling machine's water spray system. The effectiveness of the dust controls examined in this study was evaluated by measuring the reduction in the respirable dust and respirable quartz exposures in personal and area samples collected during this typical milling job. Increasing the total water flow to the water-spray nozzles from about 12.5 gallons per minute (gpm) to about 20 gpm did not result in overall reductions in measured respirable dust concentrations at area air monitoring locations around the machine. Instead, the results were quite anomalous, and revealed large differences in the change in concentrations at the sampling locations on one side of the machine compared to the other. Specifically, on the left side of the machine, mean respirable dust concentrations from three sampling and data analysis techniques ranged from 70% to 87% lower during operation at the high water-flow rate than at the low-flow rate, but on the right side of the machine, comparable mean respirable dust concentrations ranged from 4 to 16 times *greater* at high water flow than at low flow. These anomalous results have been considered carefully by NIOSH researchers and machine-manufacturer representatives, and an adequate explanation has not been developed. Clear conclusions cannot be reached from these data. Given the unexplained increases in respirable dust levels associated with the periods of high water flow, the personal breathing-zone exposures measured during the high water-flow periods may be unreliable. However, the measurements did reveal crystalline silica exposures in excess of the NIOSH recommended limit for during low water-flow periods. Ongoing NIOSH research is expected to lead to recommended measures to better control respirable dust and crystalline silica exposures from pavement milling.

INTRODUCTION

The National Institute for Occupational Safety and Health (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 dust that contains crystalline silica, a long-recognized occupational respiratory hazard. Chronic overexposures 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. 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 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, these three 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.

The cold-milling work evaluated during this field survey was a "mill and fill" job, so called because the top layer of pavement surface is milled (usually about 1 to 4 inches is removed), imperfections are filled as needed, the surface is repaved, and the repaired area is reopened to traffic, all within a limited time frame (usually the same day). According to the contractor, the milling work on the New York State Thruway removed between 1 and 4 inches of the existing asphalt pavement, thus correcting surface imperfections such as ruts, super elevations (improperly raised areas of the surface), and cracks. The contractor salvaged the milled material and added it to the asphalt-aggregate mix that was used in repaving the roadway.

This study is facilitated by the Silica/Milling-Machines Partnership, which is affiliated with and coordinated through the National Asphalt Pavement Association (NAPA), and which 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.

NIOSH, a component of the U.S. Centers for Disease Control and Prevention (CDC), was established in 1970 by the federal Occupational Safety and Health Act at the same time that the Occupational Safety and Health Administration (OSHA) was established within the U.S. Department of Labor (DOL). The OSH Act legislation mandated NIOSH to conduct research and education programs separate from the standard-setting and enforcement functions conducted by OSHA. An important field of NIOSH research involves methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the NIOSH Division of Applied Research and Technology (DART) has responsibility within NIOSH to study and develop engineering exposure control measures and assess their impact on reducing the risk of occupational illness. Since 1976, EPHB (and its predecessor, the Engineering Control Technology Branch) has conducted a large number of studies to evaluate engineering control technology based upon industry, process, or control technique. The objective of each of these studies has been to evaluate and document control techniques and to determine their effectiveness in reducing potential health hazards in an industry or for a specific process.

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 Permissible Exposure Limit (PEL), or the American Conference of Governmental Industrial Hygienists (ACGIH®) Threshold Limit Value (TLV®) [NIOSH 2002; 29 CFR 1910.1000 and 29 CFR 1926.55; ACGIH 2009]. The NIOSH REL is 0.05 milligrams (mg) of respirable crystalline silica per cubic meter (m^3) of air, or 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 an equation. For quartz, the following equation applies [29 CFR 1910.1000]:

$$\text{Respirable PEL} = \frac{10\ \text{mg/m}^3}{\%\ \text{Silica} + 2}$$

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].

METHODS

Descriptive data collection

Descriptive data about the milling machine were collected during the field survey and in consultation with the manufacturer's representative. In particular, information about the machine's water-spray system was recorded. During the actual milling and data collection, the forward speed of the mill was recorded by NIOSH researchers observing and periodically recording the foot speed reading on the instrument panel of the mill. The researchers also noted the time when each dump truck was loaded and pulled away from the milling machine as a measure of productivity. Depth of cut was measured periodically during the milling days using a tape measure held at the edge of the cut pavement. The width of the cut was also recorded.

The work practices and use of personal protective equipment by the milling crew were observed and recorded. To help place the sampling results in proper perspective, workers were queried for their perceptions of whether the workloads on the days of the field survey were typical. Observations were recorded describing other operations nearby that generated dust, including the process or activity, its location relative to the milling machine, and whether it was upwind or downwind of the milling machine.

Water-flow and pressure measurements for the water-spray system

Water-flow rate was measured using a digital water-flow meter with a range of 2 to 20 gallons per minute (gpm) installed in the main water-supply line on the mill. Water pressure was measured using a standard analog pressure gauge attached to a "T fitting" also installed in the main water line. NIOSH personnel supplied the manufacturer's representative with the water-flow meter and a pressure gauge. The readings on these devices were observed and recorded periodically during milling.

Air-sampling measurements for respirable dust and crystalline silica

On both days of sampling, personal breathing-zone (PBZ) samples for respirable dust and crystalline silica were collected for both members of the milling crew. During this survey, the PBZ samplers were operated only during actual milling and were stopped at other times. These samples were collected and analyzed according to the following standardized procedures. Each PBZ sample is collected using a battery-operated sampling pump attached to the worker's belt to draw air at a nominal air-flow rate of 4.2 liters per minute (L/min) through a sampling head consisting of a particle-size-selecting cyclone followed by a filter in a cassette, which is connected to the pump via flexible plastic tubing. The air inlet is placed in the worker's breathing zone by clipping it in the shirt-collar area. The filter is a preweighed 37-mm diameter, 5-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. The cyclone (GK 2.69 Respirable/Thoracic Cyclone, BGI Inc., Waltham, MA) is a respirable size-selective device with a machined stainless-steel or aluminum body [NIOSH 1994; HSE 1997]. Filters are submitted for subsequent laboratory analysis as described below.

Area air samples were collected on all three days of sampling at eight locations on the milling machine using an array of instruments mounted on a metal frame which was attached to the machine at each location. The locations, which are shown in Figure 1, included the railings on both sides of the operator's platform, the area near the level controls on both sides of the mill near the rear corners, the area near the cutter drum on both sides of the mill, and on both sides near the transition from the primary conveyor to the loading conveyor. The sampling instruments in each array included a light-scattering aerosol photometer (*p*DR, Thermo Electron Corp., Franklin, MA) operated in the passive-sampling, real-time monitoring mode, with data logging for subsequent download of electronic computerized data files. Concentration measurements were recorded every 5 seconds. Also included in each sampling array were two battery-operated sampling pumps. Each pump was connected via flexible tubing to a standard 10-mm, nylon, respirable size-selective cyclone and a preweighed 37-mm diameter, 5-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 Method 0600. This arrangement is similar to that used for PBZ sampling, except the nominal air-flow rate used with the nylon cyclones is 1.7 L/min. When this apparatus is used for area sampling on a milling machine as during this survey, both the pump and sampling-head assembly are attached to the metal frame. The purpose of these two area samples is to establish the correct time-integrated respirable dust concentration for each sampling location for each entire day so that a correction factor can be calculated to apply to the real-time *p*DR measurements. This is necessary because the *p*DR instruments are calibrated using an aerosol with standardized particle densities and size distributions, and it is necessary to correct the gravimetric concentrations displayed and logged by each instrument to represent those of the actual aerosol measured in the field. A correction factor for each *p*DR instrument for each entire-day period is determined by comparing the mean of all the estimated concentration measurements on that day for that instrument with the mean of the concentration measurements from the two full-day (time-intergated) pump/cyclone/filter samples at the same location. This correction factor is then applied to each concentration measurement from that *p*DR instrument on that day.

Additional "high-flow" area air samples were collected at the same eight locations using the same type of samplers as the PBZ samples (with a nominal air-flow rate of 4.2 L/min and a BGI cyclone), again with both the pump and sampling-head assembly attached to the metal frame mounted at each location. During this survey, the high-flow area samplers were operated only during actual milling, and were stopped at other times, just as with the PBZ samplers.

Gravimetric analysis of each filter for respirable particulate was carried out in accordance with NIOSH Method 0600 [NIOSH 1994]. After this analysis was completed, crystalline silica analysis of each filter from the PBZ and "high-flow" area samples collected at 4.2 L/min with a BGI cyclone was performed using X-ray diffraction in accordance with

NIOSH Method 7500 [NIOSH 1994]. The samples were analyzed for quartz, cristobalite, and tridymite, but only quartz will be reported below. (No tridymite was detected, and only one sample contained cristobalite, at the minimum detectable level.) The filters from the area samples collected at 1.7 L/min with the nylon cyclones were not analyzed for crystalline silica because the only purpose of these samples was to provide respirable-dust data for use in the determination of the correction factors for the real-time *p*DR instrument data as described above.

For the PBZ and "high-flow" area samples, the analytical limits of detection (LODs) were 0.03 mg per sample for particulate mass by gravimetric analysis and 0.01 mg per sample for quartz by X-ray diffraction. For air samples collected at the nominal 4.2 L/min air-flow rate for 100 min, about typical for these samples, the air volume sampled would be 420 L. This sample volume and the listed analytical LODs result in the following minimum detectable concentrations, which may be considered typical for these samples: 0.07 mg/m^3 for respirable dust; and, 0.02 mg/m^3 for respirable quartz. Air-sample results reported as "not detectable" for either of these two air contaminants would indicate concentrations below these values, for air samples of about 100 min in duration.

Experimental design

The participating manufacturers and other Partnership members agreed that testing new or late-model highway-class milling machines with the latest water spray configurations on common "mill-and-fill" highway resurfacing jobs would be preferred. The reason for these choices is to test the best existing dust-suppression technology during the most commonly encountered conditions, which are the mill-and-fill jobs. In this case, the manufacturer provided a late-model mill equipped with the manufacturer's latest spray-system design.

In order to assess the impact of increasing the water-flow rate on dust control, the mill operator was asked to vary the water flow between the flow rate typically used by the operator and the highest available flow rate. The order in which this was done was randomized.

The randomization resulted in the following testing orders:

- September 25—trial of high water flow followed by trial of low water flow; and,
- September 26—trials of low water flow, high water flow, and high water flow

The intention was to collect data again on the night of September 27. However, heavy rain was forecast for later that night and into the early hours of the next morning, when paving would have been required to be completed. Therefore, the milling on the night of September 27 was cancelled, and only two nights of milling were evaluated. (As implied, this was a nighttime mill-and-fill job.)

In order for each time-integrated PBZ and area air sample (with the 4.2-L/min flow rate and BGI cyclone) to measure respirable dust and silica during either a high or low water-flow trial, the filters in these samples were changed between each high or low trial. The target for the actual run time for each filter, in order to sample an adequate air volume, considering the detection limits for crystalline silica, was nominally 2 hours. In practice, as low as 100 minutes was considered acceptable. At approximately 2 hours each, the numbers of trial periods considered possible each night was approximately four, but as noted above, the two nights of the evaluation actually included only two trials on the first night and three on the second night.

RESULTS AND DISCUSSION

Descriptive data and information

This mill was equipped with a spraying system capable of delivering a total of approximately 20.5 gpm. The water system had on-the-fly flow adjustment, whereby the operator could increase or decrease flow by turning a knob. The system provided water spray to both the cutter-drum housing, to cool the teeth and suppress dust via spray bars containing multiple nozzles within the housing, and to the conveyor-transition point to suppress dust via spray nozzles in the transition area. The 7-foot-2-inch-wide cutter drum held metal bits arranged in helical coils around the drum. New bits were installed as needed during the two days of the evaluation.

The milling machine made partial-width and full-width (7-foot-2-inch-wide) cuts on September 25 and 26, but most of the time made full-width cuts. The job was described as a 1- to 4-inch-depth removal, but the milling depth was noted to be about 2 inches most of the time. A broom vehicle followed the mill during this job, sweeping away debris and wetting the milled pavement, but generally stayed an appreciable distance behind. Therefore, airborne dust generated by this vehicle is believed to have had no appreciable effect on measured dust levels.

Productivity was recorded in terms of the number of trucks that were loaded. On September 25, during the high water-flow trial 30 trucks were loaded compared to 24 trucks during low flow. On September 26, during the first high water-flow trial, 19 trucks were loaded, and 26 trucks were loaded during the second high-flow trial, compared to 34 trucks loaded during the low water-flow trial. On average, trucks held between 20 and 23 tons (U.S.) of material.

Both milling crewmen wore safety glasses, safety shoes, and traffic safety vests. The operator spent all of his time on the mill, running the mill from the operator's station. The ground man spent the majority of his time walking alongside the mill, operating the grade controls.

The ambient air temperatures fell quickly both nights after sunset. The temperatures during the work shifts were predominantly in approximately the 5°C-to-9°C range (in the 40ºFs).

Water-spray system water-flow and pressure measurements

During the high water-flow trial on September 25, the total water-flow rate (to the cutter-housing water-spray bars and conveyor-transition water-spray nozzles combined) was about 20.2 gpm. During the low-flow trial, the total water flow averaged about 12.6 gpm. The corresponding water-pressure readings at the main water supply line averaged 46.5 pounds per square inch-gauged (psig) during the high water-flow trial, and 20 psig during the low water-flow trial.

On September 26, the average total water-flow rate was approximately 12.3 gpm during the low water-flow trial and 20.5 gpm during the high-flow trials. The corresponding water-pressure readings at the main water supply line averaged 20 psig during the low water-flow trial and 50 psig during the high-flow trials.

Time-integrated air-sampling results

Personal breathing-zone sample results for September 25 and 26 are presented in Table 1. A total of 10 samples was collected, 5 for the operator and 5 for the ground man. Two samples were collected for each employee on September 25 and three samples for each employee on September 26. The September 25 sample trials were one long-term high-water-flow and one long-term low water-flow trial. On September 26, there was one low-water flow and two high-water flow trials. For both days of sampling, the same employee served as operator and, likewise, for both days of sampling, the same employee served as ground man.

The respirable dust exposures for the operator ranged from 0.31 to 0.62 mg/m^3 during low water flow, and from 0.57 to 2.2 mg/m^3 during high water flow. The ground man's respirable dust exposures ranged from 0.42 to 0.53 mg/m^3 during low water flow and from 0.66 to 0.89 mg/m^3 during high water flow. PBZ respirable dust exposures were higher during the high water-flow trials than during the low-flow trials; on average, about 130% higher. Eight-hour time-weighted average (TWA) exposures were not calculated for these results because the test conditions (water flow rates) were varied during each day of sampling.

Note that in Table 1, time-weighted averages (but not 8-hour) were computed three different ways:

1. First, a time-weighted average is shown for the actual sampling period, which excluded periods of inactivity, i.e., when no asphalt was being milled. (The breathing-zone air samplers were stopped during these periods, and the times recorded.) A worker's full-workshift TWA exposure would be best approximated by this TWA value if the observed milling activity during the particular low or high water-flow trial had been sustained continuously for an entire shift, using the indicated water-flow rate. However, since milling jobs always include some periods of inactivity, this value represents an upper estimate for a full-shift TWA

exposure under the observed conditions and water-flow rate.

2. Second, an estimated time-weighted average of exposure during both periods of activity and inactivity is shown, for which estimated exposures during periods of inactivity were based on *p*DR real-time area-sampling results. For the operator, the *p*DR measurements at the right and left operator locations during periods of inactivity were averaged to obtain estimates of what the corresponding breathing-zone exposures would have been, and for the ground man, the *p*DR measurements at the cutter left and right and rear-corner left and right locations were averaged to obtain the required estimates for periods of inactivity. (A relationship between operator breathing-zone exposures and average operator-location area concentrations is discussed below.) This is the best available estimate of the worker's potential full-shift TWA exposure if the observed milling activity and periods of inactivity during the particular low or high water-flow trial had continued for an entire shift, with the ratio of the respective time periods for activity and inactivity remaining similar to that recorded for the actual trial, while using the indicated water-flow rate during the milling.

3. Last, an estimated time-weighted average of exposure during both periods of activity and inactivity is shown, for which estimated exposures during periods of inactivity were assigned respirable-dust concentrations of 0. This alternate method of estimating exposures during inactivity periods is used in recognition of some amount of uncertainty in the estimates produced using the second method, which depend on the quality of the correlation between actual breathing-zone exposures and average *p*DR real-time concentrations measured at adjacent areas. Since exposures to respirable dust at a highway construction site are unlikely to cease entirely even during periods of inactivity, this value represents a lower-end estimate for a full-shift TWA exposure under the observed conditions and water-flow rate.

As this discussion suggests, the three different methods usually yield results as follows: method #1 yields the highest TWA, method #2 yields an intermediate TWA, and method #3 yields the lowest TWA. Thus, when the computed TWA exposures are compared to the calculated OSHA construction-industry PELs (see footnotes to Table 1), method #1 yields one of eight exposures that exceed the PEL, method #2 yields no exposures that exceed the PEL and one of eight that equals it, and method #3 yields no exposures out of eight that exceed the PEL. Since the TWAs in Table 1 do not represent actual 8-hour TWA exposures, the results indicate only *potential* full-shift exposures if the calculated TWA exposures continued for a full 8-hour shift. In that case, the higher of the two calculated TWA exposures in question would have exceeded the calculated OSHA construction-industry PEL and the other would have equaled it. (If similar calculations are performed using the more-stringent general-industry PEL formula, more of the exposures potentially would exceed PELs so determined.)

PBZ respirable quartz results are also given in Table 1. The individual sample results ranged from (0.04) to 0.060 mg/m^3 for the operator at low water flow and from 0.097 to 0.36 mg/m^3 for the operator at high water flow. (Note that the parentheses around a value indicate that the measurement is less than the limit of quantification, but greater than the limit of detection.) Corresponding values for the ground man were (0.02) to 0.098 mg/m^3 at low water flow and 0.12 to 0.16 mg/m^3 at high water flow. Table 1 includes results from two methods for calculating the TWA—the same as methods #1 and #3 described above for the respirable dust. Method #2 is not presented because the real-time results used in method #2 apply only to respirable dust, not to quartz. For both TWA-computation methods #1 and #3, six of the eight TWAs exceeded the 0.05 mg/m^3 REL. Also for both TWA-computation methods #1 and #3, seven of the eight TWAs exceeded the 0.025 mg/m^3 TLV for quartz. As discussed for the PELs, these would be considered actual exceedances of these recommended exposure limits if the calculated TWAs represented exposures for full 8-hr shifts.

Time-integrated area air sample results for respirable dust and quartz are presented in Tables 2 and 3. A total of 40 area samples was collected, representing five sets of samples collected at the eight locations on the milling machine. Two of these sets of samples were collected on September 25 and three were collected on September 26. For the 24 area samples collected during high-flow trials over the two days, the arithmetic mean respirable dust concentration was 4.37 mg/m^3 (σ [standard deviation] = 1.78), with a geometric mean of 1.57 mg/m^3 (GSD [geometric standard deviation] = 1.37), where both standard deviations represent variation between days. Analyses of the 16 area samples collected at the eight locations around the mill during a total of two low-flow trials over the two days revealed an arithmetic mean respirable dust concentration of 3.38 mg/m^3 (σ = 2.56) and a geometric mean concentration of 1.45 mg/m^3 (GSD = 1.67). The ratio of geometric means for the samples collected during high water-flow trials to those from the low-flow trials was 1.08, indicating an increase of about 8% in the respirable dust concentrations when the high water flow rate was used.

Results for the time-integrated air samples also were evaluated by day. The geometric mean for the area samples collected during the high water-flow trial on September 25 was 1.96 mg/m^3, and the corresponding geometric mean for that day's low-flow trial was 1.01 mg/m^3. The ratio for high-flow to low-flow results was 1.94, corresponding to an increase of about 94% during high water flow. For September 26, the geometric mean for the area samples collected during high water flow was 1.25 mg/m^3, and the corresponding low-flow geometric mean was 2.08 mg/m^3. The resulting ratio of high-to-low water-flow results is 0.60, which corresponds to a reduction in geometric-mean respirable-dust concentration of about 40% during high water flow. The corresponding respirable-dust results for the personal samples were 0.71 and 1.24 mg/m^3, respectively, during high water flow on September 25 and 26. At the low flow levels the results were 0.40 and 0.51 for those dates. The overall reductions in exposures were −78% and −143% for the two dates, or, equivalently, 78% and 143% increase for the two dates, at high water flow relative to respirable-dust exposures during low water flow.

For respirable quartz, the area-sample results were as follows. For high water flow, the arithmetic mean was 0.58 mg /m^3 (σ = 0.12) while the geometric mean was 0.27 mg/m^3 (GSD = 1.25). For low water flow, the arithmetic mean was 0.273 mg/m^3 (σ = 0.018) while the geometric mean was 0.13 mg/m^3 (GSD = 1.05). From the geometric means, there is greater than 100% increase in respirable-quartz concentrations associated with high water flow.

A better understanding of how to interpret these surprising results – the failure of higher water flow to demonstrate reductions in respirable dust and quartz concentrations – will be obtained by examination of the real-time, direct-reading (*p*DR) sampling results.

"Real-time" continuous-monitor (*p*DR) respirable-dust results

The results of real-time monitoring for respirable dust concentrations conducted using *p*DRs at the eight area air-sampling locations on the milling machine are shown by date and location in Table 4. At each of these locations a measurement was recorded every 5 seconds. Averages of the individual measurements (both arithmetic and geometric means) from each low water-flow and high water-flow trail, for each day and location, are provided in the table. To obtain the logarithm of the data for statistical analyses, a value of 0.001 was added to every measurement of "zero". The value 0.001 corresponds to the lowest positive result obtainable from a *p*DR.

When all of the *p*DR results were combined for both days, the arithmetic mean respirable dust concentration for the high water-flow trials was 3.5 mg/m^3 (σ = 1.2). The geometric mean respirable dust concentration for the high-flow trials was 0.17 mg/m^3 (GSD = 2.3). The two-day combined arithmetic mean respirable dust concentration for the low water-flow trials was 2.8 mg/m^3 (σ = 2.9). The overall geometric mean respirable dust concentration for the low-flow trials was 0.11 mg/m^3 (GSD = 5.59). The ratio of the high water-flow to low water-flow geometric mean results is 1.6. This indicates that the respirable dust concentrations overall during the high water-flow trials were about 60% higher than those measured during the low-flow trials.

By day, the geometric mean respirable dust concentration during the high water-flow trials on September 25 was 0.32 mg/m^3 and 0.047 mg/m^3 during the low-flow trials; the resulting ratio shows concentrations about 580% higher during the high-flow trials. On September 26, the geometric mean concentration during the high water-flow trials was 0.10 mg/m^3, while it was 0.54 mg/m^3 during the low-flow trials, corresponding to a reduction of about 81%. This large difference between days is evident in the bar chart shown in Figure 2. Figure 3 is a plot of the fractional reduction of trial geometric-mean respirable-dust concentrations from high to low water flow versus the geometric mean at low water flow. The figure suggests that as the low flow geometric mean becomes relatively large, the reduction due to high water flow becomes consistently positive. Note that three of the four highest geometric means in the figure occurred on September 26. An interpretation of this information is that higher water flow being effective in reducing respirable-dust concentrations is only evident when the "baseline" concentration at low water flow is relatively high.

Short-period subset data. An alternative analysis was carried out with the *p*DR real-time data collected during the long-time trials. Subsets of the data were selected from relatively short periods of time just before and just after the time when a transition was made from one water control level to the other. The aim was to select data during limited time periods of milling equivalent to the removal of between two and four truck loads of asphalt at each of the adjacent water-flow settings. By this procedure, one short-period pair consisting of data from a high and a low water-flow trial was constructed for each of the two days of sampling. The data are summarized in Table 5. The plots for these data that correspond to Figures 2 and 3 for the full-trial-period data are shown in Figures 4 and 5. The data that constitute the short-period subset pairs are included in large braces in Figure 6.

For these short-period data subsets during high water-flow trials across all sampling locations, the arithmetic mean respirable dust concentration was 3.2 mg/m^3 (σ = 1.7) while the geometric mean concentration was 0.16 mg/m^3 (GSD = 1.2). The arithmetic mean respirable dust concentration for the short-period subset data during the low-flow trials was 2.4 mg/m^3 (σ = 3.0) and the geometric mean was 0.10 mg/m^3 (GSD 5.7). The ratio of geometric mean concentrations was 1.60, representing an increase of 60% in respirable dust concentrations. There is again considerable difference by day. Whereas a 450% concentration increase at high flow relative to that at low flow occurred on September 25, on September 26, a 63% reduction occurred.

Figure 6 demonstrates the considerable variability over the period of sampling for these data. For both dates, the concentration levels decreased considerably over the first two trials. Whether this relates to the night work and the drop in temperature after dark is unclear.

Differences by Side of Machine. Examination of the full-trial *p*DR data indicates that whereas substantial reductions in respirable-dust concentrations were measured at the sampling locations on the left side of the milling machine during high water-flow trials, compared with the concentrations during low flow, there were substantial increases at high flow on the right side. In particular, the geometric means for the four locations on the right side at high water flow was 0.61 mg/m^3, compared to 0.036 mg/m^3 at low flow. The ratio is about 17, indicating a 1600% increase. On the other hand, the left side geometric mean was 0.046 mg/m^3 for the high flow and 0.35 mg/m^3 for the low flow. The ratio of 0.05 to 0.35 indicates an 87% reduction at high flow. The bar chart in Figure 2 indicates how consistent this is by date — for both dates the right side reduction values are strongly negative (indicating large *increases*), compared with the left side reductions, which are mostly positive. In general, the full-trial *p*DR results are consistent with the time-integrated area-sample results in this regard.

Further discussion of short-period subset data. The reason to include the short-period subset data was to perhaps obtain better control of variability over time and space. For instance, by limiting the data in each trial to several trucks selected close to the time of transition from one water-flow setting to the other, in many instances there would not be much change in physical location or in the outdoor conditions. In theory, this would allow for a better comparison. The results, however, are somewhat different from those in Figure 2. Whereas the full trial data do show respirable dust concentration increases at high water flow on the right side on both dates (though much larger increases occurred on September 25), the subset data show substantial reduction on the right side on September 26. The left side shows reduction on both dates for both data sets.

Relating side effects in *p*DR area data to PBZ exposure data

The *p*DR area dust samples have been used to model the respirable dust exposures of the workers. A simple model expresses operator exposure as a linear function of the average of the right side and the average of the left side sample results. However, only the operator right side area samples are statistically significant.

Using explanatory variables

In statistical modeling, the variable Y is often referred to as the response variable, while the variables X_1, X_2, etc. are called explanatory variables, because of their use in *explaining* the *response* in Y. Table 6 contains the average results of responses and selected explanatory variables for each of the long-term pairs. For the variables “real-time,” “respirable,” and “quartz,” the averages shown in Table 6 are the geometric means. For the explanatory variables analyzed (respirable dust time-integrated sample results, real-time *p*DR data for respirable dust, and respirable quartz results from the time-integrated samples), whether the geometric means or the natural log of the geometric means was used as the response variable, the model that explained the most variability was that which included the flow rate or the water pressure, when the data are modeled separately by side. The other variables did not contribute much explanatory power.

CONCLUSIONS AND RECOMMENDATIONS

Increasing the total water flow to the water spray nozzles from about 12.5 gpm to about 20 gpm did not result in overall reductions in measured respirable dust and quartz concentrations at area air-monitoring locations around the machine. Instead, the results were quite anomalous, and revealed large differences in the change in concentrations at the sampling locations on one side of the machine compared to the other. Specifically, on the left side of the machine, mean respirable dust concentrations from three sampling and data analysis techniques ranged from 70% to 87% lower during operation at the high water-flow rate than at the low-flow rate, but on the right side of the machine, comparable mean respirable dust concentrations ranged from 4 to 16 times *greater* at high water flow than at low flow. These anomalous results have been considered carefully by NIOSH researchers and machine-manufacturer representatives, and an adequate explanation has not been developed. Clear conclusions cannot be reached from these data.

Given the unexplained increases in respirable dust levels associated with the periods of high water flow, the personal breathing-zone exposures measured during the high water-flow periods may be unreliable. However, the measurements did reveal crystalline silica exposures in excess of the NIOSH recommended limit for during low water-flow periods.

Recommendation #1. The potential for pavement-milling workers to be overexposed to crystalline silica should be assessed based upon the results of all field work in the ongoing NIOSH study, rather than the results from this field survey alone, as should the efficacy of increased water flow in controlling respirable dust and crystalline silica emissions. The unexplained, anomalous results from this survey for the measured air-contaminant concentrations during high water-flow trials seem unreliable as an indicator of exposures or the performance of this milling machine.

Recommendation #2. Decisions regarding continuing research should be based upon the results of all field work in the ongoing NIOSH study, including this field survey.

Recommendation #3. As the results of continuing research being conducted by NIOSH become available and lead to recommendations for better controlling pavement-milling workers' exposures to respirable dust and crystalline silica, the manufacturers and users of these machines should assure that these recommendations are implemented.

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Table 1. Personal Breathing Zone Air Sample Results by Job

Job Title	Water Flow-Rate Condition	Sample Duration (min)	Respirable Dust Exposure – Sample Concentration (mg/m^3)	Respirable Dust TWA Exposure, Exclude periods of inactivity – Concentration (mg/m^3)	Respirable Dust TWA Exposure, Include estimated exposure during periods of inactivity* – Concentration (mg/m^3)	Respirable Dust TWA Exposure, Treat periods of inactivity as "zero exposure" – Concentration (mg/m^3)	Respirable Quartz Exposure – Sample Concentration (mg/m^3)	Respirable Quartz TWA Exposure, Exclude periods of inactivity – Concentration (mg/m^3)	Respirable Quartz TWA Exposure, Treat periods of inactivity as "zero exposure" – Concentration (mg/m^3)
Sept 25									
Operator	Low	114	0.31	0.31	0.30	0.26	(0.04)**	(0.04)	(0.03)
	High	147	0.57	0.57	0.44	0.34	0.097	0.10	0.058
Ground Man	Low	116	0.53	0.53	0.51	0.45	0.098	0.098	0.086
	High	176	0.89	0.89	0.71	0.54	0.16	0.16	0.093
Sept 26									
Operator	Low	127	0.62	0.62	0.66	0.58	0.060	0.060	0.056
	High	121	2.1	2.2†	1.2†	1.0	0.31	0.33	0.17
	High	116	2.2				0.36		
Ground Man	Low	129	0.42	0.42	0.42	0.42	(0.02)	(0.02)	(0.02)
	High	91	0.77	0.71	0.58	0.34	0.13	0.12	0.061
	High	120	0.66				0.12		

*The *p*DR area respirable-dust determinations were used to estimate exposures during periods of inactivity. See text.

** Values in parentheses indicate that the collected mass was between the analytical limit of detection and limit of quantification.

† OSHA construction-industry PELs were calculated and compared with calculated equivalent respirable-dust exposures in mppcf, as described in the text. The calculated ratio of exposure to PEL is the "severity factor." Severity factors smaller than 1 indicate no exceedance of the calculated PEL, and those exceeding 1 indicate exceedance of the PEL. The severity factors for the two TWA exposure levels footnoted, 2.2 and 1.2, are, respectively, 1.8 and 1.0. This indicates exposures that would, if continued for an entire 8-hr shift, exceed and equal, respectively, the calculated PELs.

Table 2. Time-Integrated Area Air Sample Results by Location, September 25, 2006

Sampling Location	Water Flow-Rate Condition	Sample Duration (min)	Respirable Dust – Sample Concentration (mg/m^3)	Respirable Dust – TWA Concentration (mg/m^3)	Respirable Quartz – Sample Concentration (mg/m^3)	Respirable Quartz – TWA Concentration (mg/m^3)
Operator Platform – Left	Low	115	1.3	1.3	0.22	0.22
	High	138	1.2	1.2	0.20	0.20
Operator Platform – Right	Low	115	0.31	0.31	(0.04)*	(0.04)
	High	147	1.3	1.3	0.24	0.24
Cutter Drum – Left	Low	104	3.6	3.6	0.60	0.60
	High	140	2.0	2.0	0.32	0.32
Cutter Drum –Right	Low	105	0.86	0.86	0.17	0.17
	High	142	3.3	3.3	0.62	0.62
Left Rear	Low	71	0.59	0.59	(0.09)	(0.09)
	High	132	0.63	0.63	0.11	0.11
Right Rear	Low	103	(0.2)*	(0.2)	(0.04)	(0.04)
	High	142	1.1	1.1	0.20	0.20
Conveyor – Left	Low	102	3.8	3.8	0.56	0.56
	High	139	2.5	2.5	0.41	0.41
Conveyor – Right	Low	105	1.9	1.9	0.35	0.35
	High	125	13	13	1.2	1.27

* Values in parentheses represent results between the limit of detection and limit of quantification of the analytical method.

Table 3. Time-Integrated Area Air Sample Results by Location, September 26, 2006

Sampling Location	Water Flow-Rate Condition	Sample Duration (min)	Respirable Dust – Sample Concentration (mg/m^3)	Respirable Dust – TWA Concentration (mg/m^3)	Respirable Quartz – Sample Concentration (mg/m^3)	Respirable Quartz – TWA Concentration (mg/m^3)
Operator Platform – Left	Low	128	1.8	1.8	0.11	0.11
	High	121	(0.09)*	(0.07)	(0.02)	(0.02)
	High	125	(0.05)		(0.02)	
Operator Platform – Right	Low	132	0.52	0.52	(0.05)	(0.05)
	High	121	2.4	2.4	0.32	0.34
	High	120	2.3		0.36	
Cutter Drum –Left	Low	125	6.0	6.0	0.35	0.35
	High	116	1.3	1.3	0.20	0.21
	High	125	1.3		0.22	
Cutter Drum –Right	Low	125	4.6	4.6	0.32	0.32
	High	115	19	14	2.5	2.0
	High	124	10		1.4	
Left Rear	Low	126	0.37	0.37	(0.03)	(0.03)
	High	116	ND	(0.05)**	(0.02)	(0.02)
	High	125	(0.06)		(0.02)	
Right Rear	Low	126	0.20	0.20	(0.02)	(0.02)
	High	65	0.66	1.3	(0.10)	0.24
	High	37	2.3		0.48	
Conveyor – Left	Low	125	11	11	0.53	0.53
	High	120	1.5	1.4	0.23	0.22
	High	125	1.3		0.22	
Conveyor – Right	Low	125	17	17	0.87	0.87
	High	130	24	24	2.5	2.9
	High	124	24		3.4	

ND indicates a value less than the limit of detection of the analytical method.
* Values in parentheses represent results between the limit of detection (LOD) and limit of quantification of the method.
** For TWA calculations, value for "ND" is estimated using the following formula to estimate the collected mass: LOD / √2.

Table 4. Real-Time *p*DR Area Air Monitoring Results by Location and Day –
Full Long-Time Trial-Period Arithmetic Means (AM) and Geometric Means (GM)

	Sept. 25			Sept. 26		
Sampling Location	Water Flow-Rate Condition	AM of Respirable Dust Concentrations (mg/m³)	GM of Respirable Dust Concentrations (mg/m³)	Water Flow-Rate Condition	AM of Respirable Dust Concentrations (mg/m³)	GM of Respirable Dust Concentrations (mg/m³)
Operator Platform – Left	Low	1.11	0.49	Low	1.46	0.16
	High	1.10	0.41	High	0.097	0.002
				High	0.074	0.003
Operator Platform – Right	Low	0.23	0.0043	Low	0.78	0.24
	High	1.02	0.20	High	3.49	1.24
				High	2.76	1.00
Cutter Drum – Left	Low	2.70	1.05	Low	2.79	0.77
	High	2.27	0.58	High	0.35	0.009
				High	0.34	0.013
Cutter Drum – Right	Low	0.61	0.011	Low	1.85	0.44
	High	2.73	0.75	High	7.20	2.97
				High	5.24	2.33
Left Rear	Low	0.27	0.073	Low	0.27	0.047
	High	0.44	0.15	High	0.083	0.004
				High	0.064	0.004
Right Rear	Low	0.0042	0.0018	Low	– *	–
	High	1.39	0.051	High	0.70	0.18
				High	0.64	0.14
Loading Conveyor – Left	Low	1.65	0.55	Low	9.19	1.65
	High	1.42	0.27	High	0.94	0.013
				High	0.83	0.023
Loading Conveyor – Right	Low	1.55	0.014	Low	19.63	12.62
	High	11.06	1.45	High	26.77	11.84
				High	19.40	10.82

* Data not available.

Table 5. Real-Time *p*DR Area Air Monitoring Results by Location and Day – Short-Period Subset Data – Geometric Means* of Respirable-Dust Concentrations (mg/m^3)

Sampling Location	Water Flow-Rate Condition	Sept. 25, 2006	Sept. 26, 2006
Operator Platform – Left	Low	0.0046	0.03
	High	0.23	0.00
Operator Platform – Right	Low	0.47	1.04
	High	0.27	0.47
Cutter Drum – Left	Low	0.085	0.33
	High	0.41	0.08
Cutter Drum – Right	Low	0.63	1.73
	High	1.07	0.0063
Rear Left	Low	0.025	0.04
	High	0.084	0.02
Rear Right	Low	0.005	– **
	High	0.0046	0.005
Loading Conveyor – Left	Low	0.21	0.46
	High	0.20	0.21
Loading Conveyor – Right	Low	7.86	15.19
	High	2.87	7.86

* Geometric means are provided for each entire day, not for each trial within each day.
** Data not available.

Table 6. Explanatory Variables

Variable	Low Water Flow, Sept. 25	High Water Flow, Sept. 25	Low Water Flow, Sept. 26	High Water Flow, Sept. 26	High Water Flow, Sept. 26
Real-Time Respirable Dust (mg/m^3)	0.047	0.32	0.54	0.0981	0.103
Real-Time Respirable Dust (mg/m^3) – Right Side	0.0059	0.33	1.10	1.674	1.367
Real-Time Respirable Dust (mg/m^3) – Left Side	0.38	0.31	0.31	0.00575	0.0078
Time-Integrated Respirable Dust (mg/m^3)	1.0	2.0	2.08	1.23	1.27
Time-Integrated Respirable Dust (mg/m^3) – Right Side	0.564	2.766	1.692	5.157	6.055
Time-Integrated Respirable Dust (mg/m^3) – Left Side	1.793	1.393	2.549	0.296	0.267
Respirable Quartz (mg/m^3)	0.169	0.318	0.145	0.214	0.252
Respirable Quartz (mg/m^3) – Right Side	0.100	0.437	0.132	0.672	0.956
Respirable Quartz (mg/m^3) – Left Side	0.285	0.231	0.159	0.068	0.066
Number of Trucks	24	30	34	19	26
Water Flow (gpm)	12.6	20.2	12.3	20.7	20.3
Water Pressure (psi)	20	46.5	20	50	50

Figure 1. Air Sampling Locations on Milling Machine

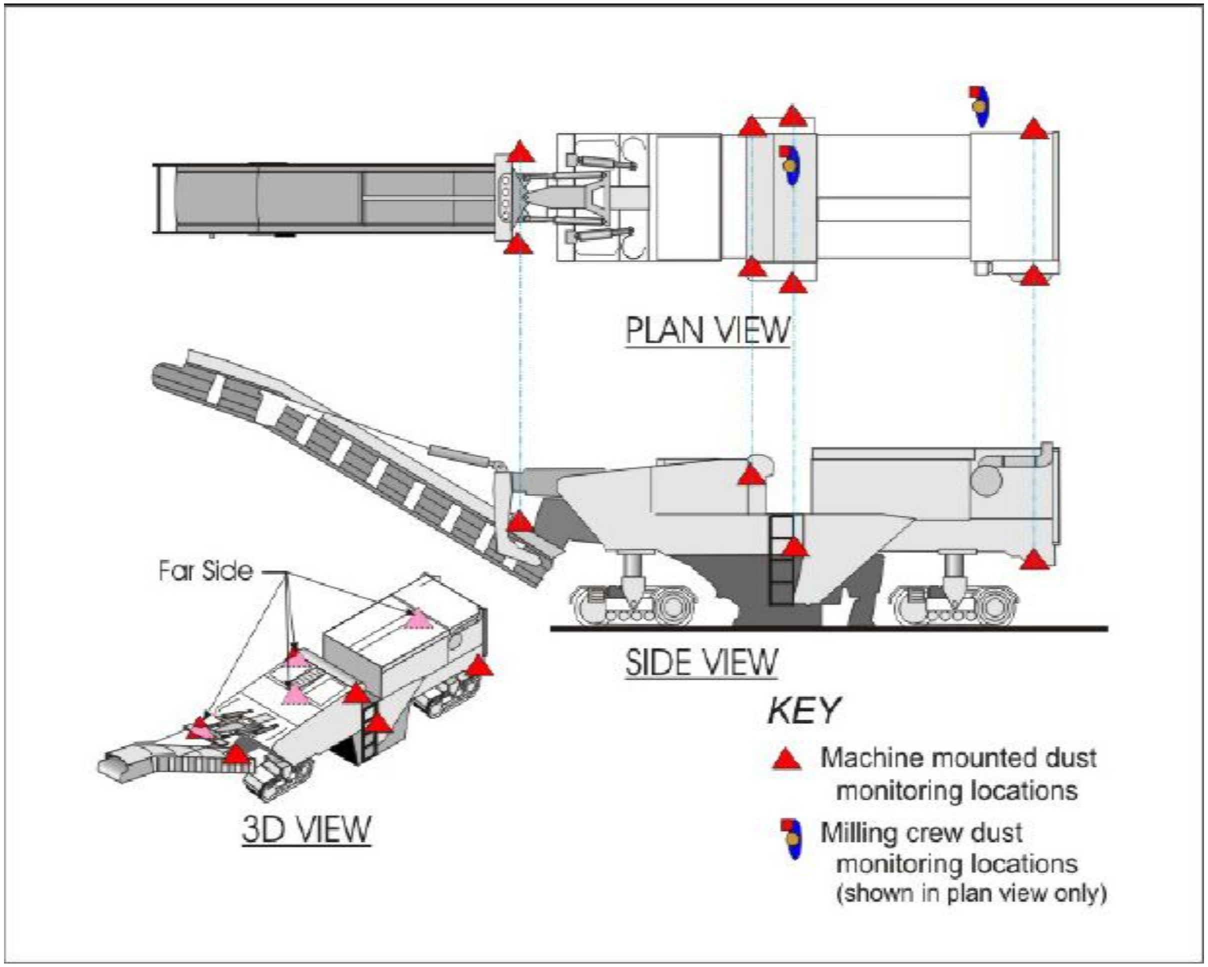
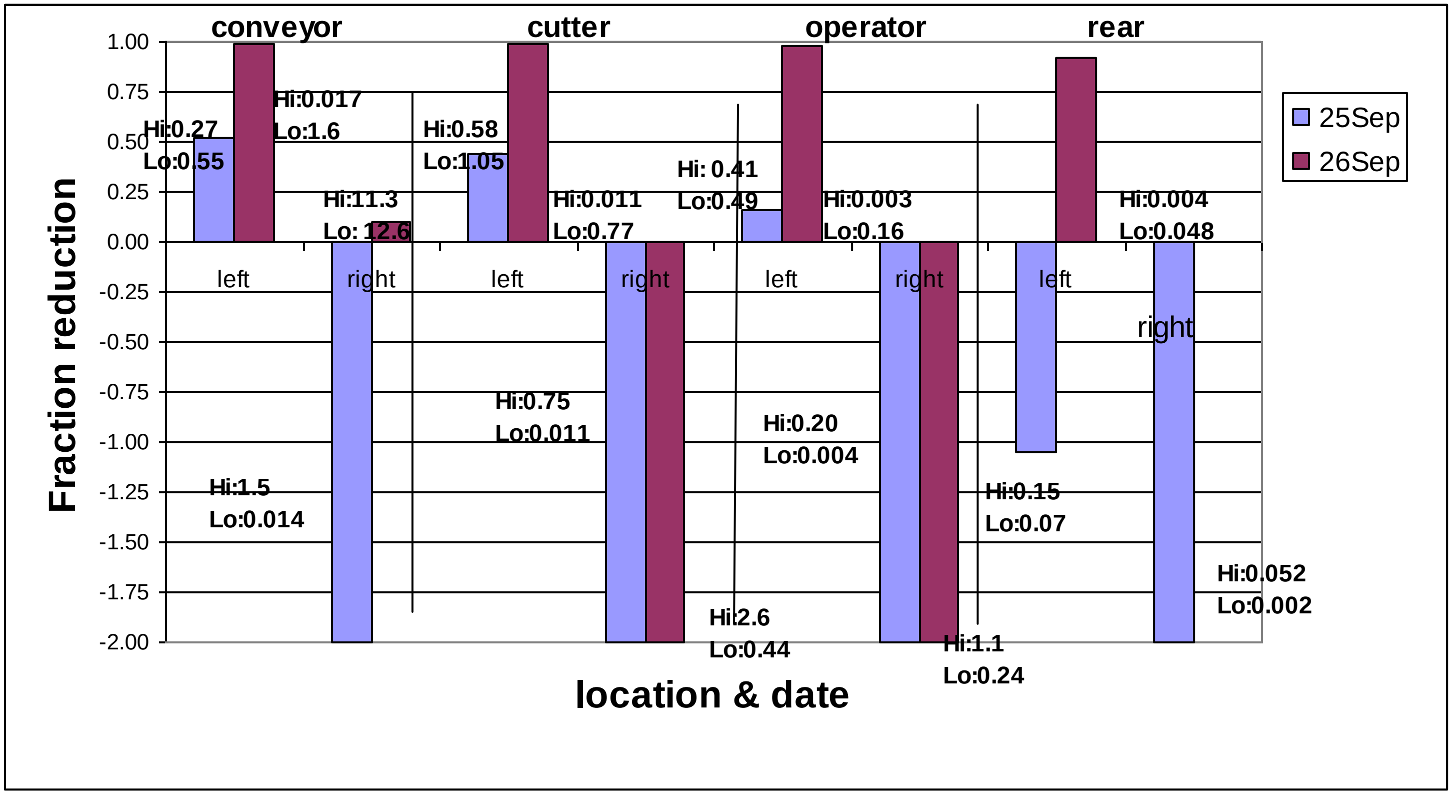
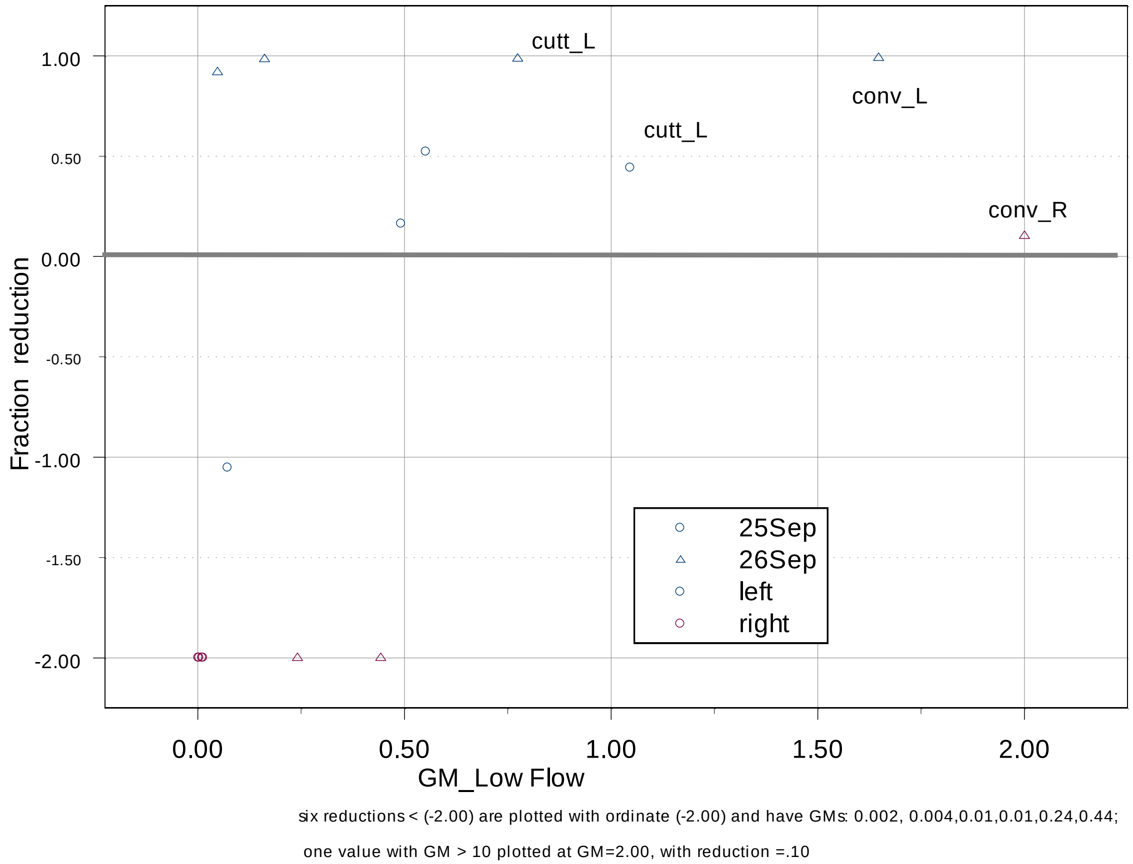


Figure 2. Fractional Reduction in Geometric-Mean Respirable-Dust Concentration for High vs. Low Water Flow (with High and Low Water-Flow Trial-Mean Concentrations Displayed, mg/m^3) by Date, Location, and Side, for Full-Trial *p*DR Real Time Area Air-Monitoring Data



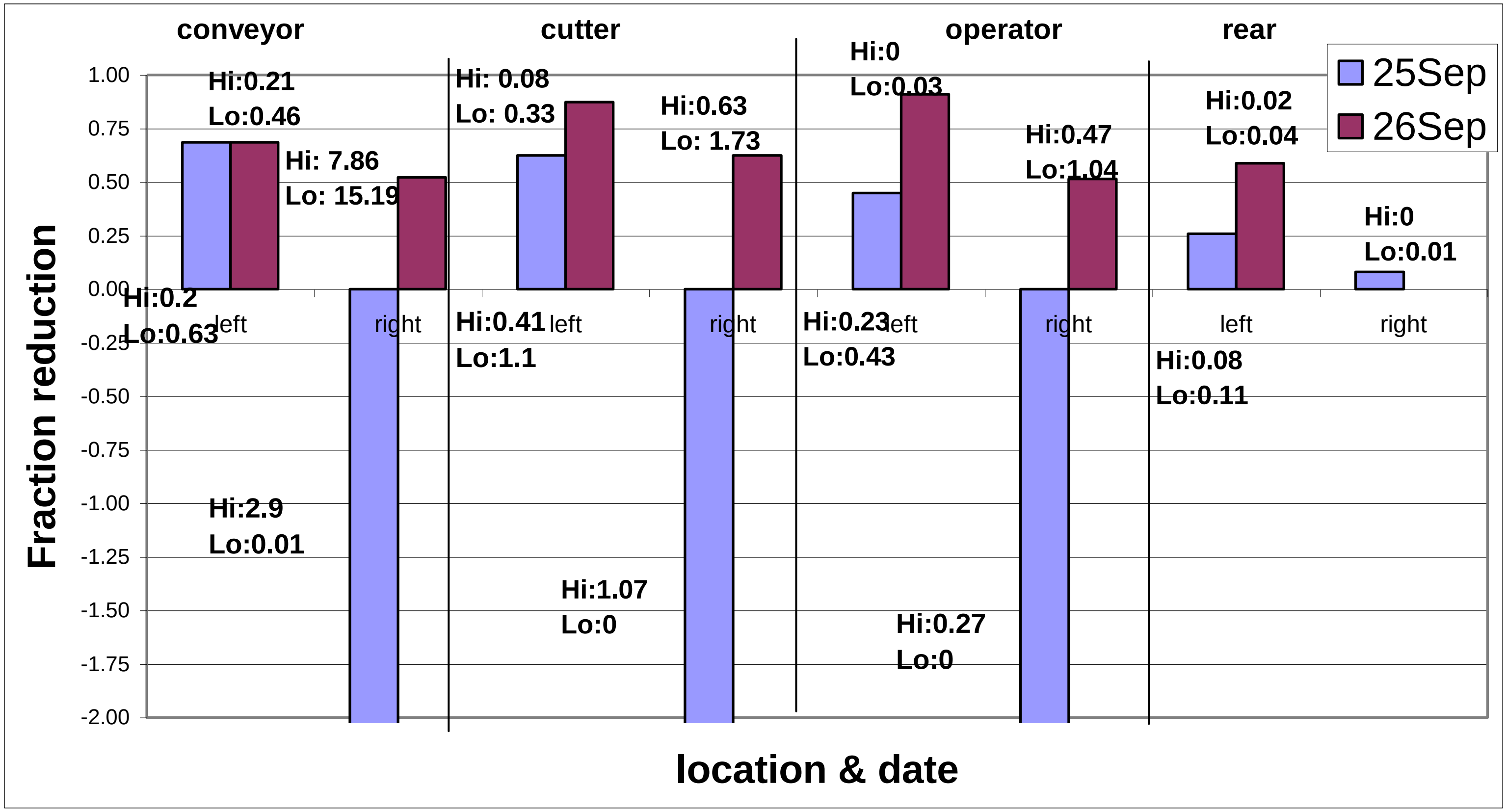
Notes: (1) Negative values indicate *increases* in concentration. (2) Data not available for right-rear location on Sept. 26, 2006.

Figure 3. Fractional Reduction in Respirable Dust Concentrations at High Water-Flow Rate Vs. Low Water-Flow Rate, Plotted Against Baseline (Low Water-Flow) Respirable Dust Concentration (mg/m^3) – Based on Real-Time *p*DR Data, Full Trial-Period Geometric-Mean Values for Each Location on Each Day



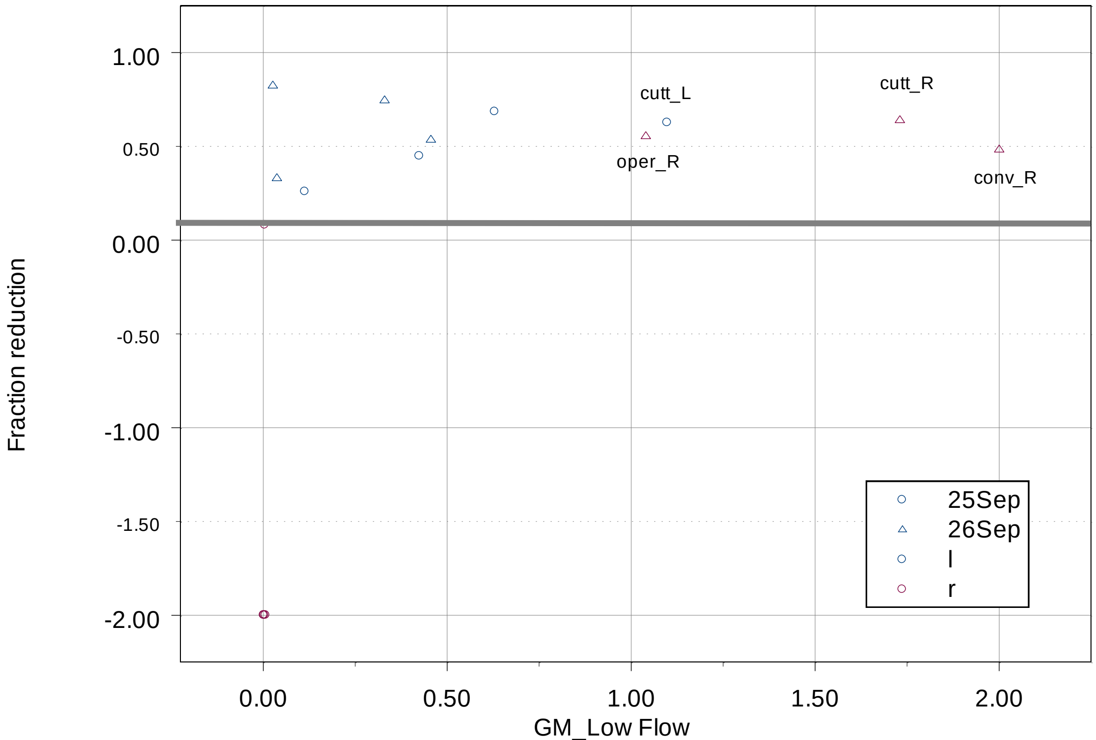
Note: Negative reduction values indicate *increases* in concentration.
conv_R = conveyor right; conv_L = conveyor left; cutt_L = cutter left

Figure 4. Fractional Reduction in Geometric-Mean Respirable-Dust Concentration at High Water-Flow Rate Vs. Low Water-Flow Rate (with High and Low Water-Flow Trial-Mean Concentrations Displayed, mg/m^3) by Date, Location, and Side, for *p*DR Real Time, Short-Period Subset, Area Air-Monitoring Data.



Notes:
(1) Negative values indicate ***increases*** in concentration. (2) Data not available for right-rear location on Sept. 26, 2006. (3) Bars cut off at -2.00 indicate values less than -2.00

Figure 5. Fractional Reduction in Respirable Dust Concentrations at High Water-Flow Rate Vs. Low Water-Flow Rate, Plotted Against Baseline (Low Water-Flow) Respirable Dust Concentration (mg/m^3) – Based on Real-Time *p*DR Short-Period Subset-Data Geometric-Mean Values for Each Location on Each Day



three reductions < (-2.00) are plotted with ordinate (-2.00) and have GMs: 0.002, 0.004,0.007;

one value with GM > 10 plotted at GM=2.00, with reduction =.48

Negative reduction values indicate increases in concentration.
conv_R = conveyor right; cutt_R = cutter right; cutt_L = cutter left; oper_R = operator right

Figure 6. Real-Time *p*DR Respirable-Dust Measurements (Natural Logarithms of Geometric-Mean Concentrations from Eight Area Locations During 5-Min Periods) by Time of Day, Day, and High or Low Water-Flow Condition, with Measurements Included in Short-Period Subsets Shown in Brackets