In-Depth Survey Report

CONTROL TECHNOLOGY FOR DOWEL-PIN DRILLING IN CONCRETE PAVEMENT

ALAN ECHT, MPH, CIH; CAPTAIN, U.S. PUBLIC HEALTH SERVICE

KENNETH MEAD, PhD, PE; CAPTAIN, U.S. PUBLIC HEALTH SERVICE

H. AMY FENG, MS

DAWN FARWICK, MS

Division of Applied Research and Technology
Engineering and Physical Hazards Branch
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Site Surveyed: E-Z Drill, Inc., 320 Ash St., Perry, Oklahoma

NAICS Code: 333120 Construction Machinery Manufacturing

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Survey Conducted By:

Alan Echt, Industrial Hygienist

Kenneth Mead, Mechanical Engineer

H. Amy Feng, Statistician (Health)

Dawn Farwick, Research Chemist

Employer Representatives Contacted:

Randy L. Stevens, Vice President – Sales

(800) 272-0121

Frank Douglass, Plant Manager

(580) 336-9874

Employee Representatives: None contacted

Analytical Work Performed By: Bureau Veritas North America

Manuscript Prepared By: Terry Lewis

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Abstract

This study evaluated the ability of a commercially-available dust-control system to reduce respirable dust emissions during dowel drilling. Dowel drilling is a task performed during new concrete runway and highway construction (e.g., when a lane is added) or during full-depth repair of concrete pavement to provide load transfer across transverse pavement joints. Dowel drilling machines typically contain one or more pneumatic or hydraulic percussion drills aligned in parallel in a frame that acts to control drill alignment and prevent wandering. The dust control evaluated in this report included a close-capture hood surrounding each of the steels and bits at the work surface, a length of corrugated flexible hose connected to each hood, and a dust collector at the back of the dowel drill unit. Compared with the use of no dust control during dowel drilling in concrete, the dust-control system significantly ($p<0.0001$) reduced geometric mean respirable dust emissions by 93% to 96% when measured with filter samples. Arithmetic mean respirable dust emissions measured on filters were significantly ($p<0.0001$) reduced 92% to 96% by the use of the dust control system. The use of the dust control also significantly reduced respirable dust emissions ($p<0.0001$) by 87% to 94% when measured with a nephelometer. The different measurement techniques probably account for the disparity in results obtained with filter samples and the nephelometers. The dust-control system significantly ($p<0.0001$) reduced geometric mean respirable quartz emissions by 92% to 96% when measured with filter samples and significantly ($p<0.0001$) reduced arithmetic mean respirable quartz emissions measured on filters by 90% to 96%. The measurements were conducted in a tent to exclude diesel exhaust particulate emitted by the compressor used to power the dowel-pin drill and isolate the drill from the effects of wind and weather during the tests. The use of this technique means that it would not be appropriate to compare the results to any exposure indices. Recommendations are offered at the end of the report to improve the system. These include recommending that the manufacturer consider installing a pressure gauge across the filter in the dust collector to provide the drill operator with information needed to determine when to clean or change the filter. The manufacturer should also consider installing static pressure taps near the duct connection to each hood that can be connected to vacuum gauges on the operator's instrument panel. Monitoring hood static pressure would indicate to the operator when the dust collection system was not performing as designed.

Introduction

Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Applied Research and Technology has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial process, or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for or availability of an effective system of hazard control measures.

These studies involve a number of steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concept techniques. Next, in-depth surveys are conducted to determine both the control parameters and the effectiveness of these controls. The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

Background for this Study

Crystalline silica refers to a group of minerals composed of silicon and oxygen; a crystalline structure is one in which the atoms 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 crystalline silica refers to that portion of airborne crystalline silica dust 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]. Silicosis, a fibrotic disease of the lungs, is an occupational respiratory disease caused by the inhalation and deposition of respirable crystalline silica dust [NIOSH 1986]. 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.

Crystalline silica is a constituent of several materials commonly used in construction, including brick, block, and concrete. Many construction tasks have been associated with overexposure to dust containing crystalline silica [Chisholm 1999, Flanagan et al. 2003, Rappaport et al. 2003, Woskie et al. 2002]. Among these tasks are tuckpointing, concrete cutting, concrete grinding, abrasive blasting, and road milling [Nash and Williams 2000, Thorpe et al. 1999, Akbar-Kanzadeh and Brillhart 2002, Glindmeyer and Hammad 1988, Linch 2002, Rappaport et al. 2003]. Highway construction tasks that have been associated with silica exposures include jackhammer use, concrete sawing, milling asphalt and concrete pavement, clean-up using compressed air, and dowel drilling [Valiante et al. 2004]. Linch [2002] also identified dowel drills as sources of dust emissions on highway construction sites.

Dowel-pin drilling machines (or dowel drilling machines) are used to drill horizontal holes in concrete pavement. Steel dowels transfer loads between adjacent concrete pavement slabs [Park et al. 2008]. They are typically used in “transverse joints in rigid airport and highway pavement to transfer shear from a heavily loaded slab to an adjacent less heavily loaded slab” [Bush and Mannava 2000]. Typical dowel-pin drilling machines have one or more drills held parallel in a frame that aligns the drills and controls wandering [FHWA 2006]. The dowel-pin drilling machine may be self propelled or boom mounted, and may ride on the slab or on the subbase [FHWA 2006]. After drilling to a typical depth of 22.9 centimeters (cm) (9 inches (in)) (the diameter is determined by the use of cement-based grout or epoxy anchoring formulations), the hole is cleaned with a compressed air nozzle, the anchoring material is placed, and the dowel is installed [FHWA 2006].

The study by Valiante et al. [2004] reported that dowel drilling respirable crystalline silica exposures ranged from 0.05 milligrams per cubic meter (mg/m^3) to 0.16 mg/m^3, 8-hour (hr) time weighted average (TWA). Linch [2002] also documented silica exposures during dowel drilling. The Linch [2002] study reported 8-hr TWA quartz exposures for an operator and laborer using a boom-mounted dowel drilling machine. The operator’s 8-hr TWA exposure ranged from less than the limit of detection to 0.11 mg/m^3, with a geometric mean respirable crystalline silica exposure of 0.037 mg/m^3 for 8 samples. The highest result was 2.2 times the NIOSH Recommended Exposure Limit (REL) for crystalline silica of 50 micrograms per cubic meter ($\mu g/m^3$). The laborer’s 8-hr TWA respirable crystalline silica exposures ranged from 0.12 -1.3 mg/m^3 (2.4 – 26 times the NIOSH REL), with a geometric mean of 0.24 mg/m^3 (4.8 times the NIOSH REL) for 8 samples. Linch [2002] concluded his study of dowel drilling exposures with this statement:

> Means of controlling the respirable dust generated from concrete drilling during all operations needs to be developed, tested, and

employed. Pneumatic drilling is the common method of drilling concrete pavement. Methods of using small amounts of water through the drill stem should be developed for these specific applications. High-velocity dust collection systems that effectively control respirable dust should be tested and made available.

There are only two American manufacturers of dowel-pin drills. Both manufacturers offer optional dust control systems for their machines. The manufacturers both make local exhaust ventilation (LEV) dust control systems to capture the dust generated by the dowel drilling process. In addition, they both sell water kits to suppress the dust that results from drilling holes for dowels. One manufacturer's water kit supplies water through the drill steel, while the other manufacturer's water kit sprays water on the surface to be drilled. This study aims to evaluate the effectiveness of current dust controls for dowel-pin drilling machines, work with manufacturers to improve dust controls if necessary, and promote the use of tools with dust controls.

Two approaches are planned to evaluate the effectiveness of current dust controls. The first will measure respirable dust emissions from dowel drilling machines in a controlled setting, isolated from the effects of wind, weather, and other sources of particulate, assessing the effectiveness of the controls in reducing emissions. Emissions with and without the use of controls will be compared. The second approach will assess personal respirable dust and respirable crystalline silica exposures of workers operating dowel drilling machines with dust controls in place in a real-world setting to determine the ability of the dust controls to limit exposures.

Background for this Survey

This survey, performed at the equipment manufacturer's factory, was intended to quantify the relative extent to which the local exhaust ventilation (LEV) dust control system was able to reduce respirable dust and respirable crystalline silica emissions from a dowel drilling machine in a controlled setting. The LEV system utilized close-capture hoods that surrounded the drill steels and bits and were in close contact with the concrete substrate. The dust was conveyed from the hoods to a dust collection system utilizing flexible corrugated hose with a smooth interior. The dust collector utilized a pneumatic fan to provide suction and filtered the air prior to discharge to the atmosphere.

Plant and Process Description

Introduction

E-Z Drill's offices are located in Stillwater, Oklahoma. The manufacturing facility is located in Perry, Oklahoma. E-Z Drill produces on-slab, on-grade, and equipment-mounted dowel-pin drills, as well as concrete drills for special applications. A variety of models are produced, ranging from single drills to five-gang drills. E-Z Drill began making dowel-pin drills in 1987. Every drill is tested on a slab behind the factory before it is shipped to a customer.

Process Description

The dowel drilling machine tested was an E-Z Drill model 210-3 SRA four-drill, self-propelled, on-slab unit equipped with a remote on/off switch (Figure 1). The machine used 2.2 cm (⅞-in) diameter whirlibits (Brunner and Lay, Springdale, AR) to drill holes 46 cm (18 in) deep. The drills (pneumatic rock drills) cause the bit to rotate and impact to produce the desired hole in the concrete. The selection of the drill bit and steel was left to the manufacturer. While the type of bit and steel may influence dust generation, the study was not designed to compare one manufacturer's dust control with another. As long as the same bit and steel type was used for both "control on" and "control off" trials, the experimental design is adequate for determining the relative effectiveness of the dust control system.

Figure 1 - E-Z Drill model 210-3 SRA four-drill, self-propelled, on-slab dowel-pin drill

Methodology

Sampling Strategy

The aim of this survey was to determine the relative reduction in respirable dust and respirable crystalline silica emissions achieved through the use of the LEV system. This reduction was measured by comparing the emissions when the LEV system was in operation ("control on") with the emissions when the LEV system was not in operation ("control off"). In order to measure this reduction, trials of the dowel drilling machine dust control were conducted in sampling rounds consisting of two paired trials in each sampling round – one "control on" trial and one "control off" trial. The order of the trials was randomized within each sampling round. Real-time and on-filter dust samples were collected during each trial. The on-filter samples were also used to assess respirable crystalline silica dust emissions.

Each dowel-pin drilling machine trial consisted of using a four-gang dowel-pin drilling machine (Model 210-3 SRA, E-Z Drill, Inc., Stillwater, OK) to drill four holes in a concrete slab in the outdoor testing area behind the E-Z Drill factory in Perry, OK. The dowel-pin drilling machine was placed on top of a 25 cm (10 in) thick slab of 24 megapascal (MPa) (3500 pounds/square-inch (psi)) concrete (Perry Ready Mix, Perry, OK). The slab was poured on September 17, 2010. The pneumatically-powered dowel-pin drilling machine was maneuvered on the slab in order to drill four new 22 mm (⅞-in) diameter holes for each trial. The dowel-pin drilling machine was positioned so that none of the close-capture hoods in use covered a portion of an existing hole. On the second day of the evaluation, the hoods were also positioned to avoid any spalling around previously-drilled holes. The position of the dowel-pin drilling machine was adjusted in order to place the hoods in close contact with the surface of the concrete. The drill advanced along the length of the slab as needed to continue the tests. The dowel-pin drilling machine could be driven from side to side and steered, and the array of drills raised or lowered as a unit. The dowel-pin drilling machine and its dust collector were powered by a portable diesel-powered air compressor (XAS 756 (CD), Atlas-Copco, Commerce City, CO).

In order to conduct the evaluation in a controlled environment, free from the effects of the wind and to minimize interference from diesel exhaust particulate, the dowel-pin drilling machine was placed inside a tent (10 x 20 Garage - Unicage, Item No. MAC-GAR04, MAC-Automotive, Inc. Laverne, CA) equipped with a roll-up front door that could be closed with two zippers (Figure 2). Polyethylene sheeting (0.1 mm (4-mil), Film-Gard, Covalence Plastics, Minneapolis, MN) was duct-taped to the bottom of the side and rear walls to improve the tent-to-ground seal to reduce air infiltration and inhibit dust from escaping. The bottom edge of the polyethylene sheeting was held to the ground using pallets and lumber. The exhaust from the pneumatic fan motor was routed outdoors through a corner of the tent to minimize interference from the oil mist in the motor exhaust (Figure 3).

Figure 2 - The dowel-pin drill inside the tent

Figure 3 - The exhaust from the pneumatic fan motor was routed outside the tent

Sampling Procedures

Respirable dust emission concentrations under the “control on” and “control off” conditions were assessed using Personal Dataram (Model pDR-1000AN, Thermo Electron Corp., Franklin, MA) instruments. The pDR is nephelometer that uses light scattering to produce a measure of dust over a size range of 0.1-10 µm and a concentration range of 0.001 to 400 mg/m^3. These readings are relative to a gravimetric calibration performed by the manufacturer in mg/m^3 using standard SAE fine (ISO fine) test dust. For this study, the pDRs were programmed to record the average dust concentration once every second.

Air samples for respirable particulate and respirable crystalline silica were collected at a flow rate of 2.2 liters/minute using a battery-operated sampling pump (Aircheck Sampler model 224, SKC, Inc., 84, PA) calibrated before and after each day’s use. The pump was connected via Tygon® tubing and a tapered Leur-type fitting to a pre-weighed, 37-mm diameter, 5-micron (µm) pore-size polyvinyl chloride filter supported by a backup pad in a three-piece filter cassette sealed with a cellulose shrink band (in accordance with NIOSH Methods 0600 and 7500) [NIOSH 1994a,b]. The front portion of the cassette was removed and the cassette was attached to a Higgins-Dewell type respirable dust cyclone (Model 4L, BGI Inc., Waltham, MA). Bulk samples of dust were also collected in accordance with NIOSH Method 7500 [NIOSH 1994b].

The filter samples were analyzed for respirable particulate according to NIOSH Method 0600 [NIOSH 1994a]. The filters were allowed to equilibrate for a minimum of two hours before weighing. A static neutralizer was placed in front of the balance (model AT201, Mettler-Toledo, Columbus, OH) and each filter was passed over the neutralizer before weighing. The limit of detection was 50 µg/sample. The limit of quantitation was 160 µg/sample. The results in this report were corrected for laboratory and field blanks.

Crystalline silica analyses of filter and bulk samples were performed using X-ray diffraction according to NIOSH Method 7500 [NIOSH 1994b]. Each filter was removed from the sampling cassette and transferred to a 15 milliliter (mL) vial. Then, 10 mL of tetrahydrofuran (THF) was added to each vial. The samples were allowed to stand for five minutes then vortexed for two minutes. After vortexing, the samples were placed in an ultrasonic bath and sonicated for ten minutes. Next, a silver membrane filter was placed in the vacuum filtration unit. Then, 2 mL of THF was placed on the filter followed by the sample suspension, three vial rinsings, and a final vial cap rinse. Finally, vacuum was applied to deposit the suspension onto the filter. The silver membrane filter was then transferred to an aluminum sample plate and placed in the automated sample changer for analysis by X-ray diffraction. The LODs for quartz, cristobalite and tridymite were 5 µg/sample, 10 µg/sample, and 10 µg/sample, respectively. The LOQs for quartz, cristobalite and tridymite were 17 µg/sample, 33 µg/sample, and 33 µg/sample, respectively. The results in this report were corrected for laboratory and field blanks.

Each pDR and air sampling pump with cyclone and filter were placed in tripod-mounted brackets approximately 1.5 meters (m) (60 in) above grade (either the ground or the concrete slab) to sample at personal breathing zone height. The tripods were placed at three locations: in front of the dowel-pin drilling machine, at the side of the machine at the control panel, and at the side of the machine adjacent to the dust collector (see Figures 2 and 4). Reference points were marked on the front of the dowel-pin drill, on the side by the control panel, and on the dust-collector frame to orient the tripods so that they could be easily repositioned before each trial. The tripod in front of the dowel drilling machine was aligned with the center of the drilling array and placed about 1.8 m (72 in) in front of the mark on the front of the dowel-pin drill. The tripod to the left of the control panel was placed 0.61 m (24 in) from the mark on the control panel. The tripod to the left of the dust collector was also placed 0.61 m (24 in) from the mark on the dust collector frame.

Figure 4 – Tripods were placed in three locations around the dowel-pin drill

Measurement of Control Parameters

Exhaust air and bailing air flow rates were measured using a Sierra Instruments, Inc. (Monterey, CA) model 730-N5-1 fast response in-line mass flow meter (range

0-2.83 m^3/min (0-100 cfm)). A Sierra Instruments, Inc. Model 904M Flo-Box was used to read the signal from the meter. The dowel-pin drilling machine was connected to 758 kiloPascals (kPa) (110 psi) shop air for these tests. Bailing air flushes the cuttings out of the drill hole. It is conveyed through the hollow steel and an outlet in the bit.

Bailing air was measured using the mass flow meter. To conduct the measurement, a sampling tube was created to contain and channel the bailing air into the mass flow meter. One end of a 7.6 cm (3 in) to 7.6 cm (3 in) PVC-DWV Schedule 40 coupler was slipped over the rubber tube on the exhaust hood on the number 4 drill (duct tape was used to make the connection secure and reasonably air tight). The other end of the coupler was connected to a 61 cm (2 ft) length of 7.6 cm (3 in) diameter PVC-DWV Schedule 40 pipe. This length of pipe surrounded the whirlibit and allowed it to move freely. The length of 7.6 cm (3 in) diameter pipe was connected to a 7.6 cm (3 in) to 5 cm (2 in) PVC-DWV Schedule 40 adapter. This adapter was connected to a 30 cm (12 in) long piece of 5 cm (2 in) diameter PVC-DWV Schedule 40 pipe. A threaded 5 cm (2 in) to 5 cm (2 in) adapter connected the assembly to the inlet of the mass flow meter. A second threaded adapter connected the mass flow meter outlet to a 27 cm (10½ in) long piece of PVC-DWV Schedule 40 pipe. The sampling tube assembly is shown in Figure 5. Bailing air flow measurements were made at the number 4 drill position in three ways, all with the exhaust system off and the drill running: with the exhaust hose disconnected, with the exhaust hose connected, and with the exhaust hose disconnected and the hood take-off blocked (with duct tape).

Figure 4 - Bailing air measurement set-up

Exhaust air flow measurements were made in three ways. First, the same sampling tube assembly described above was used in the same position as above, except the mass flow meter was reversed to align properly with the direction of the air flow. For all three exhaust air flow measurements, the drill was off and the exhaust system was running. This measurement was made with the boots of the other drills against the concrete and repeated with the boots of the other drills not in contact with the concrete surface.

The second set of measurements was made at the dust collector at the inlet for the number 4 drill (Figure 6). This required an extended straight inlet into the dust collector. A 5 cm (2 in) to 5 cm (2 in) flexible coupling (Model RC 50, American Valve, Greensboro, NC) was used to attach a 30 cm (12 in) long piece of PVC-DWV Schedule 40 pipe to the hose near the dust collector inlet. A threaded 5 cm (2 in) to 5 cm (2 in) adapter connected the pipe to the outlet of the mass flow meter. A second threaded 5 cm (2 in) to 5 cm (2 in) adapter was connected to the inlet of the mass flow meter. This adaptor was attached to a 27 cm (10½ in) long piece of PVC-DWV Schedule 40 pipe. The other end of the pipe was open to the atmosphere. The hood on the number 4 drill was not in contact with the concrete surface.

Figure 6 - Exhaust ventilation measured at collector with hose disconnected

Third, the flow meter was placed in line in the exhaust hose between the number 4 drill and the dust collector (Figure 7) This measurement also required an extended straight inlet to properly accommodate the flow meter. A 5 cm (2 in) to 5 cm (2 in) flexible coupling (Model RC 50, American Valve, Greensboro, NC) was used to attach a 30 cm (12 in) long piece of PVC-DWV Schedule 40 pipe to the hose near the dust collector inlet. A threaded 5 cm (2 in) to 5 cm (2 in) adapter connected the pipe to the outlet of the mass flow meter. A second threaded 5 cm (2 in) to 5 cm (2 in) adapter was connected to the inlet of the mass flow meter. This adapter was attached to a 27 cm (10½ in) long piece of PVC-DWV Schedule 40 pipe. A second 5 cm (2 in) to 5 cm (2 in) flexible coupling was used to connect this pipe to the flexible exhaust hose. While all four hoods were connected to the dust collector, only the flow from the hood on the number 4 drill was measured. The hood on the number 4 drill was not in contact with the concrete surface.

Figure 7 - Exhaust ventilation measured with meter in line

Test Procedure

For a given trial, the drills were positioned on the slab. The NIOSH researchers started the data collection period with each of the samplers and recorded the sampling start time. The NIOSH researchers lowered the tent door and closed its zippers. An E-Z Drill employee started the dowel drilling machine and dust collector from outside the tent using a remote control. The NIOSH researchers recorded the drill start time. The drills shut off automatically and withdrew from the holes after reaching a pre-set depth of 46 cm (18 in). The NIOSH researchers recorded the last drill stop time. The NIOSH researchers waited five minutes after the last drill stopped. They donned half-facepiece dual-cartridge respirators with HEPA filters, unzipped and raised the tent door, entered the tent and stopped the data collection period for each of the samplers. The NIOSH researchers recorded the sampling stop time. Next, they rolled up the front tent door, raised the tent flap in the right rear corner and installed a 76 cm (30 in) fan (Maxx Air High Velocity, Ventamatic, Ltd., Mineral Wells, TX) to push air into the tent. They continued to purge the tent using the fan until the respirable dust concentration fell below 0.05 mg/m^3 (equal to the NIOSH REL for crystalline silica) as indicated by a handheld pDR temporarily located on top of the dowel drilling machine's center panel. Once the concentration had dropped to this level, E-Z Drill personnel entered the tent and repositioned the dowel drilling machine for the next test. The NIOSH researchers then moved the samplers to the designated positions relative to the dowel drilling machine, attached new filter cassettes to the cyclones, removed the fan and re-sealed the tent flap, and repeated the process. Three rounds of sampling were conducted in this manner on September 21, 2010 and five rounds of sampling were conducted on September 22, 2010.

For the "control off" trials conducted on the first day, the exhaust hose was physically disconnected from each hood by loosening a screw, moving a clamp, and sliding the hose off the hood connection. In addition, the drill array was raised between runs on the first day to remove dust from the hood assemblies. For the "control off" trials conducted on the second day, the entire hood assembly was removed from each drill prior to each "control off" trial.

Statistical Methods

Study variables included location (center, front, and rear), control condition ("control on" and "control off"), and respirable dust measurements. The pDR and respirable dust on filter samples measured the respirable fraction. The on-filter samples were also used to measure the respirable crystalline silica dust concentration.

Data collection using all of the dust sampling methods (respirable dust and crystalline silica on filters, pDR) were all started shortly before the drills started and stopped approximately five minutes after the last drill stopped. The pDR automatically calculates the average respirable dust concentration during the sampling period. Since the data collection began before the drills started, that average included the background dust concentration in the tent for the period between the sample start and the drill start, plus the time required for the dust concentration to reach a steady response. In order to exclude those data and calculate a new average dust concentration for the pDR analyses, the initial time for each analysis was determined by finding the time the dust concentration first rose 2 mg/m^3 above baseline and adding 1 minute to that time. The four minutes of data after that point were included in the analyses.

Fourteen of the respirable dust filter sample results were less than the limit of detection (LOD) of 50 µg/sample. Twenty-two of the quartz dust samples were less than the LOD of 5 µg/sample. For those results, the LOD divided by the square root of 2 ($LOD/\sqrt{2}$) was used in place of the sample mass to calculate the concentration [Hornung and Reed 1990].

Data from the two days were analyzed separately because of differences in the way "control off" trials were conducted from the first testing day to the second. On the first day the hoses were removed from the hoods for "control off" trials. After discussions with EZ Drill personnel, the hoods were completely removed from the drills for "control off" trials on the second day. The hoods were positioned to avoid covering any spalled areas around previously-drilled holes on the second day as well.

For each data series, the logarithm was calculated for each value of the data sets defined above. The arithmetic mean of the log values was then computed. These mean values were used for analyses, including calculating the geometric means of the data, and for mixed model analyses.

Geometric means for each location and control condition were calculated. The geometric mean reduction ratio (1-geometric mean "control on"/geometric mean "control off') was also calculated. SAS version 9.2 (SAS Institute Inc., Cary, NC) was used to analyze the data. The mixed model procedure was used to estimate the lower 95% confidence limit for the reduction ratio.

Control Technology

The application of the control principles used by E-Z Drill for dowel-pin drilling is discussed below. LEV systems "operate on the principle of capturing a contaminant at or near its source" [ACGIH 2010]. Four components make up a typical LEV system: the hood(s), duct(s), an air cleaner, and a fan [ACGIH 2010]. The hood(s) collects the contaminant, which is produced in an air stream directed toward the hood. Duct(s) convey the contaminant and air to the air cleaner. The air cleaner removes the contaminant from the airstream. The fan must produce the desired air flow despite losses due to friction, fittings, and hood entry [ACGIH 2010].

Description of the Engineering Control Technology

Each of the steels and bits was surrounded by a close-capture hood at the work surface (Figures 8 and 9). Each hood take-off was attached to a length of 5 cm (2 in) diameter corrugated flexible hose (the interior finish is smooth). The other end of the hose was attached to a dust collector at the back of the dowel drill unit. There were four hoods and one dust collector on the unit tested. Suction is provided by a pneumatic fan. A filter in the dust collector traps the dust captured by the hood and transported to the collector through the hose. The dust build up collected on the filter falls into a plastic bag at the bottom of the dust collector for disposal. A valve reverses the flow of air through the filters and causes the dust to drop into the bag.

Figure 8 – Side view of one of the exhaust hoods

Figure 9 – Another view of the hood

Results

Sampling Results From Dowel-Pin Drilling

The study was performed in about a day and a half utilizing the tent described above. The goal was to assess the effectiveness of the dust controls by comparing emissions measured during “control on” and “control off” trials. There were 8 rounds of sampling conducted. Data were collected in three locations, in both “control on” and “control off” trials. This resulted in the collection of 48 filter samples and 48 sets of pDR data.

Ventilation Measurements

The average bailing air flow was 0.82 m^3/min (29 cfm) at the number 4 drill with the hose disconnected from the hood and the drill running. It was 0.76 m^3/min (27 cfm) with the drill running and the exhaust hose connected to the hood. Bailing air flow was 0.51 m^3/min (18 cfm) with the drill running and the hood takeoff blocked. The average exhaust air flow at the exhaust hood of the number 4 drill was 1.1 m^3/min (37 cfm) with the other drills’ boots against the concrete surface and 0.99 m^3/min (35 cfm) when the other boots were not in contact with the concrete. The average exhaust air flow at the dust collector with the flow meter in line between the exhaust hose and the dust collector was 1.4 m^3/min (51 cfm). The average exhaust air flow at the dust collector with the exhaust hose disconnected was 2.4 m^3/min (86 cfm).

Respirable Dust Filter Sampling Results

The results of the respirable dust samples collected on filter cassettes are presented in Table 1. For the fourteen respirable dust results less than the LOD of 50 µg/sample, the representative estimate of the concentration was calculated by using a value of the LOD/√2 in the numerator and the sample volume in the denominator [Hornung and Reed 1990]. All fourteen samples below the LOD were collected with the dust control running. During the first day, the “control on” results ranged from a low of 1.9 mg/m^3 at the rear during round 2 to a high of 6.0 mg/m^3 at the front during round 1. The “control off” results on the first day ranged from 31 mg/m^3 at the rear during round 1 to 53 mg/m^3 both at the front during round 2 and at the rear during round 3. On the second day, the “control on” results ranged from 2.0 mg/m^3 at the front during round 7 to 5.6 mg/m^3 at the side in round 6. The day 2 “control off” results ranged from 48 mg/m^3 both at the front in round 5 and at the side in round 7 to 82 mg/m^3 at the rear during round 6.

Table 2 provides measures of central tendency for the respirable dust samples by day, location, and test condition (i.e., “control on” and “control off”). On the first day, the arithmetic mean respirable dust concentration during “control on” trials ranged from 2.0 mg/m^3 at the rear to 3.4 mg/m^3 in the front sampling location. The geometric mean of the “control on” respirable dust samples ranged from 2.0 mg/m^3 at the rear to 2.9 mg/m^3 in front of the drills. The “control off” arithmetic means ranged from 40 mg/m^3 at the side to 45 mg/m^3 at the front of the machine. The geometric mean “control off” respirable dust concentrations ranged from 40 mg/m^3 at the side sampling location to 44 mg/m^3 at the front of the drills.

On the second day of sampling, the arithmetic mean respirable dust results during the “control on” trials ranged from 2.3 mg/m^3 at the front to 4.5 mg/m^3 at the side. The geometric mean dust concentration during “control on” trials ranged from 2.3 mg/m^3 at the front to 4.4 mg/m^3 at the side on the second day. When the dust control was not running, the arithmetic mean dust concentration ranged from 62 mg/m^3 in front of the drills to 65 mg/m^3 at the rear position on the second day. The “control off” geometric mean dust concentration on day 2 ranged from 61 mg/m^3 at the front to 64 mg/m^3 at the rear.

Table 3 reports the reductions in respirable dust emissions measured at each sampling location by day and location. Comparison of the geometric means resulted in a 93% reduction at the front, a 95% reduction at the rear, and a 93% reduction at the side sampling position on the first sampling day. Using the arithmetic means for comparison resulted in a 93% reduction in emissions at the front, a 95% reduction at the rear, and a 92% reduction at the side position on day 1. On the second sampling day, the reductions in the geometric mean concentration were 96% at the front, 95% at the rear, and 93% at the side. Comparison of the “control on” and “control off” arithmetic mean respirable dust results for the second day show a 96% reduction at the front, a 95% reduction at the rear, and a 93% reduction at the side.

Table 4 shows the lower 95% confidence limit for the reduction based on a mixed model by day and location. On day one, these ranged from 87% at the side to 91% at the rear sampling location ($p<0.0001$). This result means that if the test were repeated, in 95% of the repeated tests, the observed reduction will be greater than or equal to that lower limit (but in 5% of the tests, it will not be). On the second sampling day, the lower 95% confidence limit for the reduction based on a mixed model ranged from 92% at the side to 96% at the front.

Direct-Reading Respirable Dust Mass Results

Table 1 presents the pDR results for each trial, including the overall average concentration provided by the instruments and the concentration calculated and used for the subsequent analyses. Table 5 reports several results from the pDR data. On the first day, for the “control on” condition, the geometric mean of the arithmetic means of the logarithms of the measured respirable dust concentrations ranged from 8.1 mg/m^3 at the rear to 12 mg/m^3 at the front. During “control off” testing on the first day, the range for that statistic was 68 mg/m^3 at the rear of the drill to 99 mg/m^3 at the front sampling location.

On the second sampling day, Table 5 shows that the “control on” geometric mean dust concentration ranged from 6.9 mg/m^3 at the front to 8.0 mg/m^3 at the rear, and that the “control off” geometric mean dust concentration ranged from 107 mg/m^3 at the front to 117 mg/m^3 at the rear.

Table 6 shows the emission reductions achieved through the use of the dust control by day and location. The effectiveness is expressed as the reduction in the geometric mean respirable dust concentrations measured with the pDRs. The geometric mean reduction was 88% at all three sampling locations on day 1. On the second day of sampling the geometric mean reduction ranged from 93% at the rear and side to 94% at the front.

Table 7 provides the lower 95% confidence limit for the reduction based on a mixed model for the pDR data by day and location. Based on the pDR results from day 1, the mixed model predicts that the control should achieve at least a 75% reduction in respirable dust emissions measured at the side of the machine ($p=0.0012$), and at least a 76% reduction in emissions measured at the remaining locations ($p= 0.0011$). Using the pDR data from day 2, mixed modeling predicts that the control should reduce emissions by 92% if measured at the rear of the machine ($p<0.0001$) and at least a 93% reduction in emissions if measured at the other two locations.

Respirable Crystalline Silica Dust Results

No cristobalite or tridymite were detected in any samples. A bulk sample collected from the bag attached to the dust collector contained 27% quartz by weight. A second bulk sample collected from the edge of the concrete slab contained 20% quartz by weight. Table 1 shows the results for respirable quartz samples by day, location, and condition. Twenty-two of 24 quartz samples collected with the “control on” were below the LOD of 5 µg/sample. The quartz concentration for those samples was calculated by using a value of the LOD/√2 in the numerator and the sample volume in the denominator. The “control on” results on the first day ranged from 0.2 mg/m^3 at several locations to 0.8 mg/m^3 at the front during round 1. The "control off" quartz results ranged from 2.8 mg/m^3 at the front sampling location during round 3 to 4.8 mg/m^3 at the front sampling location during round 2. On day 2, the quartz result with the "control on" was 0.2 mg/m^3 at every location and round, except at the rear position during round 8, where it was 0.3 mg/m^3. The quartz results with the "control off" on day 2 ranged from 4.0 mg/m^3 at the front during round 5 to 6.8 mg/m^3 at the rear during round 6.

Table 8 reports the measures of central tendency for the quartz data by day, location, and condition. On day 1, the arithmetic mean quartz concentration with the "control on" was 0.2 mg/m^3 at the side and rear positions to 0.4 mg/m^3 at the front of the drills. During "control off" trials on day 1, the arithmetic mean quartz concentration ranged from 3.5 mg/m^3 at the side of the drilling machine to 4.0 mg/m^3 at the front sampling location. The geometric mean quartz concentration with the "control on" on the first sampling day ranged from 0.2 mg/m^3 at the rear and side to 0.3 mg/m^3 at the front. With the "control off," the geometric quartz concentration on day 1 ranged from 3.5 mg/m^3 at the side to 3.9 mg/m^3 in front of the drills.

On the second sampling day, the arithmetic mean quartz concentration was 0.2 mg/m^3 with the "control on" at all three locations, and ranged from 4.7 mg/m^3 at the front to 5.1 mg/m^3 at the side and rear with the dust "control off." The geometric mean quartz concentration on day 2 with the "control on" was also 0.2 mg/m^3 at all three sampling positions. The geometric mean quartz concentration with the "control off" on day 2 ranged from 4.7 mg/m^3 at the front to 5.1 mg/m^3 at the side.

Table 9 shows the reduction in arithmetic and geometric mean quartz emissions achieved by the use of the dust control by day and location. On the first day of sampling, the geometric mean reduction ranged from 92% at the front to 95% at the rear, while the arithmetic mean reduction ranged from 90% at the front to 95% at the rear. On day 2, the geometric mean and arithmetic mean quartz concentrations were both reduced by 96% at all three locations.

Table 10 provides the lower 95% confidence limit for quartz reductions based on a mixed model. Based on the results from day 1, the control is predicted to reduce respirable quartz emissions by at least 86% at the front, 90% at the rear, and 88% at the side. Utilizing the results from day 2, the control should achieve at least a 95% reduction in respirable quartz emissions at all three locations.

Discussion

This study was not designed to compare the manufacturers' controls, and the results should not be used for that purpose. The results reflect the dust emissions from the machine in a controlled environment, and should not be compared to occupational exposure limits. In addition to the effects of wind and weather on a construction site, personal exposures are influenced by work practices, the aerodynamic effects of placing the sampler on a worker, the non-uniform distribution of dust in the workplace air, and other factors. Actual occupational exposure measurements at actual work sites with the dust control in use will be collected as a future part of this study to assess whether or not the reductions quantified in this survey result in exposures below applicable occupational exposure limits.

On sampling day 2, E-Z Drill representatives suggested that the entire exhaust hood assembly be removed, rather than simply removing the exhaust hose as was done on day 1. They also pointed out that the drilling machine should be positioned more carefully so that hoods did not cover spalled areas around previously-drilled holes, since those might interfere with tight contact between the hood and concrete surface. The drill was positioned more carefully so the hoods were in close contact with the concrete on day 2.

The results show that the measured effectiveness of the dust control did improve from day1 to day 2. The hood without the hose attached surrounds the hole and probably suppresses dust generation by acting as a physical barrier, since the dust-laden air has to make several turns to escape from the hood assembly. Removing that barrier typically resulted in higher “control off” dust concentrations, which account for the improved ratio of “control on” to “control off” used as the performance measure in this study. This also is a more realistic measurement scenario, since drills in the field without dust controls are not equipped with hoods. Careful positioning to ensure close contact of the hood with the concrete surface can be added to best-practice guidance supplied to drill operators. Hole-spacing requirements on runways and highways may not always make it possible to avoid covering spalled areas with the hood at actual work sites.

Ventilation testing results show that the bailing air flow rate varied with the configuration of the exhaust hose connection, ranging from 0.51 m^3/min (18 cfm) with the drill running and the hood takeoff blocked to 0.82 m^3/min (29 cfm) with the drill running and the exhaust hose only disconnected. These differences are probably the result of the bailing air inducing a secondary air flow through the open hood. The measurements made with the hood takeoff blocked were probably the most realistic measurement of bailing air flow.

The ratio of exhaust air flow to bailing air flow was 2:1 at the hood for drill number 4 (1.1 m^3/min (37 cfm) to 0.51 m^3/min (18 cfm)). This value is the lowest ratio (2:1) identified by Page et al. [2008] that was shown to respond positively to decreases in shroud leakage area for a large rock drill. Since the E-Z Drill shroud design appeared to have tight contact with the drilled surface, it is believed to similarly benefit from the low leakage area design. The Page et al. [2008] study further showed that significant improvements (contaminant concentration reductions exceeding 60% and 90%) for already tight-fitting shrouds could also be obtained by increasing the ratio of exhaust air flow to bailing air flow from 2:1 to 3:1 or even 4:1. The increase in the exhaust air flow measured at the collector (2.4 m^3/min (86 cfm)) compared to that measured at the hood (1.1 m^3/min (37 cfm)) is likely due to the airflow dynamics introduced by the measurement method. When the flow was measured at the collector, the presence of the long straight inlet into the collector (see Figures 5 and 6) aerodynamically improved the collector's inlet airflow characteristics. This difference in inlet airflow conditions can be seen by comparing the bends in the hoses in Figures 5 and 6 to the straightened flow imposed by the measurement technique. Removing those bends by using a straight length of pipe is believed to be responsible for the difference. This result illustrates the performance value in minimizing the bends and overall length of the hose, using smooth-walled (preferably rigid) duct and increasing the length of the straight inlet pipe into the collector.

The velocity of 8.6 meters/second (m/sec) (1700 feet per minute (fpm)) (based on a flow rate of 1.1 m^3/min (37 cfm) through a 5 cm (2-in) diameter duct) may not be sufficient to prevent concrete dust from settling in the duct and reducing flow or plugging the duct. ACGIH [2010] recommends a duct velocity of 18 to 20 m/sec (3500 to 4000 fpm) for dusts such as granite dust, limestone dust, brick cutting, and clay dust. However, the repeated flexing of the duct that occurs when the drills are raised and lowered coupled with the turbulence in the flexible duct may act to prevent plugging at the lower transport velocity. Installation of suction pressure indicators near the hood inlet could also serve to warn the operator of the development and presence of clogs. Monitoring customer reports of plugged ducts or reduced system performance should determine if clogging due to settling is a problem.

The results of this study demonstrate that the evaluated dust control system was very effective. Based on a review of day 2 results, the dust control was capable of reducing geometric and arithmetic mean respirable dust emission mass concentrations measured on filter samples by as much as 96% (from 93% to 96%) and is predicted to be capable of reducing respirable dust emission mass concentrations measured on filter samples by at least 92% (from 92% to 96%) during repeated tests. Silica sampling results also showed similar effectiveness, demonstrating reductions in geometric and arithmetic mean quartz concentrations of 96% at all three sampling locations, with the mixed model predicting reductions of at least 95% at all three locations during repeated tests.

Comparing the mass data from the filter samples and the pDR results reveals a discrepancy between the results depending upon the method used. The filter data provides a direct and reliable means to assess the difference in emissions between "control on" and "control off," but those data include the period before the drill started. Comparing the pDR data in the next columns with the filter data shows that the pDR tends to overestimate the dust concentration in comparison with the filter data, but not by a consistent ratio. However, the ability to edit the pDR data to exclude the period before the drills started makes the pDR data a useful measure for “control on” “control off” comparisons. The overall average concentration provided by the pDR should be lower than the average concentration calculated by excluding the background dust concentration in the tent for the period between the sample start and the drill start, plus the time required for the dust concentration to reach a steady response. In 13 trials, this was not the case. This is due to calibration and the fact that the instrument is not specific.

The pDR is calibrated using standard SAE fine (ISO fine) test dust, while this study measured concrete dust, which may in part explain the discrepancy on individual trial results. The pDR’s manufacturer recommends performing a “field gravimetric calibration” to correct the individual pDR concentrations. This is accomplished by multiplying individual pDR data points by the ratio of the gravimetric concentration to the average pDR concentration. However, studies have shown that samples collected side-by-side can vary, so this correction was not carried out with the data in this study [Kauffer et al. 2010, Werner et al. 1996]. This correction was also not performed because the design of this study compares the dust measured with the “control on” with the dust measured with the “control off,” so it is the relationship between those measures that is of interest. Applying the same correction factor to both the numerator and denominator of such a ratio does not affect the result. This assumes that the composition of the concrete dust is consistent for “control on” and “control off” trials.

Conclusions and Recommendations

The dust control system functioned very effectively. Compared with the use of no control during dowel drilling in concrete, the dust control system significantly ($p<0.0001$) reduced geometric mean respirable dust mass concentrations by 93% to 96% when measured with filter samples. Arithmetic mean respirable dust concentrations measured on filters were significantly ($p<0.0001$) reduced 92% to 96% by the use of the dust control system. The use of the dust control system also significantly reduced respirable dust emissions ($p<0.0001$) by 87% to 94% when measured with a nephelometer. Geometric mean respirable quartz emissions were significantly ($p<0.0001$) reduced by 92% to 96% by the use of the dust control. The use of the dust control significantly ($p<0.0001$) reduced arithmetic mean respirable quartz concentrations by 90% to 96%. While these results should not be compared with occupational exposure limits, they indicate that the dust control system tested should be effective in reducing exposures. Actual occupational exposure measurements must be conducted at actual work sites with the dust control in use to assess whether or not the reductions result in exposures below applicable occupational exposure limits. Those occupational exposure measurements will be collected as a future part of this study.

The ventilation system’s duct velocity may be too low to prevent dust settling and plugging the ducts. The manufacturer should be alert to reports from customers about plugged ducts or decreased duct collection system performance. If problems with settling emerge, the transport velocity can be increased somewhat by installing rigid, smooth-walled ductwork to the extent possible in place of the current flexible, smooth-walled corrugated hose and minimizing bends in the flexible hose or elbows in rigid ducts. The duct material selected should be durable enough to withstand the abrasive nature of concrete dust. Increasing the length of straight duct into the dust collector may also be worthy of investigation. Another step to take to increase the transport velocity, if needed, is to increase the system's volumetric flow rate. Consider installing a pressure gauge across the filter in the dust collector to provide the drill operator with information needed to determine when to clean or change the filter. The filter manufacturer should be able to provide the reference data needed to provide this information. Consider installing static pressure taps near the duct connection to each hood that can be connected to vacuum gauges on the operator's instrument panel. These taps would be used to measure the "hood static pressure," which is a valuable monitoring metric that can be used to determine if the dust collecting system is working properly. Measuring the hood static pressure when the system is working as designed can provide the baseline value for future comparison. Finally, consider adding instructions on careful hood placement to the operating instructions. If desired, NIOSH can provide more detailed guidance on how to implement these recommendations.

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Table 1 – Summary of Air Sampling Results

Day	Round	Position	Control Condition	Respirable Dust on Filters (µg/sample)	Respirable Quartz on Filters (µg/sample)	Sample Duration (minutes)	Pump Sample Volume (L)	Respirable Dust on Filters (mg/m^3)	pDR Calculated Average (mg/m^3)	pDR Overall Average (mg/m^3)	Respirable Quartz on Filters (mg/m^3)
1	1	Front	off	780	80	7:53	18	44	102	75.0	4.5
1	1	Front	on	(100)	(14)	7:27	17	6.0	18.2	14.6	0.80
1	1	Rear	off	570	55	8:15	19	31	52.3	52.7	2.9
1	1	Rear	on	ND	ND	7:55	18	2	13.7	11.7	0.20
1	1	Side	off	640	66	8:15	18	35	60.4	55.6	3.7
1	1	Side	on	(90.0)	(5.0)	8:10	18	5.0	14.6	12.8	0.30
1	2	Front	on	ND	ND	7:50	17	2.1	7.21	6.20	0.20
1	2	Front	off	710	64	6:05	13	53	102	88.3	4.8
1	2	Rear	on	ND	ND	8:10	18	1.9	4.96	4.80	0.20
1	2	Rear	off	600	49	6:05	14	44	67.5	80.2	3.6
1	2	Side	on	ND	ND	8:01	18	2.0	5.88	5.50	0.20
1	2	Side	off	560	44	6:05	14	41	78.6	87.4	3.2
1	3	Front	on	ND	ND	7:58	18	2.0	12.0	10.3	0.20
1	3	Front	off	580	45	7:10	16	36	92.4	68.0	2.8
1	3	Rear	on	ND	ND	7:48	17	2.1	7.91	7.81	0.20
1	3	Rear	off	820	70	7:02	15	53	87.5	89.0	4.5
1	3	Side	on	ND	ND	7:26	17	2.1	8.34	8.96	0.20
1	3	Side	off	690	56	7:02	16	43	83.2	76.3	3.5
2	4	Front	on	ND	ND	6:38	15	2.4	4.96	4.52	0.20
2	4	Front	off	1100	84	7:19	16	68	76.4	68.0	5.2
2	4	Rear	on	(77)	ND	6:55	15	5.0	6.71	7.12	0.20
2	4	Rear	off	1200	83	7:36	17	71	107	107	4.9
2	4	Side	on	(67)	ND	6:55	15	4.4	5.84	5.92	0.20
2	4	Side	off	1100	82	6:59	15	72	98.4	94.6	5.3
2	5	Front	off	790	67	7:27	17	48	80.6	65.0	4.0
2	5	Front	on	ND	ND	6:57	15	2.3	6.26	5.55	0.20

Day	Round	Position	Control Condition	Respirable Dust on Filters (µg/sample)	Respirable Quartz on Filters (µg/sample)	Sample Duration (minutes)	Pump Sample Volume (L)	Respirable Dust on Filters (mg/m^3)	pDR Calculated Average (mg/m^3)	pDR Overall Average (mg/m^3)	Respirable Quartz on Filters (mg/m^3)
2	5	Rear	off	1000	79	7:30	16	61	116	99.5	4.8
2	5	Rear	on	ND	ND	6:45	15	2.4	8.36	8.58	0.20
2	5	Side	off	1000	80	7:30	16	61	108	89.0	4.9
2	5	Side	on	(57)	ND	6:29	14	4.0	7.09	7.75	0.20
2	6	Front	on	ND	ND	7:00	15	2.3	8.05	6.63	0.20
2	6	Front	off	980	77	6:35	14	68	122	109	5.3
2	6	Rear	on	(77)	ND	7:00	16	4.9	8.62	8.55	0.20
2	6	Rear	off	1200	100	6:35	15	82	137	133	6.8
2	6	Side	on	(87)	ND	7:05	16	5.6	9.32	9.46	0.20
2	6	Side	off	1200	93	6:50	15	80	146	140	6.2
2	7	Front	on	ND	ND	8:02	18	2.0	7.37	5.83	0.20
2	7	Front	off	970	70	7:28	16	59	130	105	4.3
2	7	Rear	on	(57)	ND	8:22	18	3.1	7.55	6.50	0.20
2	7	Rear	off	1000	81	7:48	17	58	100	95.3	4.1
2	7	Side	on	(67)	ND	8:45	19	3.4	7.39	5.94	0.20
2	7	Side	off	860	85	8:05	18	48	92.2	84.2	4.5
2	8	Front	off	1300	92	8:48	19	67	144	101	0.20
2	8	Front	on	ND	ND	6:35	14	2.4	8.75	8.13	5.9
2	8	Rear	off	1000	82	8:50	19	52	127	98.8	4.7
2	8	Rear	on	ND	ND	6:25	14	2.5	8.96	11.0	0.30
2	8	Side	off	1200	87	8:52	20	61	128	100	4.2
2	8	Side	on	(77)	ND	6:50	15	5.1	8.91	9.60	0.20

ND means a result less than the limit of detection (LOD) of 50 µg/sample for respirable dust and 5 µg/sample for quartz. Numbers in parentheses indicate a result between the LOD and the limit of quantitation of 160 µg/sample for respirable dust and 17 µg/sample for quartz. These are trace values with limited confidence their accuracy. The value of LOD/√2 was used in place of ND to calculate concentration.

Table 2 – Measures of Central Tendency for the Respirable Dust Filter Samples by Day, Location, and Test Condition

Day	Location	Control Condition	Number of Samples	Arithmetic Mean Dust Concentration (mg/m^3)	Standard Deviation (mg/m^3)	Geometric Mean Dust Concentration (mg/m^3)	Geometric Standard Deviation (mg/m^3)
1	front	off	3	45	8.6	44	1.2
1	front	on	3	3.4	2.3	2.9	1.9
1	rear	off	3	42	11	41	1.3
1	rear	on	3	2.0	0.10	2.0	1.1
1	side	off	3	40	4.1	40	1.1
1	side	on	3	3.0	1.7	2.8	1.7
2	front	off	5	62	8.7	61	1.2
2	front	on	5	2.3	0.16	2.3	1.1
2	rear	off	5	65	12	64	1.2
2	rear	on	5	3.6	1.3	3.4	1.4
2	side	off	5	64	12	63	1.2
2	side	on	5	4.5	0.87	4.4	1.2

Table 3 – Reductions in Respirable Dust Emissions Measured on Filters by Day and Location

Day	Location	Reduction in Geometric Mean Dust Emissions	Reduction in Arithmetic Mean Dust Emissions
1	front	0.93	0.93
1	rear	0.95	0.95
1	side	0.93	0.92
2	front	0.96	0.96
2	rear	0.95	0.95
2	side	0.93	0.93

Table 4 - Lower 95% Confidence Limit for Respirable Dust on Filters Emission Reduction Based on a Mixed Model, by Day and Location

Day	Location	Estimate	Standard Error	Degrees of Freedom	t -Value	p-Value	Estimated Reduction
1	front	-2.7097	0.2595	5.24	-10.44	0.0001	0.88
1	rear	-3.03	0.2595	5.24	-11.67	<.0001	0.91
1	side	-2.6696	0.2595	5.24	-10.29	0.0001	0.87
2	front	-3.2944	0.07376	12	-44.67	<.0001	0.96
2	rear	-2.9333	0.07376	12	-39.77	<.0001	0.94
2	side	-2.6585	0.07376	12	-36.04	<.0001	0.92

Table 5 – Measures of Central Tendency for pDR Respirable Dust Samples by Day, Location, and Test Condition

Day	Location	Control Condition	Number of Samples	Standard Deviation of the Mean (mg/m^3)	Geometric Mean of the Arithmetic Mean Concentration (mg/m^3)
1	front	off	3	1.1	99
1	front	on	3	1.6	12
1	rear	off	3	1.3	68
1	rear	on	3	1.7	8.1
1	side	off	3	1.2	73
1	side	on	3	1.6	9.0
2	front	off	5	1.3	107
2	front	on	5	1.3	6.9
2	rear	off	5	1.1	117
2	rear	on	5	1.1	8.0
2	side	off	5	1.2	113
2	side	on	5	1.2	7.6

Table 6 - Reductions in Respirable Dust Emissions Measured with the pDR by Day and Location

Day	Location	Geometric Mean of the "Control On" Mean Concentration (mg/m^3)	Geometric Mean of the "Control Off" Mean Concentration (mg/m^3)	Reduction in Geometric Mean of the Mean Concentration
1	front	12	99	0.88
1	rear	8.1	68	0.88
1	side	9.0	73	0.88
2	front	6.9	107	0.94
2	rear	8.0	117	0.93
2	side	7.6	113	0.93

Table 7 - Lower 95% Confidence Limit for pDR Respirable Dust Emission Reduction Based on a Mixed Model, by Day and Location

Day	Location	Estimate	Standard Error	Degrees of Freedom	t -Value	p-Value	Estimated Reduction
1	front	-2.1387	0.2951	4.6	-7.25	0.0011	0.76
1	rear	-2.1175	0.2951	4.6	-7.18	0.0011	0.76
1	side	-2.1038	0.2951	4.6	-7.13	0.0012	0.75
2	front	-2.7356	0.04728	12	-57.9	<.0001	0.93
2	rear	-2.6808	0.04728	12	-56.7	<.0001	0.92
2	side	-2.6985	0.04728	12	-57.1	<.0001	0.93

Table 8 - Measures of Central Tendency for Quartz Data by Day, Location, and Condition

Day	Location	Control Condition	Number of Samples	Arithmetic Mean Quartz Concentration (mg/m^3)	Standard Deviation (mg/m^3)	Geometric Mean Quartz Concentration (mg/m^3)	Geometric Standard Deviation (mg/m^3)
1	front	off	3	4.0	1.1	3.9	1.3
1	front	on	3	0.40	0.35	0.30	2.2
1	rear	off	3	3.7	0.80	3.6	1.3
1	rear	on	3	0.20	0.00	0.20	1.0
1	side	off	3	3.5	0.25	3.5	1.1
1	side	on	3	0.20	0.06	0.20	1.3
2	front	off	5	4.7	0.56	4.7	1.1
2	front	on	5	0.20	0.00	0.20	1.0
2	rear	off	5	5.1	1.0	5.0	1.2
2	rear	on	5	0.20	0.040	0.20	1.2
2	side	off	5	5.1	0.70	5.1	1.1
2	side	on	5	0.20	0.00	0.20	1.0

Table 9 - Reduction in Arithmetic and Geometric Mean Quartz Emissions Achieved Use of Dust Control by Day and Location

Day	Location	Geometric Mean Quartz Concentration "Control On" (mg/m^3)	Arithmetic Mean Quartz Concentration "Control On" (mg/m^3)	Geometric Mean Quartz Concentration "Control Off" (mg/m^3)	Arithmetic Mean Quartz Concentration "Control Off" (mg/m^3)	Reduction in Geometric Mean Quartz Emissions	Reduction In Arithmetic Mean Quartz Emissions
1	front	0.32	0.40	3.9	4.0	0.92	0.90
1	rear	0.20	0.20	3.6	3.7	0.95	0.95
1	side	0.23	0.23	3.5	3.5	0.93	0.93
2	front	0.20	0.20	4.7	4.7	0.96	0.96
2	rear	0.22	0.22	5.0	5.1	0.96	0.96
2	side	0.20	0.20	5.1	5.1	0.96	0.96

Table 10 - Lower 95% Confidence Limit for Quartz Reductions Based on a Mixed Model

Day	Location	Estimate	Standard Error	Degrees of Freedom	t -Value	p-Value	Estimated Reduction
1	front	-2.5148	0.2519	6.29	-9.98	<.0001	0.86
1	rear	-2.8927	0.2519	6.29	-11.5	<.0001	0.90
1	side	-2.7157	0.2519	6.29	-10.8	<.0001	0.88
2	front	-3.1554	0.0807	17.2	-39.1	<.0001	0.95
2	rear	-3.1398	0.0807	17.2	-38.9	<.0001	0.95
2	side	-3.2316	0.0807	17.2	-40.0	<.0001	0.95

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