IN-DEPTH FIELD EVALUATION…

DUST-CONTROL TECHNOLOGY FOR ASPHALT PAVEMENT MILLING

at

U.S. Highway 2 resurfacing project
Midwest Asphalt, contractor
Wilton, Minnesota, June 20 through 22, 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.
Jay Colinet
Gregory Chekan
Alberto Garcia

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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:	U.S. Highway 2 resurfacing project Midwest Asphalt, contractor Wilton, Minnesota
SIC CODE:	1611 (Highway and Street Construction)
SURVEY DATE:	June 20 through 22, 2006
SURVEY CONDUCTED BY:	Leo Michael Blade, NIOSH/DART Alberto Garcia, NIOSH/DART Jay Colinet, NIOSH/PRL Gregory Chekan, NIOSH/PRL
EMPLOYER REPRESENTATIVES CONTACTED:	Dave Petersen, Midwest Asphalt

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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 water-flow rates to the spray nozzles at the cutter drum from an average of about 16 gallons per minute (gpm) to an average of about 18.5 gpm resulted in no clear reduction in measured respirable dust concentrations at area air monitoring locations around the machine. The following factors make the possibility of detecting sizable reduction unlikely for this study:

1. the relatively small difference in the water flow rates
2. the considerable interruption in the flow of trucks removing the milled asphalt, leading to substantial down time in the actual milling

Both of these may explain the ineffectiveness of the water-flow levels seen, which is evident from examination of the data collected. Long time-period respirable dust and quartz results reveal a minimal average reduction from low to high water-flow rates, and the various examinations of the real-time monitoring data, using both long and short time periods, reveal conflicting results with no evidence of reductions in respirable dust concentrations.

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 U.S. Highway 2 removed approximately 1.5 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 also was 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 mill's water supply line feeding the water-spray bars in the cutter housing. A similar meter installed in the line supplying the water-spray nozzles at the conveyor transition did not function properly. Water pressure was measured using standard analog pressure gauges attached to "T fittings" also installed in the water supply lines at those two locations. NIOSH personnel supplied the manufacturer's representative with the water-flow meters and pressure gauges. 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 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 10 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 a small minority of the samples contained cristobalite, at barely detectable levels.) 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 0.05 mg per sample for particulate mass by gravimetric analysis and 0.005 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: 0.1 mg/m^3 for respirable dust; and, 0.01 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-material samples of the milled pavement were collected periodically 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 new 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:

- June 20—trial of low water flow followed by trial of high water flow;
- June 21—trial of low water flow followed by trial of high water flow; and,

- June 22—trial of high water flow followed by trial of 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 of active milling each, was four; as noted above, however, the three days of this evaluation actually included only two trials each day. This was due to extended periods of milling-machine inactivity each day.

RESULTS AND DISCUSSION

Descriptive data and information

Productivity was recorded in terms of the number of trucks that were loaded and the number of miles traveled each day. On June 20, during the high water-flow trial, 31 trucks were loaded and 2.09 miles of milling were done during high flow, compared to 46 trucks and 2.94 miles of milling during the low water-flow trial. On June 22, during high water flow, 22 trucks were loaded, and 1.59 miles milled, compared to 39 trucks loaded and 2.46 miles milled during low water flow. On June 22, 44 trucks were loaded and 4.62 miles milled during the high water-flow trial, compared to 52 trucks loaded and 7.97 miles milled during the low-flow period.

The milling machine, which was equipped with a 7-foot-2-inch-wide drum, made mainly full-width cuts. The milling depth was approximately 1.5 inches most of the time, except for a 3-inch cut during several hundred feet on June 21.

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.

Water-spray system water-flow and pressure measurements

During the high water-flow trial on June 20, the water flow to the cutter-drum spay bars was about 17.7 gallons per minute (gpm). During the low-flow trial, the water flow to the cutter-drum spray bars averaged 15.2 gpm. On June 21, the average water flow to the cutter-drum spray bars was 19.5 gpm during the high-flow trial and 15.7 gpm during the low-flow trial. On June 22, the average water flow to the cutter-drum spray bars was 18.7 gpm during the high water-flow trials and 16.3 gpm during the low-flow trials.

On June 20, the average water pressure to the cutter-drum spray bars during high water flow was 20 pounds per square inch – gauge (gauge pressure, above the ambient), or psig. The average pressure to those sprays during the low-flow trial was 20 psig. The corresponding values for the conveyor-transition spray nozzles were 22.5 psig at high flow and 20 at low flow.

On June 21, the average water pressure to the cutter-drum spray bars during high water flow was 20 psig. The average pressure to those sprays during the low water-flow trial was 15 psig. The corresponding values for the conveyor-transition spray nozzles were 35 psig at high flow and 20 psig at low flow.

On June 22, the average water pressure to the cutter-drum spray bars during the high water-flow was 22.5 psig. The average pressure to those sprays during the low-flow trial was 20 psig. The corresponding values for the conveyor-transition spray nozzles were 20 psig at high flow and 20 at low flow.

Time-integrated air-sampling results

Personal breathing-zone air-sample results for June 20, 21, and 22 are presented in Table 1. A total of 12 samples was collected, 6 for the operator and 6 for the ground man. Two samples, one during the low water-flow trial and one during high flow, were collected for each employee on each of the days. For all three days of sampling, the same employee served as operator and, likewise, for all three days of sampling, the same employee served as ground man.

The respirable dust results for the operator ranged from (0.2) to 0.65 mg/m^3 during low water-flow trials and from ND (not detectable) to 0.3 mg/m^3 during high-flow trials. (A value in parentheses indicates that the measured mass was between the limit of detection, or LOD, and the limit of quantification, or LOQ.) The ground man's respirable dust results ranged from 0.29 to 0.79 mg/m^3 during the low water-flow trials and between 0.76 and 1.1 mg/m^3 during high-flow trials. Respirable dust concentrations measured in personal breathing-zone samples were lower during the high water-flow trials than during the low-flow trials; on average, about 20% lower. However, the reduction differed by the job. The operator reduction was about 60%, but the ground man data indicate an increase of about 60%. (Results are based on geometric means.)

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 ground man, the *p*DR measurements at the six non-operator locations were averaged to obtain the required estimates for periods of inactivity. (A correlation 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 construction-industry PEL described earlier.

Area air sample results for respirable dust are presented in Tables 2, 3, and 4. A total of 48 area samples was collected, representing six sets of samples collected at the eight locations on the milling machine. On each of the three days of sampling, one set was collected at low water flow and one set at high water flow. For the 24 area samples collected during high-flow trials over the three days, the arithmetic mean respirable dust concentration was 2.3 mg/m^3 (σ [standard deviation] = 0.69) and the geometric mean was 0.98 mg/m^3 (GSD [geometric standard deviation] = 1.3). Both standard deviations represent variation between days. For the 24 area samples collected at the eight locations around the mill during the low-flow trials over the three days,the arithmetic mean respirable dust concentration was 1.9 mg/m^3 (σ = 0.085) and the geometric mean concentration was 0.99 mg/m^3 (GSD = 1.4). The ratio of geometric means of the high water-flow trials' samples to the low-flow samples was 0.99, indicating a reduction of about 1% in the respirable dust concentrations when the high water flow was used.

Results are also available by day; these results are displayed by date and location in Figure 2. On June 20 for the area samples, the high water-flow geometric mean was 0.84 mg/m^3, and the low-flow geometric mean was 0.88 mg/m^3 for all respirable dust samples. The ratio of the high water-flow to low water-flow results was 0.95, corresponding to a reduction of about 5%. On June 21 for the area samples, the high water-flow geometric mean was 1.31 mg/m^3, and the low-flow geometric mean was 1.45 mg/m^3, corresponding to a ratio of 0.90, or a reduction of about 10%. On June 22 for the area samples, the high-flow geometric mean was 0.86 mg/m^3, and the low-flow geometric mean was 0.75 mg/m^3, corresponding to a ratio of 1.14, or an increase of about 14%. Figure 3 is a plot of fraction reduction versus geometric mean at low-water flow for each day-and-location combination. The highest respirable-dust geometric-mean concentrations during low water flow are associated with reductions in concentration during the corresponding high-flow trials.

The corresponding geometric-mean results for the personal exposures from both job titles were 0.43, 0.46, and 0.24 mg/m^3 respectively, at the high water-flow level for June 20, 21, and 22. At the low-flow levels the results were 0.56, 0.72, and 0.22 for the same three dates. These values produce overall reductions of 23%, 36%, and −9% (i.e., a 9% increase) for the three dates.

The time-integrated air-sampling results for respirable quartz are also presented in Tables 1, 2, 3, and 4. In Table 1, time-weighted average quartz exposures were computed using methods similar to those described above for respirable-dust exposures, except that the second method is not used. This is because real-time area concentration data are not available for quartz. Exposures during periods of inactivity can only be estimated as in the third method, which assigns the value of "0." The two TWA respirable-quartz exposure estimates for each job during each water-flow trial therefore represent an upper and a lower-end estimate for a full-shift TWA exposure under the observed conditions and water-flow rate.

The operator's quartz exposures were all not detectable at both water-flow levels. The ground man's quartz exposures varied between 0.02 and 0.06 mg/m^3 at high water flow, and between 0.004 and 0.06 mg/m^3 at low water flow. Both worker occupations combined showed a 17% increase in mean respirable-quartz exposure at the high water-flow level. However, as with the respirable dust exposures, the operator had a 10% decrease compared to a 41% increase for the ground man at the high water-flow level. Of the twelve personal measurements, three of them (all for the ground man, two at high flow and one at low flow) exceeded the NIOSH REL of 0.05 mg/m^3 when periods of inactivity are excluded. The TWAs based on inclusion of periods of inactivity had no exceedances.

For the area samples, the quartz geometric mean at the high water-flow level was 0.056 mg/m^3, compared to 0.058 mg/m^3 at the low water-flow level, indicating a reduction of about 3% (not statistically significant) at high water flow.

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

The results of real-time monitoring for respirable dust concentrations conducted using *p*DRs at eight locations on the milling machine are shown in Table 5. Averages (both arithmetic and geometric means) by day and location are provided. At each of these locations a measurement was recorded every 10 seconds. To obtain 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.

When all of the *p*DR results were combined for all three days, the arithmetic mean respirable dust concentration for the long-term high water-flow trials was 2.53 mg/m^3 (σ = 1.01), and the geometric mean was 0.42 mg/m^3 (GSD = 1.9). The three-day combined arithmetic mean respirable dust concentration for the low-flow trials was 2.13 mg/m^3 (σ = 0.42), and the geometric mean was 0.27 mg/m^3 (GSD = 1.3). The ratio of the high water-flow to low water-flow results is the ratio of the geometric means of those sampling periods, 1.4, which indicates an approximate 40% increase at high water flow relative to low flow.

By day, the geometric mean respirable dust concentration during the high water-flow trials on June 20 was 0.23 mg/m^3 and 0.31 mg/m^3 during the low-flow trials; the resulting ratio shows concentrations about 26% lower during the high-flow trials. On June 21, the geometric mean concentration during the long-term high-flow trials was 0.79 mg/m^3, while it was 0.32 mg/m^3 during the long-term low-flow trials, corresponding to an increase of about 150%. This is a big difference from the corresponding time-integrated sampling respirable dust results, which showed a 10% decrease. On June 22, the geometric mean concentration during the high water-flow trials was about 0.41 mg/m^3, compared to 0.20 mg/m^3 for the low-flow trials. The ratio of geometric means indicates an increase in respirable dust concentrations of about 100% during the high water-flow condition.

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 three days of sampling. The geometric means and reductions for these data are displayed in Table 6. Results are plotted by date and location in Figure 4.

Across all of these subset high water-flow trials and across all sampling locations, the arithmetic mean respirable dust concentration was 2.1 mg/m^3 ($\sigma = 0.76$), with a geometric mean concentration of 0.34 mg/m^3 (GSD = 2.1). The arithmetic mean respirable dust concentration for the short-term low-flow trials was 1.83 mg/m^3 ($\sigma = 1.06$), with a geometric mean of 0.13 mg/m^3 (GSD = 1.95). The ratio of geometric mean concentrations was 2.6, representing an increase in dust at high water flow of about 160%. Figure 5 is a plot of fraction reduction versus low water-flow geometric means. Even for the largest low-flow geometric means, only small average reductions in concentration are seen.

Short-time trials. In addition, six separate, randomized pairs of high water-flow and low water-flow short-time trials were conducted on June 22, each for a duration corresponding to the time it took to fill two trucks. The purpose of these additional trials was to provide for collection of additional high versus low water-flow respirable-dust concentration data during a period of time near the end of this day when inadequate milling remained to attempt to complete another long-time high-low trial pair. The geometric means are shown in Table 7. For these data, the average reduction is about 20%, though the reduction is not statistically significant at the 5% level. Figure 6 is a plot of the fraction reduction versus the geometric mean at low flow. Unlike the figures from the analogous comparisons for previous data sets, the fraction reduction is not highest at the highest low-flow determinations.

Differences by side of machine. Examination of the *p*DR data indicates that whereas substantial reductions in respirable-dust concentrations were measured at the sampling locations on the right side of the milling machine during high water-flow trials, compared with the concentrations during low flow, no reductions were measured on the left side. In particular, on the right side the geometric means of the four locations at high flow was 0.43 mg/m^3, compared to 0.56 mg/m^3 at low flow. The ratio is about 0.77, indicating approximately 23% reduction. On the other hand, the left side geometric means were 0.42 mg/m^3 for the high flow and 0.17 mg/m^3 for the low flow. The ratio of 0.42 to 0.17 is 2.47, indicating about a 150% increase at high flow. The bar chart in Figure 2 indicates that the effect of side varies over dates. For June 20, little difference is noted between sides. For June 21 and June 22 large increase is noted on the left side at all locations.

Further discussion of subset data and short-time pairs. The reason to include the short-period subset data and the short-time pairs 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 be little change in physical location or in the outdoor conditions. In theory, this would allow for a better comparison. The results for the subset data indicate larger increases in respirable-dust concentrations associated with high flow than the full-trial *p*DR data, though as for the full trial data, the increases on the left side of the machine were much less than those on the right. For the full trial data, a problem with considerable interruption in the flow of trucks removing the milled asphalt led to substantial down time in the actual milling, especially during the afternoons. It might have been hoped that this problem could be avoided in the subset data, but the results are no more favorable for the subset data than for the full-trial data. Note that within the June 21 data shown in Figure 7, the breaks in the data (including within the subset portion, which is shown in the large braces) are due to delays in truck arrival.

Even though the data from the short-time pairs do show evidence of reductions of repsirable-dust concentrations, the fact that the reduction occurs at the lowest concentrations measured during low water flow makes this finding less important or useful because it seems more important and more sensible to find reductions from the highest concentration levels.

Table 8 contains a summary of the fractional reduction in dust concentrations from the low to the high water-flow rates for all types of data. No convincing evidence of any reduction was seen.

Relating side effects to personal samples

The *p*DR area respirable dust samples 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, for which an R-square value of 0.82 was obtained.

Bulk-material sample results

The two bulk-material samples contained 25% and 43% quartz. No cristobalite or tridymite was detected above the limits 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 9 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 9 are the geometric means. The R-square was not statistically significant at the 5% level for any of the response variables (respirable dust, real time, or respirable quartz) for any model. The closest was the water-flow rate variable for the *p*DR data.

CONCLUSIONS AND RECOMMENDATIONS

The following factors make the possibility of detecting sizable reductions in respirable-dust concentrations from the increased water-flow level unlikely for this study:

1. The relatively small difference in the water flow rates; and,

2. The considerable interruption in the flow of trucks removing the milled asphalt, leading to substantial down time in the actual milling.

Both of these may explain the ineffectiveness of the increased water-flow level, which is evident from examination of the summary information in Table 8. As shown by this information, the long-term respirable dust and quartz results reveal a minimal average reduction from low- to high water-flow rates, and the various examinations of the *p*DR data reveal conflicting results with no evidence of reductions in respirable dust concentrations.

Recommendation #1. During this survey, any effectiveness of higher water flow may not have been observed due to the conditions evaluated (i.e., the small differences in flow rates). So, although the results from this survey do not suggest a reduction in respirable dust and crystalline silica exposures from the use of higher water-flow rates, until the full results of all the findings from this NIOSH research study are known, the use of high water-flow rates is recommended.

Recommendation #2. The need for continuing research should be evaluated based on the results of all field work in the ongoing NIOSH study, including the results of 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, Exclude periods of inactivity – Concentration (mg/m^3)	Respirable Quartz TWA Exposure, Treat periods of inactivity as "zero exposure" – Concentration (mg/m^3)
June 20									
Operator	Low	141	0.41	0.41	0.308	0.258	(0.02)**	(0.02)	(0.01)
	High	95	(0.2)**	(0.2)	(0.149)	0.074	ND	ND	ND
Ground man	Low	128	0.74	0.74	0.517	0.466	(0.06)	(0.06)	(0.04)
	High	93	1.1	1.1	0.509	0.421	(0.06)	(0.06)	(0.02)
June 21									
Operator	Low	103	0.65	0.65	0.483	0.374	ND	ND	ND
	High	75	(0.3)	(0.3)	0.082	0.049	ND	ND	ND
Ground man	Low	102	0.79	0.79	0.528	0.458	(0.04)	(0.04)	(0.02)
	High	77	0.84	0.84	0.303	0.159	(0.06)	(0.06)	(0.01)
June 22									
Operator	Low	140	(0.2)	(0.2)	0.164	0.083	ND	ND	ND
	High	110	ND	0.08	0.079	0.071	ND	ND	ND
Ground man	Low	142	0.29	0.29	0.203	0.135	(0.02)	(0.02)	(0.009)
	High	117	0.76	0.76	0.707	0.702	(0.03)	(0.03)	(0.03)

* The *p*DR area respirable-dust determinations were used to estimate exposures during periods of inactivity. See text.
ND = Not detected. Collected mass (if any) was below the analytical limit of detection.
** Values in parentheses indicate that the collected mass was between the analytical limit of detection and limit of quantification.
† OSHA PELs were calculated and compared with calculated equivalent respirable-dust exposures in mppcf, as described in the text. No PELs were exceeded. The largest calculated ratio of exposure to PEL ("severity factor") was 0.46. For TWAs including periods of inactivity, severity factors were smaller.

Table 2. Time-Integrated Area Air Sample Results by Location, June 20, 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	143	(0.2)*	(0.2)*	ND	ND
	High	98	ND	ND	ND	ND
Operator Platform – Right	Low	158	3.3	3.3	0.20	0.20
	High	95	2.8	2.8	0.15	0.15
Cutter Drum – Left	Low	149	1.4	1.4	0.086	0.086
	High	94	0.88	0.88	(0.07)	(0.07)
Cutter Drum – Right	Low	163	4.0	4.0	0.26	0.26
	High	95	3.9	3.9	0.24	0.24
Left Rear	Low	151	ND	ND	ND	ND
	High	98	(0.1)	(0.1)	ND	ND
Right Rear	Low	162	1.1	1.1	0.066	0.066
	High	95	0.98	0.98	(0.08)	(0.08)
Loading Conveyor – Left	Low	144	0.50	0.50	(0.04)	(0.04)
	High	94	0.48	0.48	(0.03)	(0.03)
Loading Conveyor – Right	Low	152	4.0	4.0	0.23	0.23
	High	95	4.4	4.4	0.24	0.24

† The quartz analysis was not performed when the respirable dust result for a 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, June 21, 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	103	0.93	0.93	(0.06)*	(0.06)
	High	75	1.0	1.0	(0.06)	(0.06)
Operator Platform – Right	Low	104	1.9	1.9	0.11	0.11
	High	74	0.55	0.55	ND	ND
Cutter Drum – Left	Low	107	4.4	4.4	0.24	0.24
	High	73	5.1	5.1	0.35	0.35
Cutter Drum – Right	Low	106	3.1	3.1	0.12	0.12
	High	72	3.2	3.2	0.16	0.16
Left Rear	Low	108	1.6	1.6	ND	ND
	High	74	1.5	1.5	(0.08)	(0.08)
Right Rear	Low	106	1.1	1.1	(0.05)	(0.05)
	High	72	1.6	1.6	(0.06)	(0.06)
Loading Conveyor – Left	Low	105	(0.2)*	(0.2)	ND	ND
	High	74	4.5	4.5	0.17	0.17
Loading Conveyor – Right	Low	108	2.6	2.6	0.17	0.17
	High	70	ND	ND	ND	ND

† The quartz analysis was not performed when the respirable dust result for a 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, June 22, 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	137	1.9	1.9	0.12	0.12
	High	110	4.8	4.8	0.28	0.28
Operator Platform – Right	Low	139	0.28	0.28	(0.02)*	(0.02)*
	High	110	ND	ND	ND	ND
Cutter Drum – Left	Low	145	4.3	4.3	0.26	0.26
	High	110	8.7	8.7	0.43	0.43
Cutter Drum – Right	Low	143	0.77	0.77	(0.05)	(0.05)
	High	89	0.80	0.80	(0.05)	(0.05)
Left Rear	Low	143	(0.2)*	(0.2)	ND	ND
	High	110	0.48	0.48	(0.03)	(0.03)
Right Rear	Low	136	ND	ND	ND	ND
	High	114	(0.1)	(0.1)	ND	ND
Loading Conveyor – Left	Low	145	6.7	6.7	0.32	0.32
	High	111	9.2	9.2	0.46	0.46
Loading Conveyor – Right	Low	142	0.84	0.84	(0.06)	(0.06)
	High	110	(0.2)	(0.2)	ND	ND

† The quartz analysis was not performed when the respirable dust result for a 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 by Location and Day – Full Long-Time Trial-Period Means

Sampling Location	Water Flow-Rate Condition	June 20, 2006		June 21, 2006		June 22, 2006	
		AM of Respirable Dust Concentrations (mg/m^3)	GM of Respirable Dust Concentrations (mg/m^3)	AM of Respirable Dust Concentrations (mg/m^3)	GM of Respirable Dust Concentrations (mg/m^3)	AM of Respirable Dust Concentrations (mg/m^3)	GM of Respirable Dust Concentrations (mg/m^3)
Operator Platform – Left	Low	0.18	0.07	0.81	0.28	2.28	0.59
	High	0.07	0.05	1.32	0.80	5.84	2.32
Operator Platform – Right	Low	4.15	2.72	3.24	0.24	0.31	0.03
	High	2.62	1.69	1.07	0.14	– *	–
Cutter Drum – Left	Low	1.62	0.05	2.49	0.28	6.72	2.02
	High	0.60	0.02	5.86	2.08	13.47	4.43
Cutter Drum – Right	Low	6.75	4.78	3.19	0.83	0.56	0.07
	High	3.77	2.54	3.75	1.87	0.67	0.09
Left Rear	Low	0.03	0.004	1.21	0.32	0.32	0.15
	High	0.05	0.01	1.69	1.35	0.74	0.34
Right Rear	Low	1.54	0.76	0.96	0.32	0.15	0.03
	High	0.83	0.37	1.13	0.80	0.12	0.03
Conveyor – Left	Low	0.44	0.16	0.09	0.07	3.73	0.96
	High	0.36	0.14	2.90	1.75	5.10	1.94
Conveyor – Right	Low	6.19	4.21	3.17	0.94	0.91	0.26
	High	6.31	4.07	0.32	0.19	0.33	0.10

AM = Arithmetic mean of full trial data
GM = Geometric mean of full trial data
* Missing data due to equipment problem.

Table 6. 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	June 20, 2006	June 21, 2006	June 22, 2006
Operator Platform – Left	Low	0.05	0.13	1.67
	High	0.05	0.79	2.72
Operator Platform – Right	Low	1.41	0.01	0.10
	High	0.87	0.07	– *
Cutter Drum – Left	Low	0.00	0.02	3.94
	High	0.01	2.60	6.49
Cutter Drum – Right	Low	2.55	0.10	0.02
	High	2.40	1.53	0.03
Left Rear	Low	0.00	0.08	0.10
	High	0.00	1.39	0.23
Right Rear	Low	0.49	0.05	0.01
	High	0.21	0.54	0.01
Loading Conveyor – Left	Low	0.10	0.05	3.98
	High	0.18	1.47	4.61
Loading Conveyor – Right	Low	10.71	0.25	0.11
	High	5.05	0.20	0.24

* Missing data due to equipment problem.

Table 7. Real-Time *p*DR Area Air Monitoring Results by Location and Day – Short-Time Trial Data – Geometric Means of Respirable-Dust Concentrations (mg/m^3)

Sampling Location	Water Flow-Rate Condition	June 22, 2006
Operator Platform – Left	Low	0.5
	High	0.65
Operator Platform – Right	Low	0.05
	High	0.03
Cutter Drum – Left	Low	0.72
	High	0.94
Cutter Drum – Right	Low	0.42
	High	0.23
Left Rear	Low	0.22
	High	0.18
Right Rear	Low	0.17
	High	0.09
Loading Conveyor – Left	Low	0.91
	High	0.81
Loading Conveyor – Right	Low	0.21
	High	0.18

Table 8. Summary of Reductions in Respirable Dust and Quartz Concentrations at High Water-Flow Condition Compared to Low Water-Flow Condition

Area Air-sample type	Right side	Left side	Overall
Respirable dust (time-integrated samples)	41%	−67%*	1%
*p*DR respirable dust (full period, long-time trials)	23%	−148%*	−40%*
*p*DR respirable dust (short-period subset data)	−80%*	−298%*	−160%*
*p*DR respirable dust (short-time trials)	38%	−6%*	20%
Respirable quartz (time-integrated samples)	46%	−76%*	3%

* A "negative reduction" indicates an increase in concentration.

Table 9. Explanatory Variables

Variable	Low Water Flow, June 20	High Water Flow, June 20	Low Water Flow, June 21	High Water Flow, June 21	Low Water Flow, June 22	High Water Flow, June 22
Real-time* (mg/m^3)	0.31	0.23	0.32	0.79	0.26	0.41
Respirable* (mg/m^3)	0.88	0.84	1.5	1.3	0.75	0.86
Quartz (mg/m^3)	0.054	0.055	0.078	0.066	0.045	0.050
Number of Trucks	46	31	39	22	52	44
Water flow (gpm)- cutter	15.2	17.7	15.7	19.5	16.3	18.7
Water pressure (psi)-cutter	20	20	15	20	20	22.5
Water pressure (psi)-conveyor	20	22.5	20	35	20	20
Wind	N/A	N/A	13.9	19	8	7
Miles milled	2.94	2.09	2.46	1.59	7.97	4.62
Cut depth	1.5in	1.5–2in	1.5	1.5 (3 in for several hundred feet)	1.5	1.5

N/A – Not available

Figure 1. Fixed Area Air-Sampling Locations

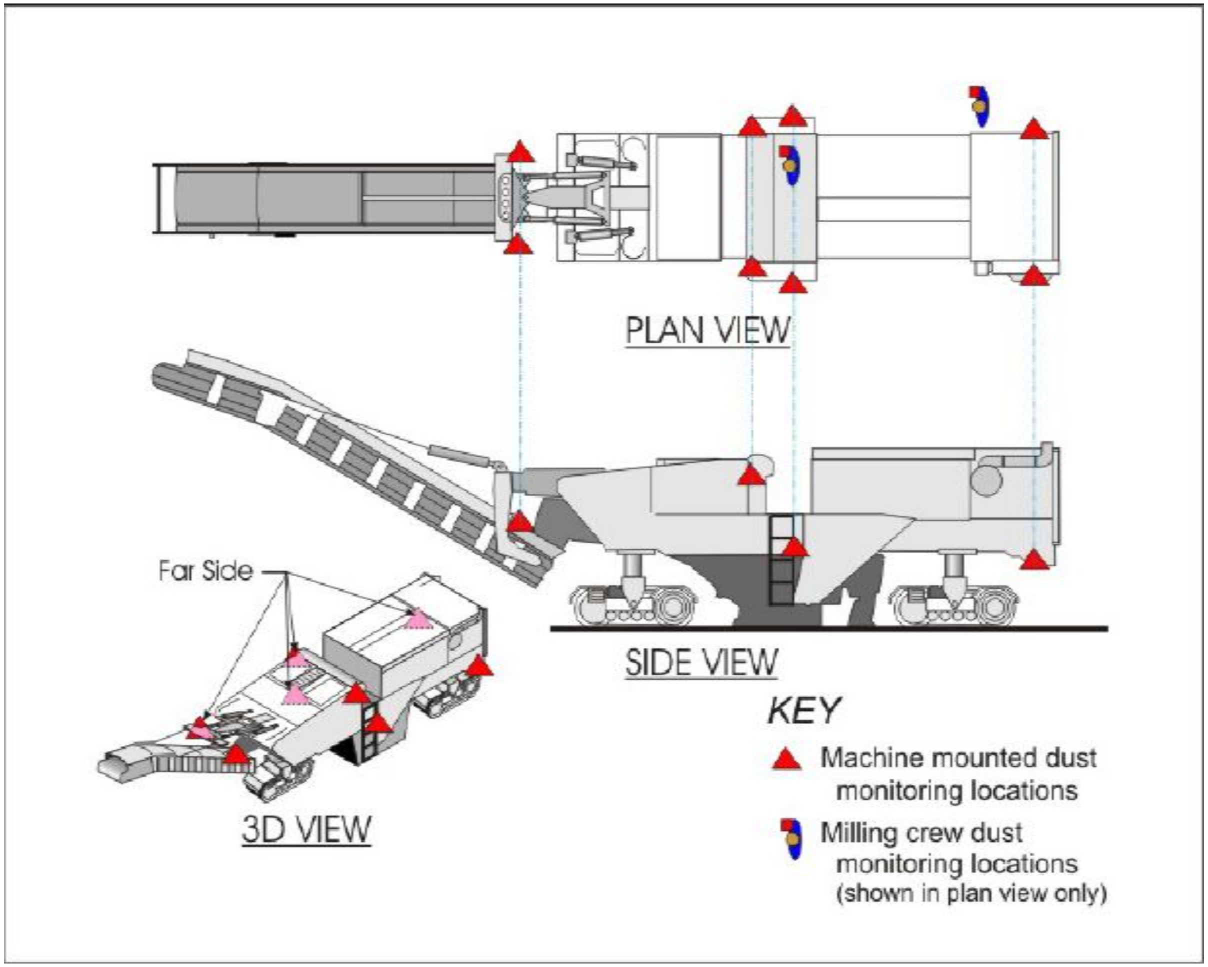
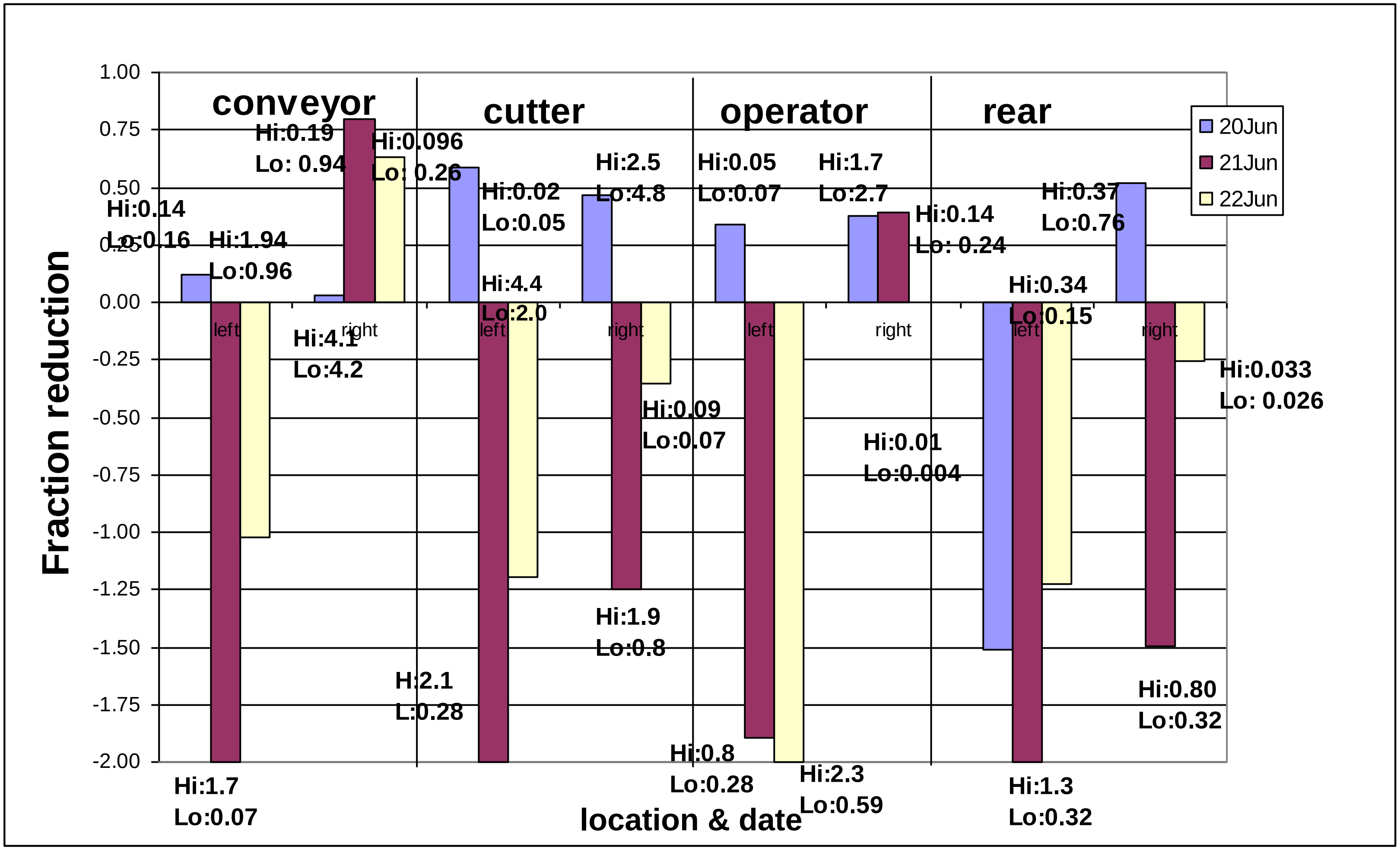
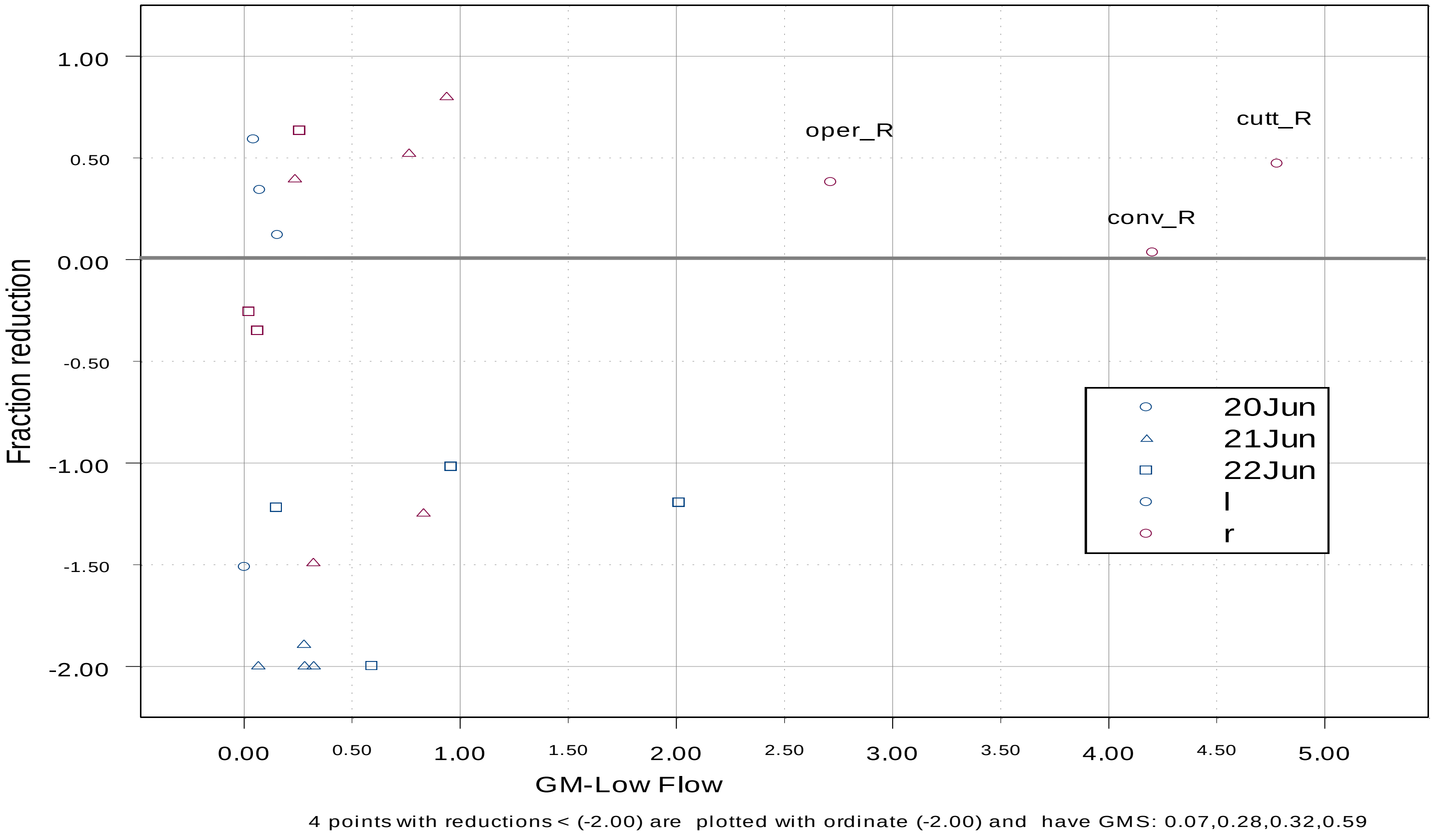


Figure 2. Fraction Reduction in Geometric-Mean Respirable-Dust Concentration for High vs. Low Water Flow (with High and Low Water-Flow Trial-Mean Concentrations Displayed, mg/m^3) by Date, Location, and Side, for Full-Trial *p*DR Real Time Area Air-Monitoring Data



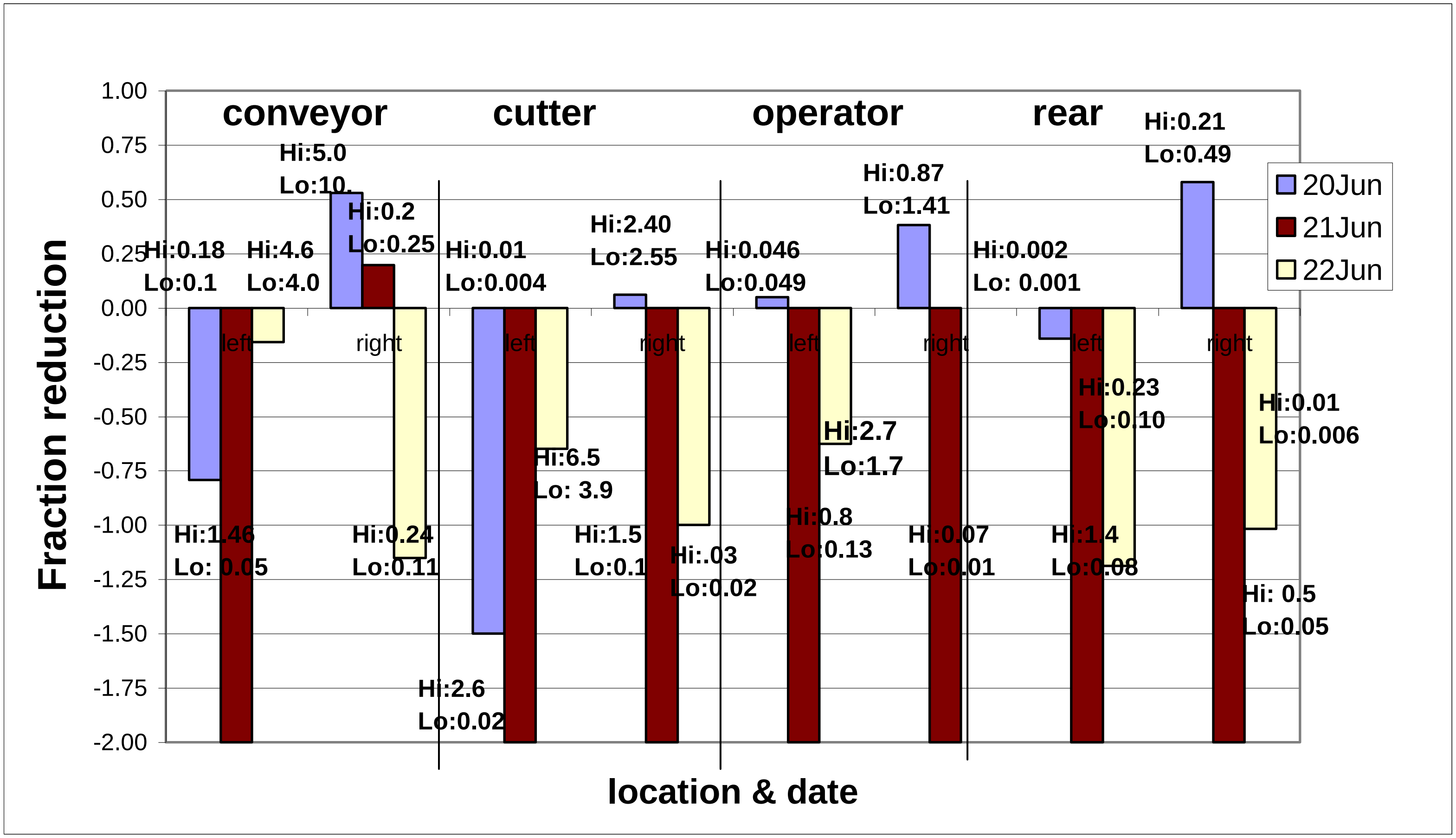
Notes: (1) *Negative reduction values indicate* increases *in concentration.* (2) *Data for operator-right location on June 22 missing due to equipment problem.*

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 Geometric-Mean Values for Each Location on Each Day



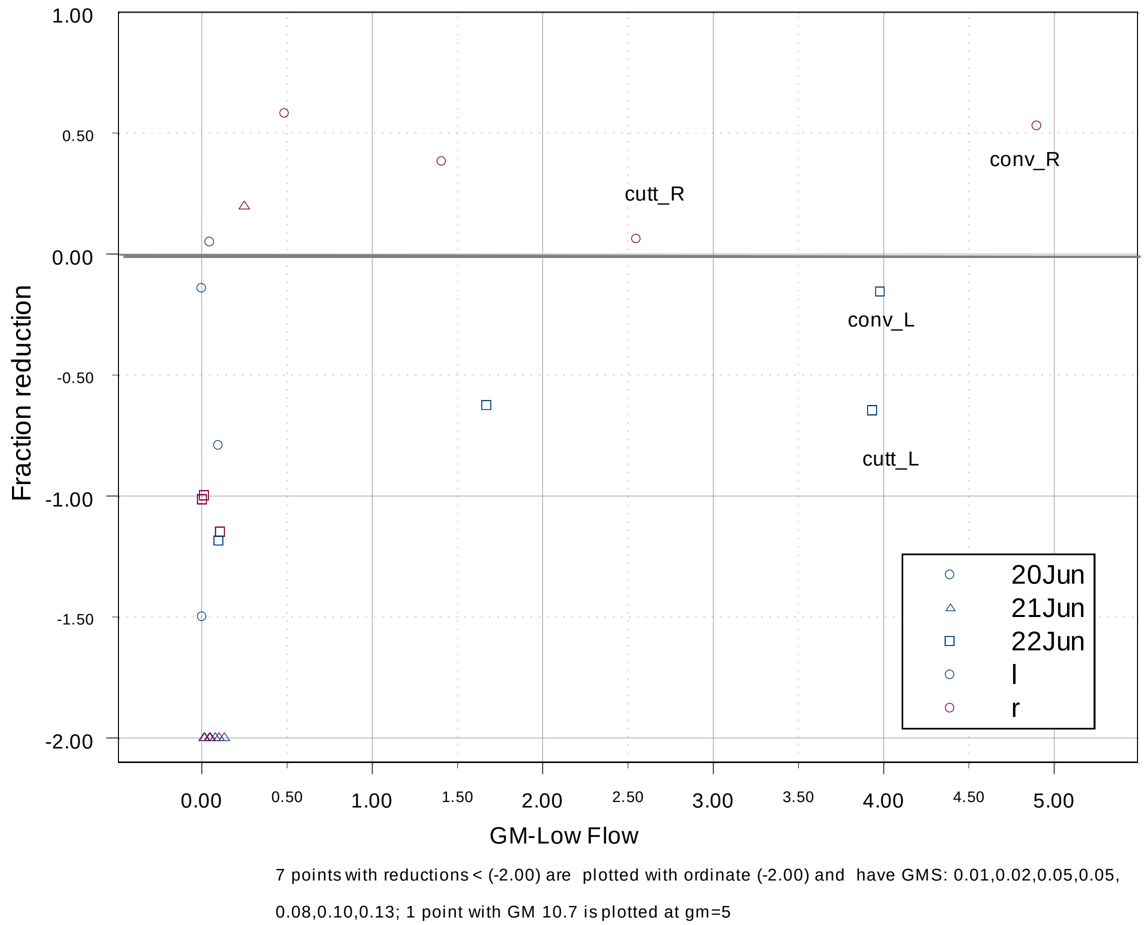
Circle, June 20, 2006; triangle, June 21, 2006; square, June 22, 2006. Blue, left side; red, right side.
conv_R = conveyor right; cutt_R = cutter right; oper_R = operator right
Note: *Negative reduction values indicate* increases *in concentration.*

Figure 4. Fraction 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.



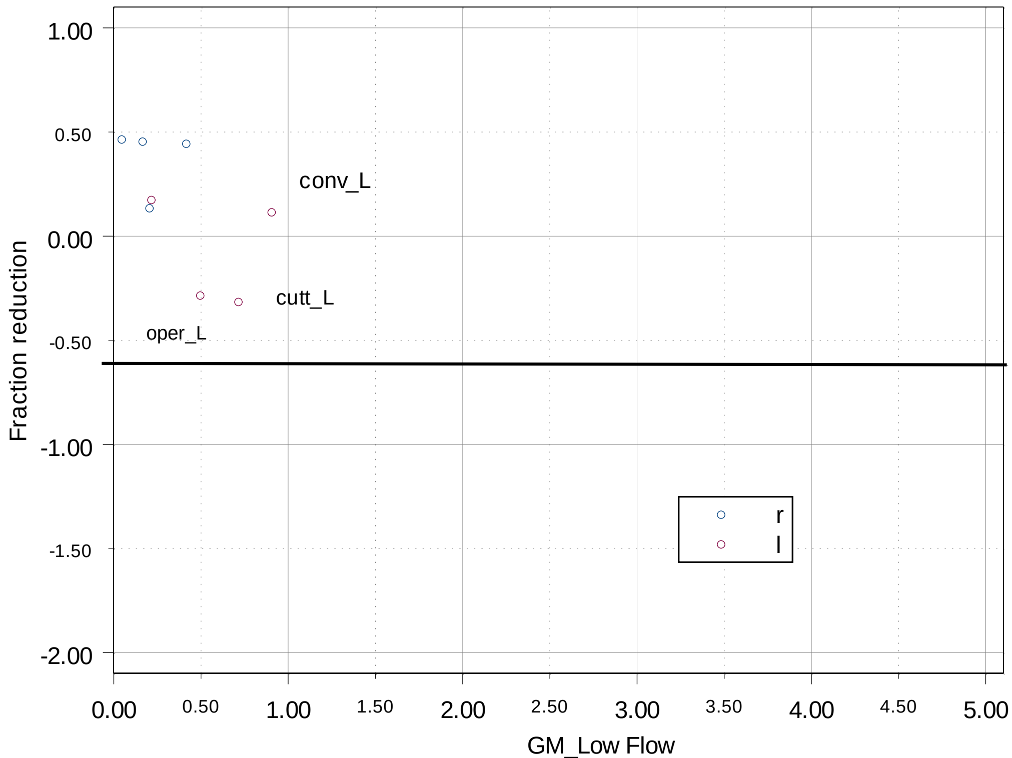
Notes: Negative values indicate ***increases*** in concentration. Bars cut off at -2.00 indicate values less than -2.00.
Data for operator-right location on June 22 missing due to equipment problem.

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 Short-Period Subset-Data Geometric-Mean Values for Each Location on Each Day



Circle, June 20, 2006; triangle, June 21, 2006; square, June 22, 2006. Blue, left side; red, right side.
conv_R = conveyor right; conv_L = conveyor left; cutt_R = cutter right; cutt_L = cutter left
Note: *Negative reduction values indicate* increases *in concentration.*

Figure 6. 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 Short-Time Trial Geometric-Mean Values for Each Location, June 22, 2006



Blue, left side; red, right side.
oper_L = operator left; conv_L = conveyor left; cutt_L = cutter left
Note: *Negative reduction values indicate* increases *in concentration.*

Figure 7. 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