IN-DEPTH FIELD EVALUATION…

DUST-CONTROL TECHNOLOGY FOR ASPHALT PAVEMENT MILLING

at

South Dakota Highway 79 resurfacing project
Border States Paving and Industrial Builders, contractors
Buffalo Gap, South Dakota, August 15 through 17, 2006

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

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SITE SURVEYED:	South Dakota Highway 79 resurfacing project Border States Paving Industrial Builders Buffalo Gap, South Dakota
SIC CODE:	1611 (Highway and Street Construction)
SURVEY DATE:	August 15 through 17, 2006
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DISCLAIMER

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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 four-lane divided 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 18.8 gpm resulted in overall reductions in measured respirable dust concentrations at area air-monitoring locations around the machine. The average overall reduction based on the results of the time-integrated air sampling method used was 41%, while that based on the mean results of the real-time data-logging instrumentation was 53%; both of these reductions were statistically significant at the 95% confidence level. In contrast, an examination of short-period subset data from the data-logging instruments (assembled from selected portions of the data sets generated closest together in time and space) revealed an average reduction of 14% that was not statistically significant. Overall, the results varied by location, with the greatest reductions occurring on the right side of the machine. Personal breathing-zone exposures to crystalline silica were below analytical limits of detection.

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 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 asphalt 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 contractors, the milling work on Highway 79 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 two digital water-flow meters, each with a range of 2 to 20 gallons per minute (gpm). One was installed in the water supply line feeding the water-spray bars in the cutter housing, and the other in the line supplying the water-spray nozzles at the conveyor transition. Water pressure was measured using two standard analog pressure gauges attached to "T fittings" installed in the same two water lines near the flow meters. NIOSH personnel supplied the manufacturer's representative with the water-flow meters and pressure gauges for installation on the machine. The readings on these devices were observed and recorded periodically during milling.

Air-sampling measurements for respirable dust and crystalline silica

On all three 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 attached 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. 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, 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 10 seconds. Also included in each sampling array were two battery-operated sampling pumps. Each pump was connected through 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 measure the time-integrated respirable dust concentration for each sampling location for each entire day. The mean of the resulting two concentrations is used to establish the corrected mean for all concentration measurements on that day from the *p*DR instrument at that location, allowing the determination of a correction factor that is then applied to each concentration measurement from that 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 Inc. cyclone), again with both the pump and sampling-head assembly attached to the metal frame. 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 was detected and is reported. 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.

Bulk-material samples

Bulk samples of the milled pavement were collected on a periodic basis from material left in or next to the cut by the milling machine. The silica content of the pavement was determined through analysis of these samples using X-ray diffraction in accordance with NIOSH Method 7500.

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 modified to utilize 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:

- August 15—trials of high water flow, low water flow, and high water flow (the last trial was ended early due to a thunderstorm);
- August 16—trials of low water flow, high water flow, low water flow, and high water flow; and,
- August 17—trials of low water flow, high water flow, high water flow, and low water flow.

In order for each time-integrated PBZ and area air sample (collected with the 4.2-L/min flow rate and BGI cyclone) to measure respirable dust and silica only during one high or low water-flow trial, the filters in these samples were changed between each high or low trial. Considering the detection limits for crystalline silica, the target for the actual run time for each filter was nominally 2 hours in order to sample an adequate air volume;

however, in practice, as low as 100 minutes was considered acceptable. The approximate numbers of trial periods considered possible each day, at approximately 2 hours each, was four; as noted above, the three days of the evaluation actually included three, four, and four trials.

RESULTS AND DISCUSSION

Descriptive data and information

This mill was equipped with a spraying system capable of delivering a total of approximately 19 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). Nearly two thirds of the total water flow (approximately 12 gpm at maximum flow) was directed to the cutter housing spray bars, while over one third (approximately 6.5 gpm at maximum flow) was directed to the conveyor-transition sprays. The 7-foot-wide cutter drum held metal bits arranged in helical coils around the drum. New bits were installed as needed during the three days of the evaluation.

The milling machine made partial-width and full-width (7-foot-wide) cuts on August 15, 16, and 17. The job was described as a 1- to 4-inch-depth removal. However, the milling depth was noted to be about 1 inch at most times except on August 15, when both 1-inch- and 2-inch-depth cuts were milled. 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.

On August 15, starting with the first high water-flow trial, the mill described in this report was milling the left side of the road, and traffic was passing the mill on the right. For the low-flow period, the loading side and the traffic side were reversed, and this arrangement was continued for the rest of the day including the second high-flow trial.

On August 16, starting with the first low-flow trial, the mill described in this report milled the center lane of the road, with trucks loading on the right and traffic passing on the left. During this trial the mill passed by a quarry. Before the first high-flow trial, the mill was backed up 3.2 miles, and then the center lane was cut, with trucks being loaded on the left and traffic passing on the right, for the rest of the shift. The quarry plant was approached again during the second high-flow period.

On August 17, starting with the first low-flow trial, the center lane was cut, trucks were loaded on the right, and traffic passed on the left.

Productivity was recorded in terms of the number of trucks that were loaded and the number of miles traveled each day. On August 15, during high flow 25 trucks were loaded, and 1.89 miles of milling were completed, compared to 14 trucks and 1.04 miles of milling during low flow. On August 16, during high flow 43 trucks were loaded and 1.63 miles milled, compared to 46 trucks loaded and 1.73 miles milled during low flow. On August 17, 42 trucks were loaded and 2.41 miles milled during high flow, compared to 40 trucks loaded and 2.15 miles milled during low flow.

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 part of his time walking alongside the mill, operating the grade controls, and some time driving the water truck.

The ambient air high temperatures in the afternoons increased during the three days of sampling. On August 15, the temperatures in the afternoon were around 30ºC (around 85ºF), on August 16 around 35ºC (around 95ºF), and on August 17 near 38ºC (100ºF). On August 15, a thunderstorm in the afternoon shortened sampling for the day due to the wet pavement.

Water-spray system water-flow and pressure measurements

During the high water-flow trials on August 15, the water flow to the cutter-housing spray bars was about 12.0 gallons per minute (gpm). The water flow to the conveyor-transition sprays was approximately 6.8 gpm during those trials. During the single low-flow trial on that day, the water flow to the cutter-drum spray bars was 7.7 gpm, while the water flow to the conveyor spray nozzles was 5.3 gpm. The average water pressure on the water line leading to the cutter-drum spray bars during that day’s high water-flow trials was 44.1 pounds per square inch – gauge (gauge pressure, above the ambient), or psig. The pressure on that line during low flow was 22.7 psig. The corresponding values for the conveyor-spray nozzles were 37.7 psig at high flow and 12.5 psig at low flow.

On August 16, the average water flow to the cutter-housing spray bars was 12.1 gpm during the high water-flow trials and 7.32 gpm during the low-flow trials. The average water flow to the conveyor-transition spray nozzles was 6.4 gpm during the high-flow trials and 5.0 gpm during the low-flow trials. The average water pressure to the cutter-drum spray bars during that day’s high water-flow trials was 42 psig. The average pressure to those sprays during low-flow trials was 26 psig. The corresponding values for the conveyor spray nozzles were 36 psig at high flow and 13.8 psig at low flow.

On August 17, the average water flow to the cutter-drum spray bars was 12.4 gpm during the high-flow trials and 7.2 gpm during the low-flow trials. The average water flow to the conveyor spray nozzles was 6.5 gpm during the high-flow trials and 5.1 gpm during the low-flow trials. The average water pressure to the cutter-drum spray bars during that day’s high water-flow trials was 42.5 psig. The average pressure to those sprays during low flow was 26.8 psig. The corresponding values for the conveyor spray nozzles were

37.7 psig at high flow and 12.5 psig at low flow.

Time-integrated air-sampling results

PBZ air-sampling results for August 15, 16, and 17 are presented in Table 1. A total of 22 samples was collected, 11 for the operator and 11 for the ground man. As noted earlier, a thunderstorm curtailed sampling during the second high water-flow period on August 15. Three samples were collected for each employee on August 15, one each during two high water-flow trials and one low water-flow trial, and four samples were collected for each employee on both August 16 and 17, one each during two high water-flow and two low water-flow trials on each day. The job of machine operator was filled by the same employee for all three days of sampling, as was the job of foreman.

The respirable dust results for the operator ranged from not detectable (ND) during one high-flow trial on each of the three days to 0.60 mg/m^3 during a low-flow trial on August 17. The foreman's respirable dust results ranged from ND (during both the second high-flow trial on August 15 and the last low-flow trial on August 17) to 0.30 mg/m^3 during the second high-flow trial on August 16. Respirable dust concentrations measured in personal breathing zone samples were on average about 31% lower during the high water-flow trials than during the low-flow trials.

Note that in Table 1, time-weighted averages (TWAs) 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 foreman, the *p*DR measurements at the six non-operator 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.

Eight-hour TWA exposures were not calculated for these results because the test conditions (water flow rates) were varied during each day of sampling. However, if any of the calculated TWA exposures in Table 1 had continued for 8 hours, none of them would have exceeded the OSHA PEL described earlier.

Area air sample results for respirable dust are presented in Tables 2, 3, and 4. A total of 88 area samples was collected, representing 11 sets of samples collected at eight locations on the milling machine. Three of these sets of samples were collected on August 15, four were collected on August 16, and four were collected on August 17. For the 44 area samples collected during high-flow trials over the three days, the arithmetic mean respirable dust concentration was 0.469 mg/m^3 (σ [standard deviation] = 0.21), with a geometric mean of 0.24 mg/m^3 (GSD [geometric standard deviation] = 1.58), where both standard deviations represent variation between days. Analyses of the 44 area samples collected at eight locations around the mill during a total of five low-flow trials over the three days revealed an arithmetic mean respirable dust concentration of 0.704 mg/m^3 (σ = 0.243) and a geometric mean concentration of 0.41 mg/m^3 (GSD = 1.23). The ratio of geometric means of the high-flow samples to the low-flow samples was 0.59, indicating a reduction of about 41% in the respirable dust concentrations when the higher water flow was used. When the results for each location are inspected, the respirable dust concentrations are usually lower during the periods when the higher water flow was used.

For personal and area samples combined, the reductions associated with the high water flow are statistically significant at the 5% level for the evaluated mill.

Results are also available by day. On August 15 for the area samples, the high-flow geometric mean was 0.403 mg/m^3, and the low-flow geometric mean was 0.383 mg/m^3 for all respirable dust samples. The ratio of high to low flow was 1.053, corresponding to an increase of about 5%. On August 16 for the area samples, the high-flow geometric mean was 0.187 mg/m^3, and the low-flow geometric mean was 0.353 mg/m^3, corresponding to a ratio of 0.530 and a reduction of about 47%. On August 17 for the area samples, the high-flow geometric mean was 0.180 mg/m^3, and the low-flow geometric mean was 0.522 mg/m^3, corresponding to a ratio of 0.344, and a reduction of about 66%. The corresponding results for the personal samples were 0.193, 0.133, and 0.073 mg/m^3 at the high-flow level for August 15, 16, and 17, respectively. At the low-flow levels the results were 0.107, 0.220, and 0.240 for the same three dates. The overall reductions were −80%, 38%, and 70% for the three dates.

The time-integrated sampling results for respirable quartz are also presented in Tables 1, 2, 3, and 4. However, almost all determinations were less than the limit of detection. Exceptions were for three samples collected on August 16 for which the results were between the limit of quantification (LOQ) and the LOD. Two of these occurred at the left operator platform, during the two low-flow trials. The third occurred during the first high-flow trial at the left cutter. The estimated quartz concentrations were 0.02 mg/m^3 at each of the three locations. Thus, none exceeded the NIOSH REL of 0.05 mg/m^3.

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

Direct-reading real-time sampling results were conducted using *p*DRs at eight locations on the milling machine. At each of these locations a measurement was recorded every 10 seconds. To permit calculation of the logarithms of the data for statistical analyses, a value of 0.001 was added to every zero result. The value 0.001 corresponds to the lowest positive result obtainable from a *p*DR. The results are summarized in Tables 5, 6, and 7.

When all of the *p*DR results were combined for all days, the arithmetic mean respirable dust concentration for the high-flow trials was 0.60 mg/m^3 ($\sigma = 0.39$), and the geometric mean was 0.090 mg/m^3 (GSD = 1.440). The three-day combined arithmetic mean respirable dust concentration for the low-flow trials was 1.0 mg/m^3 ($\sigma = 0.63$), and the overall geometric mean was 0.188 mg/m^3 (GSD = 1.222). The ratio of the high water-flow to low water-flow results is the ratio of the geometric means of those sampling periods, 0.47. This indicates that the respirable dust concentrations overall during the long-term high-flow trials were about one half of those measured during the long-term low-flow trails, or a reduction of about 53%. This result is statistically significant at the 5% level.

By day, the geometric mean respirable dust concentration during the high-flow trials on August 15 was 0.106 mg/m^3 and 0.149 mg/m^3 during the low-flow trials; the resulting ratio indicates concentrations about 29% lower during the high-flow trials. On August 16, the geometric mean concentration during the long-term high-flow trials was 0.0968 mg/m^3, while it was 0.194 mg/m^3 during the low-flow long-term trials, corresponding to a reduction of about 50%. On August 17, the geometric mean concentration during the high-flow trials was about 0.0543 mg/m^3, compared to 0.221 mg/m^3 for the low-flow trials. The ratio of geometric means indicates that respirable dust concentrations were about 75% lower during the high water-flow condition. More detail about these results is shown in Figures 2 and 3.

Short-period subset data. An alternative analysis was carried out with the *p*DR real-time data. Subsets of the data were chosen, close together in time, and close to the time when a transition was made from one water control level to another. 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, two pairs were constructed on August 15, three pairs on August 16, and two pairs on August 17.

For all of these high-flow short-period subsets and for all sampling locations, the arithmetic mean respirable dust concentration was 0.59 mg/m^3 ($\sigma = 0.040$), with a geometric mean concentration of 0.15 mg/m^3 (GSD = 1.51). The arithmetic mean respirable dust concentration for the short-period low-flow trials was 0.89 mg/m^3 ($\sigma = 0.31$) with a geometric mean of 0.17 mg/m^3 (GSD = 1.10). The ratio of geometric mean concentrations was 0.88, representing a dust reduction of 14%, which is not statistically significant at the 5% level. More detail about these results is shown in Figures 4, 5, and 6. In Figure 6, the one-minute averages (log scale) of all the *p*DR measurements are plotted for each of the three days of sampling — i.e., the averages of 48 measurements, because measurements were made at each of eight sampling locations every 10 seconds. In each of the three plots in the figure the short-term pairs are identified. In most instances, little apparent difference exists between the high- and low-flow data in these short-term pairs.

It is of some interest to determine the reduction at high water flow for the highest dust levels measured during the low water-flow trials, when it is most likely that the environment itself is not controlling the amount of dust. For the full-trial *p*DR results, the average reduction at high flow is 33% from the highest 25% of measurements at low water-flow. By comparison, for the lower 75% of low-flow measurements, the reduction at high flow averages 58%. For the subset *p*DR measurements, the reduction is > 40% for the highest 25% of low-flow measurements compared to < 2% for the lower 75%. These are large differences between the full trial and the subset data for the lower 75%. Large reductions, even at relatively low values of the low water-flow measurements, are possible if the high water-flow measurements are quite low. Figure 6 shows that the high water-flow measurements on August 16 and August 17 are often quite low when the entire trial is considered, but when the subset short periods are considered this is not so much the case.

Differences by Side of Machine. Examination of the *p*DR data indicates that whereas substantial reduction occurred on the right side, no reduction occurred on the left side. In particular, on the right side the geometric means of the four locations at high flow was 0.03 mg/m^3, compared to 0.15 mg/m^3 at low flow. The ratio is about 0.2, indicating an 80% reduction. On the other hand, the left side geometric means were 0.25 mg/m^3 for the high flow and 0.24 mg/m^3 for the low flow. The ratio of 0.25 to 0.24 indicates an 8% increase at high flow. The bar chart in Figure 2 indicates how consistent this is by date — for all three dates, the right side reductions are strongly positive compared with the left side reductions, which are consistently positive only for the conveyor left. In general, the filter sample area results support the full trial *p*DR results.

The scatter plot in Figure 3 indicates that reductions tend to occur at higher concentrations. At lower concentrations, the plot demonstrates that considerable variability in reductions can occur, though almost all right-side reductions are positive, and left-side reductions are not (that is, there are many increases in the high flow relative to the low flow). However, even on the left side, if the dust concentration is large enough, reduction does occur.

Further discussion of short-period subset data. The reason to include the subset data was to perhaps obtain better control of variability over time and space. For instance, by limiting the data from 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 be little change in physical location or in the outdoor conditions. In theory, this would allow for a better comparison. The results, however, are somewhat confusing. The overall reduction is much smaller. In fact, the bar chart in Figure 4 indicates that the side effect is reversed, so that, in most instances, the left side reductions exceed the right side. Thus, the difference between the subset results and the full trial results may be due to the arbitrariness of the subsets (although a modified selection gave similar results), or because what happens over a longer period can differ from what happens over a shorter period. Also, some of the pairings are not as close together in time as might be desirable. For instance, on August 17, a period of almost a half hour elapsed with no activity between the second high-flow period and the second low-flow period.

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

The *p*DR area respirable-dust sampling results have been used to model the respirable-dust exposure 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. Thus, the operator exposure depends on both sides, though the *p*-value of the slope for the right side is less than 0.01, and that for the left side is about 0.1.

Bulk-material sample results

Bulk-material samples of the milled material contained 13% and 15% quartz. No cristobalite or tridymite was detected. Although the bulk samples contained quartz, no personal samples and only three area samples contained quartz in excess of the analytical limit of detection. A possible explanation for this is that the measured respirable-dust concentrations in the air were quite low. Thus, although the bulk samples demonstrated the presence of quartz in the milled material at a moderate composition of about 15%, almost no filter samples collected enough respirable mass to contain sufficient quartz to exceed of the limit of detection.

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 5 contains the average results of responses and selected explanatory variables for each of the long-term pairs. For the variables "real time" and "respirable," the averages shown in Table 5 are the geometric means. For the explanatory variables analyzed (respirable dust, real-time data), whether the geometric means or the natural log of the geometric means were used as the response variable, the best model was that which included either the cutter water-flow rate or the water pressure. The other variables did not contribute much explanatory power.

CONCLUSIONS AND RECOMMENDATIONS

Increasing the water-flow rate to the cutter-housing spray bars from about 7 gpm to about 12 gpm and from approximately 5 gpm to around 6.5 gpm at the conveyor sprays resulted in overall reductions in measured respirable-dust concentrations at area air-monitoring locations around the machine. The average overall reduction based on the results of the time-integrated air sampling method used was 41%, while that based on the mean results of the real-time data-logging instrumentation was 53%, and both of these reductions were statistically significant at the 95% confidence level (or the $p < 5\%$ level). However, an examination of short-period subset data from the data-logging instruments revealed only a nonsignificant 14% reduction. The results varied by location, with the greatest reductions occurring on the right side of the machine. Personal breathing-zone exposures to crystalline silica were below analytical limits of detection.

Although the bulk-material samples of the removed material contained crystalline silica (only in the form of quartz), no PBZ samples and only three area air samples contained quartz, at least not in excess of the limit of detection. This near complete absence of detectable levels of quartz in the air samples is a curiosity of the results. A partial explanation for this is the relatively low quartz content measured, about 15% by mass, but a further possible explanation is that the airborne respirable dust concentrations were quite low. Thus, although the bulk samples demonstrated the presence of quartz, the filter samples collected too little quartz-containing dust for the quartz to exceed the limit of detection. A reason suggested for this is the heat of the pavement during sampling, which may have made the material quite sticky or cohesive and hence less prone to fractionating during milling. This is an important issue, because the nature of the material removed may have affected estimated efficiency, which could be different in a different sampling environment.

Recommendation #1. The highest possible water-flow rates should be used during asphalt pavement-milling operations to minimize exposures to respirable dust that may contain crystalline silica.

Recommendation #2. 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. The lack of exposures that exceed detection during this field survey may be an anomaly related to the conditions during this specific job rather than an indicator of the performance of this milling machine.

Recommendation #3. The need for continuing research should be evaluated based upon the results of all field work in the ongoing NIOSH study, including this field survey.

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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 – Concentration (mg/m^3)
August 15								
Operator	Low	99	0.07937	0.07937	0.103	0.035	ND	ND
	High	104	0.44	0.341	0.207	0.156	ND	ND
	High	51	0.1400				ND	
Foreman	Low	101	0.145	0.145	0.148	0.064	ND	ND
	High	72	0.1710	0.154	0.125	0.071	ND	ND
	High	53	0.132				ND	
August 16								
Operator	Low	110	0.359	0.30	0.221	0.193	ND	ND
	Low	107	0.239				ND	
	High	110	0.154	0.124	0.123	0.082	ND	ND
	High	67	0.0736				ND	
Foreman	Low	108	0.243	0.186	0.157	0.116	ND	ND
	Low	81	0.1117				ND	
	High	108	0.0948	0.1223	0.158	0.104	ND	ND
	High	17	0.2971				ND	
August 17								
Operator	Low	122	0.215	0.376	0.321	0.305	ND	ND
	Low	87	0.602				ND	
	High	114	0.0443	0.0576	0.055	0.040	ND	ND
	High	110	0.0714				ND	
Foreman	Low	102	0.147	0.153	0.176	0.126	ND	ND
	Low	29	0.174				ND	
	High	44	0.115	0.104	0.095	0.070	ND	ND
	High	80	0.0982				ND	

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

Table 2. Time-Integrated Area Air Sample Results by Location, August 15, 2006

Sampling Location	Water Flow-Rate Condition	Sample Duration (min)	Respirable Dust – Sample Concentration (mg/m³)	Respirable Dust – TWA Concentration (mg/m³)*	Respirable Quartz – Sample Concentration (mg/m³)†	Respirable Quartz – TWA Concentration (mg/m³)
Operator Platform – Left				0.402		ND
	Low	97	0.402		ND	
	High	104	1.735	1.255	ND	ND
	High	53	(0.313)		ND	
Operator Platform – Right				0.211		ND
	Low	96	(0.211)		ND	
	High	104	0.563	0.4195	ND	ND
	High	53	ND		– †	
Cutter Drum – Left				1.694		ND
	Low	97	1.694		ND	
	High	104	2.518	1.9342	ND	ND
	High	56	0.850		ND	
Cutter Drum – Right				1.235		ND
	Low	96	1.235		ND	
	High	105	2.148	1.4532	ND	ND
	High	55	ND		–	
Left Rear				0.0802		ND
	Low	98	(0.0802)		ND	
	High	104	0.8471	0.5952	ND	ND
	High	56	ND		–	
Right Rear				0.051		– †
	Low	97	ND		–	
	High	105	0.642	0.4649	ND	ND
	High	55	ND		–	
Loading Conveyor – Left				0.595		ND
	Low	96	0.595		ND	
	High	104	(0.121)	0.1241	ND	ND
	High	55	ND		–	
Loading Conveyor – Right				1.066		ND
	Low	96	1.066		ND	
	High	104	0.470	0.4084	ND	ND
	High	53	(0.2875)		ND	

*For calculation of TWA concentrations, LOD/√2 substituted for ND results.
†The quartz analysis was not done when the respirable dust sample was less than the limit of detection.
ND indicates a value less than the limit of detection of the analytical method.
Values in parentheses represent results between the limit of detection and limit of quantification of the method.

Table 3. Time-Integrated Area Air Sample Results by Location, August 16, 2006

Sampling Location	Water Flow-Rate Condition	Sample Duration (min)	Respirable Dust – Sample Concentration (mg/m³)	Respirable Dust – TWA Concentration (mg/m³)*	Respirable Quartz – Sample Concentration (mg/m³)†	Respirable Quartz – TWA Concentration (mg/m³)
Operator Platform – Left	Low	110	0.3463	0.4097	(0.02)	0.02
	Low	105	0.4762		(0.02)	
	High	109	0.2184	0.3027	ND	ND
	High	64	0.4464		ND	
Operator Platform – Right	Low	110	0.6131	0.4338	ND	ND
	Low	98	0.2326		ND	
	High	109	ND	0.06493	– †	– †
	High	43	ND		–	
Cutter Drum – Left	Low	110	1.407	1.3217	ND	ND
	Low	99	1.227		ND	
	High	110	1.277	1.0559	0.02	0.02
	High	44	0.5032		ND	
Cutter Drum –Right	Low	110	0.9302	0.6202	ND	ND
	Low	100	0.2791		ND	
	High	111	(0.1529)	0.1637	ND	ND
	High	68	(0.1813)		ND	
Left Rear	Low	110	0.6342	0.4651	ND	ND
	Low	100	0.2791		ND	
	High	110	0.6131	0.5387	ND	ND
	High	67	0.4165		ND	
Right Rear	Low	110	0.5285	0.3411	ND	ND
	Low	100	(0.1349)		ND	
	High	110	0.1966	0.2050	ND	ND
	High	67	(0.2187)		ND	
Loading Conveyor – Left	Low	110	(0.1905)	0.1655	ND	ND
	Low	100	(0.1381)		ND	
	High	110	(0.04572)	0.05663	ND	ND
	High	68	ND		–	
Loading Conveyor – Right	Low	110	(0.08034)	0.14019	ND	ND
	Low	99	(0.2067)		ND	
	High	110	ND	0.084369	–	–
	High	67	ND		–	

*For calculation of TWA concentrations, LOD/√2 substituted for ND results.
†The quartz analysis was not done when the respirable dust sample was less than the limit of detection.
ND indicates a value less than the limit of detection of the analytical method.
Values in parentheses represent results between the limit of detection and limit of quantification of the method.

Table 4. Time-Integrated Area Air Sample Results by Location, August 17, 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	0.6832	0.5747	ND	ND
	Low	88	0.4329		ND	
	High	114	0.5848	0.5079	ND	ND
	High	111	0.429		ND	
Operator Platform – Right	Low	115	0.1925	0.8640	ND	ND
	Low	87	1.7515		ND	
	High	117	ND	0.07554	– †	ND
	High	117	(0.1079)		ND	
Cutter Drum – Left	Low	118	1.7935	1.1327	ND	ND
	Low	114	0.4488		ND	
	High	120	1.2985	1.4156	ND	ND
	High	110	1.5433		ND	
Cutter Drum – Right	Low	119	0.7003	2.8773	ND	ND
	Low	92	5.6936		ND	
	High	121	ND	0.3895	–	ND
	High	112	0.7653		ND	
Left Rear	Low	120	(0.1280)	0.2318	ND	ND
	Low	92	0.3712		ND	
	High	121	ND	0.04312	–	– †
	High	119	ND		–	
Right Rear	Low	119	(0.1060)	0.8476	ND	ND
	Low	115	1.6149		ND	
	High	120	ND	0.0437	–	–
	High	111	ND		–	
Loading Conveyor – Left	Low	92	0.4141	0.2868	ND	ND
	Low	89	(0.1552)		ND	
	High	111	ND	0.3643	–	ND
	High	112	0.6803		ND	
Loading Conveyor – Right	Low	119	0.6403	0.4853	ND	ND
	Low	92	0.2847		ND	
	High	119	0.1961	0.4515	ND	ND
	High	112	0.7228		ND	

*For calculation of TWA concentrations, LOD/√2 substituted for ND results.
†The quartz analysis was not done when the respirable dust sample was less than the limit of detection.
ND indicates a value less than the limit of detection of the analytical method.
Values in parentheses represent results between the limit of detection and limit of quantification of the method.

Table 5. Real-Time *p*DR Area Air Monitoring Results – Full Long-Time Trial-Period Arithmetic and Geometric Means (AMs and GMs)

	August 15, 2007			August 16, 2007			August 17, 2007		
Sampling Location	Water Flow-Rate Condition	AM of Respirable Dust Concentrations (mg/m^3)	GM of Respirable Dust Concentrations (mg/m^3)	Water Flow-Rate Condition	AM of Respirable Dust Concentrations (mg/m^3)	GM of Respirable Dust Concentrations (mg/m^3)	Water Flow-Rate Condition	AM of Respirable Dust Concentrations (mg/m^3)	GM of Respirable Dust Concentrations (mg/m^3)
Operator Platform – Left	Low	0.68	0.27	Low	0.38	0.15	Low	0.71	0.36
				Low	0.66	0.43	Low	0.42	0.13
	High	2.1	0.89	High	0.35	0.25	High	0.54	0.32
	High	0.62	0.33	High	0.59	0.50	High	0.52	0.18
Operator Platform – Right	Low	0.38	0.08	Low	0.70	0.46	Low	0.25	0.030
				Low	0.15	0.05	Low	1.90	0.91
	High	0.73	0.1	High	0.13	0.05	High	0.016	0.013
	High	0.08	0.02	High	0.10	0.05	High	0.12	0.028
Cutter Drum – Left	Low	2.1	0.78	Low	1.03	0.57	Low	1.70	1.10
				Low	1.28	0.86	Low	0.61	0.30
	High	3.06	1.44	High	0.88	0.66	High	1.16	0.69
	High	1.04	0.42	High	0.74	0.63	High	1.40	0.56
Cutter Drum – Right	Low	2.08	0.09	Low	1.33	0.63	Low	0.76	0.011
				Low	0.30	0.01	Low	6.16	2.73
	High	3.23	0.13	High	0.28	0.02	High	0.0096	0.0014
	High	0.55	0.01	High	0.21	0.01	High	0.63	0.0082
Left Rear	Low	0.18	0.01	Low	0.79	0.27	Low	0.29	0.11
				Low	0.50	0.14	Low	0.40	0.15
	High	1.47	0.23	High	0.81	0.43	High	0.069	0.060
	High	0.08	0	High	0.70	0.60	High	0.058	0.037
Right Rear	Low	0.11	0.05	Low	0.69	0.45	Low	0.25	0.025
				Low	0.23	0.10	Low	2.31	1.67
	High	0.54	0.1	High	0.24	0.11	High	0.033	0.017
	High	0.08	0.04	High	0.50	0.20	High	0.029	0.0057
Loading Conveyor – Left	Low	1.07	0.61	Low	0.16	0.09	Low	0.74	0.47
				Low	0.27	0.17	Low	0.33	0.13
	High	0.63	0.31	High	0.10	0.08	High	0.28	0.20
	High	0.43	0.31	High	0.14	0.11	High	0.54	0.27
Loading Conveyor – Right	Low	3.05	0.53	Low	0.69	0.22	Low	1.08	0.40
				Low	0.76	0.10	Low	0.73	0.14
	High	0.73	0.03	High	0.25	0.02	High	0.50	0.20
	High	0.49	0.08	High	0.08	0.01	High	1.04	0.26

Table 6. Explanatory Variables

Variable	Low 8/15	High 1 8/15	High 2 8/15	Low 1 8/16	Low 2 8/16	High 1 8/16	High 2 8/16	Low 1 8/17	Low 2 8/17	High 1 8/17	High 2 8/17
Real-Time *p*DR Respirable Dust Concen. (mg/m^3)	0.15	0.21	0.083	0.30	0.12	0.10	0.10	0.13	0.38	0.060	0.065
Respirable Dust Time-Integrated Concen. (mg/m^3)	0.38	0.80	0.20	0.30	0.12	0.10	0.10	0.40	0.69	0.11	0.29
Number of Trucks	14	19	6	30	16	27	16	26	14	23	19
Flow Cutter (gpm)	7.7	12.1	12	7.3	7.4	12.1	N/A	7.2	7.2	12.4	12.4
Flow Conveyor (gpm)	5.3	6.7	6.8	5.0	5.1	6.4	N/A	5.0	5.1	6.6	6.5
Water Pressure (psi) Cutter	22.7	43.8	44.1	26	26	42	N/A	25.6	12.4	42.7	42.3
Water Pressure (psi) Conveyor	11.3	35.3	35.1	15	13	36	N/A	12.4	27.5	37.7	37.7
Miles Milled	0.87	1.0	0.27	1.28	0.39	1.3	0.39	1.3	0.83	1.1	1.3

Figure 1. Fixed Area Air-Sampling Locations

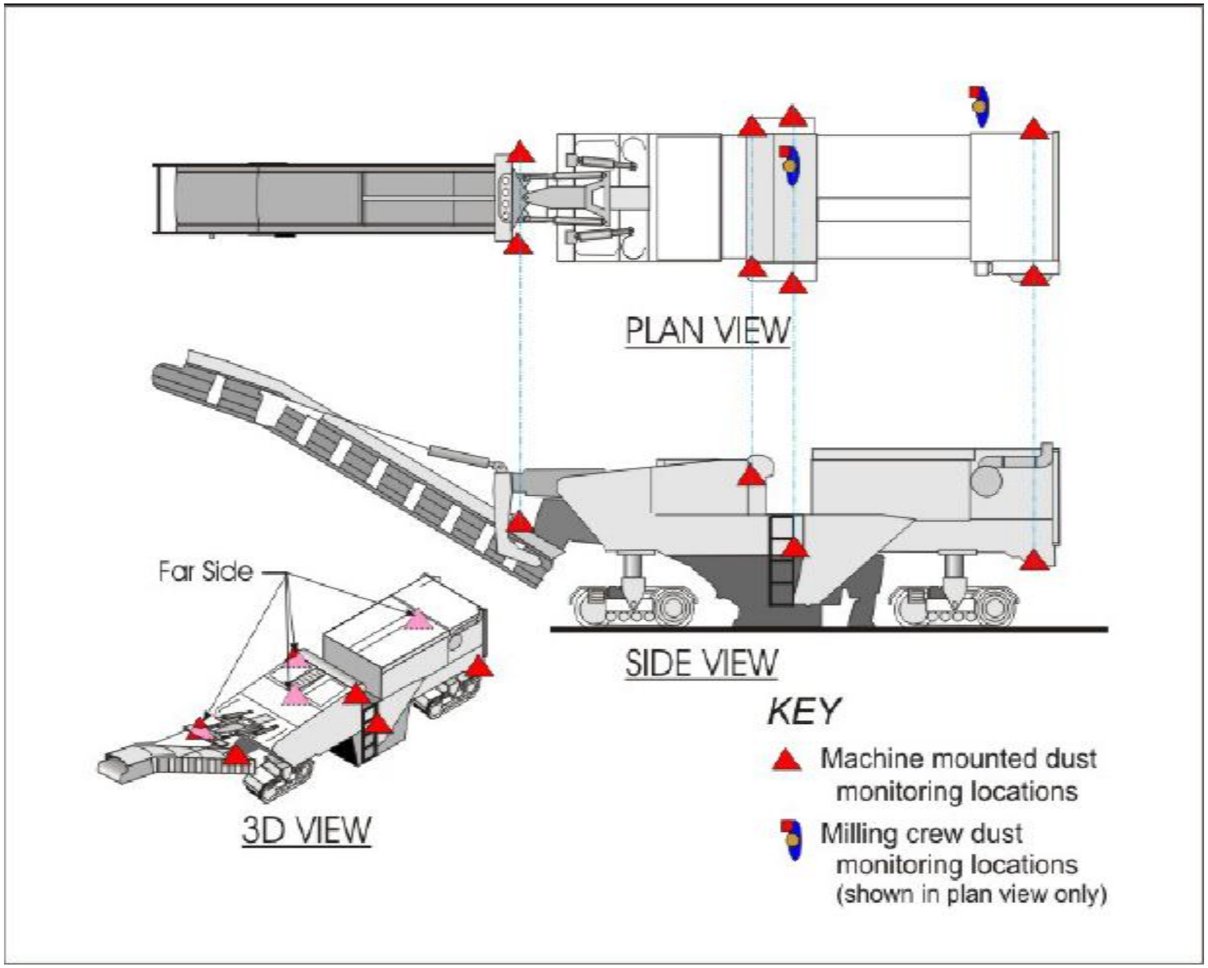
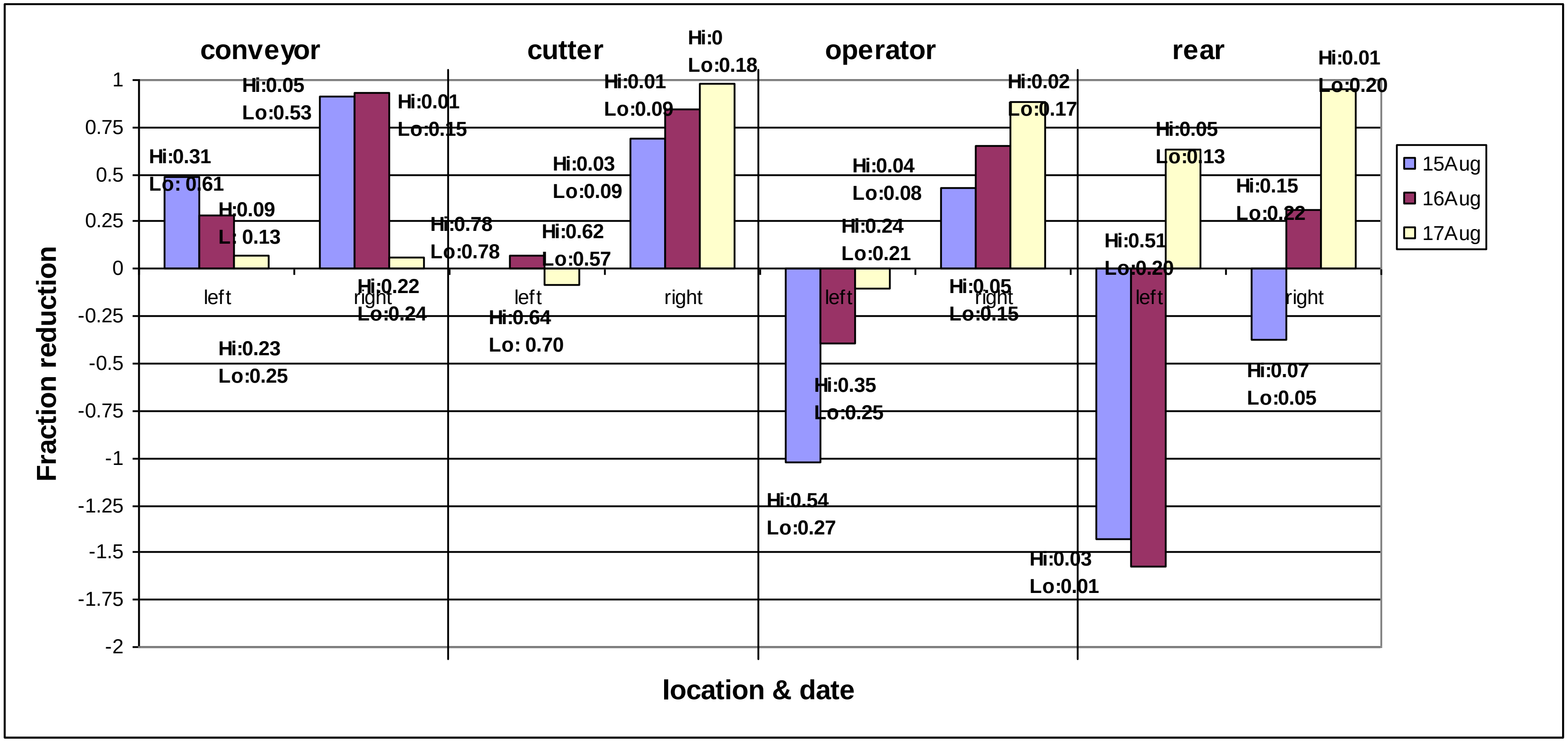
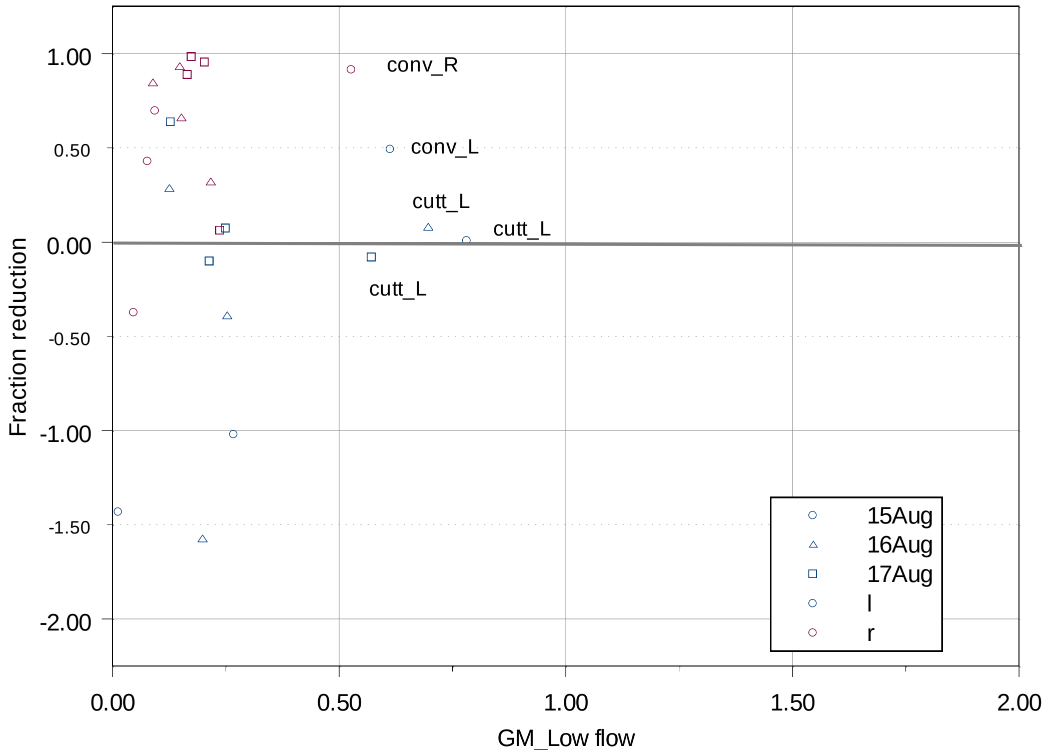


Figure 2. Fraction Reduction in Average Respirable-Dust Concentration for High vs. Low Water Flow (with High and Low Water-Flow Trial-Mean Concentrations Displayed, mg/m^3) by Date, Location, and Side, for Full-Trial *p*DR Real Time Area Air-Monitoring Data



Note: *Negative values indicate* increases *in concentration.*

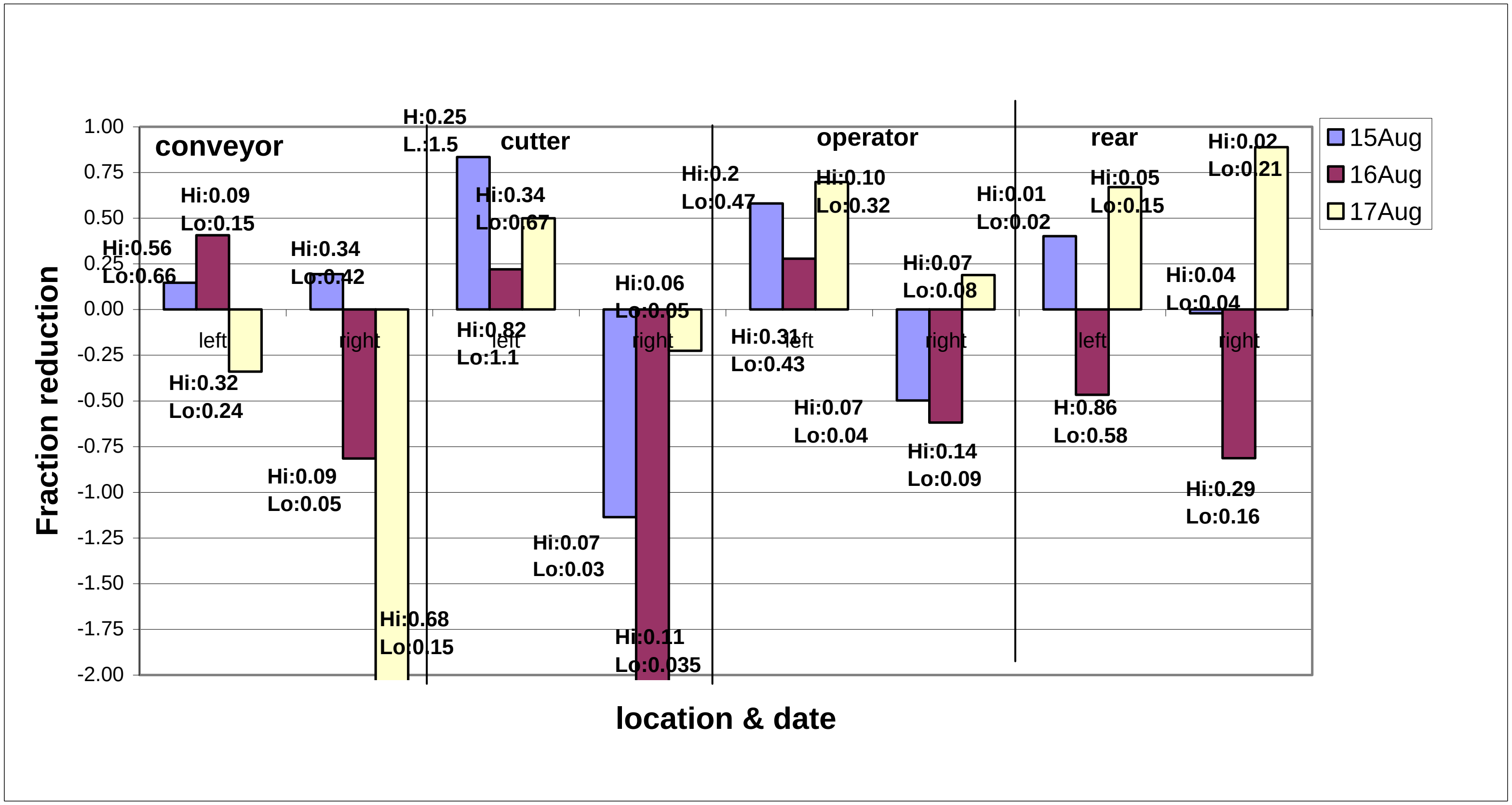
Figure 3. Reduction (Fractional) in Respirable Dust Concentrations at High Water-Flow Rate Vs. Low Water-Flow Rate, Plotted Against Baseline (Low Water-Flow) Respirable Dust Concentration (mg/m^3) – Based on Real-Time *p*DR Data, Full Trial-Period Average Values for Each Location on Each Day



Circle, Aug 15; triangle, Aug 16; square, Aug 17. Blue, left side; red, right side.
conv_L = conveyor left; conv_R = conveyor right
cutt_L = cutter left

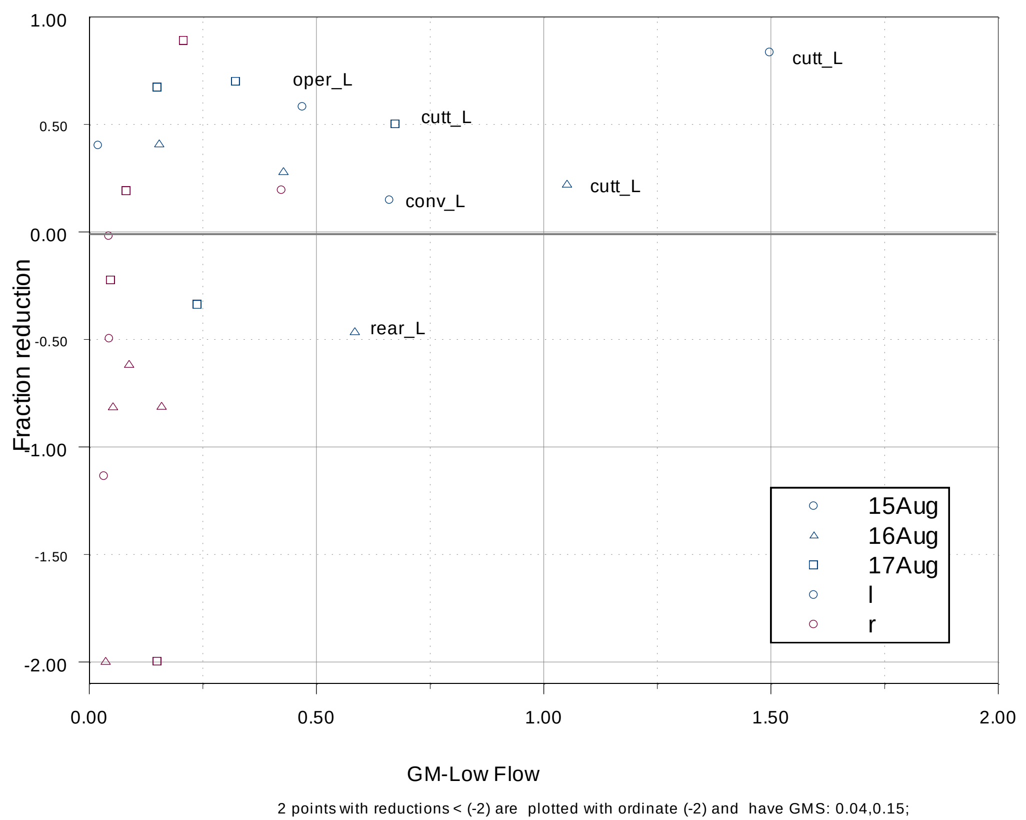
Note: *Negative reduction values indicate* increases *in concentration.*

Figure 4. Fraction Reduction in Average 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: Negative values indicate ***increases*** in concentration. Bars cut off at -2.00 indicate values less than -2.00.

Figure 5. Reduction (Fractional) 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, Short-Period Subset Geometric-Mean Values for Each Location on Each Day



Circle, Aug 15; triangle, Aug 16; square, Aug 17. Blue, left side; red, right side.
Conv_L = conveyor left
Cutt_L = cutter left
Oper_L = operator left
Rear_L = rear left

Figure 6. Respirable-dust *p*DR measurements (natural logarithms of geometric-mean concentrations from eight area locations during 1-min periods) by time of day, day, and high or low water-flow condition, with measurements included in short-period subsets shown in brackets