NIOSH/industry collaborative efforts show improved mining equipment cab dust protection

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Abstract

Mobile excavation equipment operators at surface mines generally have the highest exposure to airborne respirable silica dust. Operator cabs on newer equipment are usually enclosed and equipped with heating and air conditioning systems. Many newer cabs are also equipped with air filtration systems. However, some newer cabs and many older cabs have either inefficient or no air filtration systems. The surface mining industry in the United States is still populated with older equipment, and many of these have cabs that provide little or no respirable silica dust protection. Collaborative field studies were conducted as part of a partnership involving NIOSH, Clean Air Filter®, Red Dot, MSHA and several mine operators to demonstrate that effective dust protection can be provided by these cabs at a nominal cost to mine operators. This effort encompassed adding an external make-up air fan and filter system to a retrofitted roof-mounted heating and air conditioning system in three older equipment cabs and attempting to seal the cab enclosures to achieve interior cab pressurization. A better than 90% dust reduction was measured inside two of the three enclosed equipment cabs. It was possible to achieve positive cab pressurization inside these two cabs. A less-significant dust reduction was measured inside the third cab, where positive pressurization was not achieved. These field studies demonstrate the key elements needed to improve enclosed cab dust protection in a cost-effective manner.

Introduction

The Mine Safety and Health Administration (MSHA) permissible dust exposure for coal mine workers is a shift average of 2.0 mg of airborne respirable coal mine dust per cubic meter of air (2.0 mg/m^3), as defined by the Mining Research Establishment (MRE) Criteria (U.S. Code of Federal Regulations, 2001). If the airborne respirable dust (ARD) sample contains more than 5% quartz, the applicable dust standard is reduced to the quotient of 10 divided by the percentage of quartz in the dust, limiting the respirable quartz exposure to a maximum of 0.1 mg/m^3 (MRE equivalent) for the working shift. MSHA employs the P7 infrared method to determine the quartz content of coal mine dust samples, which is essentially equivalent to NIOSH's recommended infrared Method 7603 (NIOSH, 1983, 1994; Parobeck and Tomb, 2000). The MSHA permissible dust exposure for metal/nonmetal mine workers is a shift average of 10 mg/m^3 of total dust or nuisance particles (U.S. Code of Federal Regulations, 2001). If the airborne dust sample contains more than 1% silica, a respirable dust standard of 10 divided by the total of silica content percentage plus 2 applies, limiting the respirable crystalline silica exposure to a maximum of 0.1 mg/m^3 for the working shift. MSHA employs the NIOSH's recommended X-ray Method 7500 to determine the crystalline silica content of metal and nonmetal mine dust samples (NIOSH, 1983, 1994; Parobeck and Tomb, 2000). Compliance with these dust standards is expected to significantly reduce a worker's risk of occupational lung disease over an average life expectancy.

Quartz dust exposure is an ongoing problem at mining operations in the United States. The percentage of MSHA dust samples from 1996 to 2000 that were above the respirable dust standard due to quartz were 12.8% for sand and gravel operations, 12.9% for stone operations, 16.4% for nonmetal operations, 17.6% for metal operations and 19% for coal operations (Hale, 2002). MSHA's data shows that the occupations that have the highest frequency of exceeding the respirable dust standard at surface mining operations are commonly mobile equipment operators. At surface coal operations these include operators of drills, bulldozers, scrapers, front-end loaders and haul trucks (Tomb et al., 1995). At

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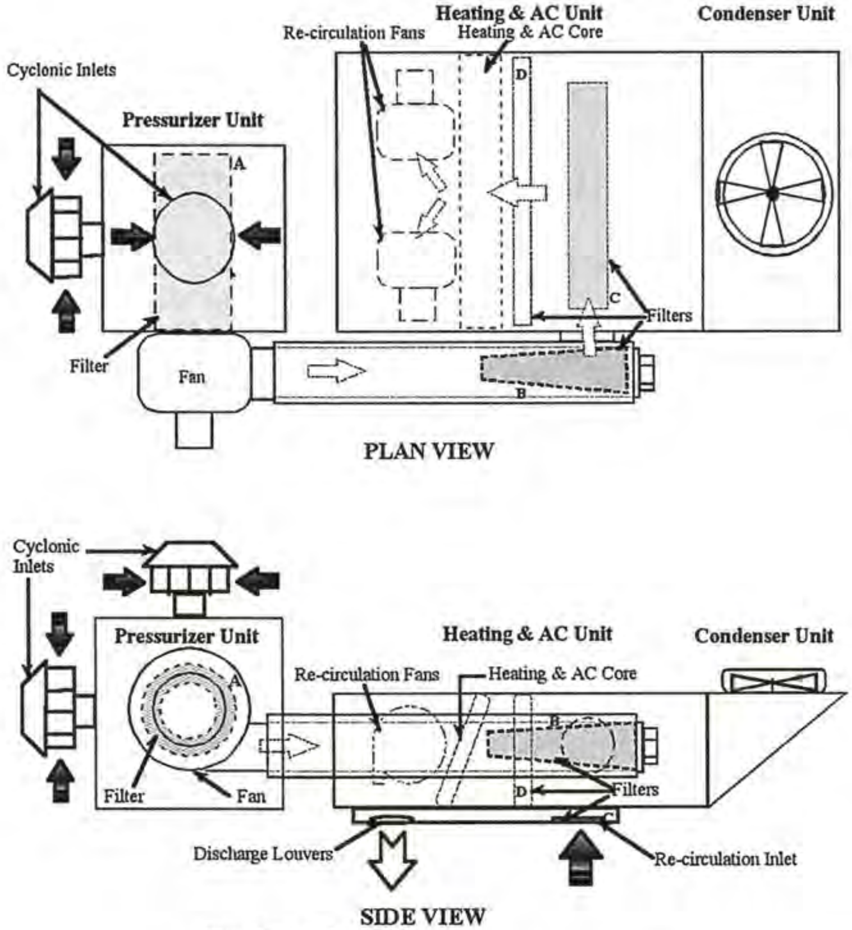

Filter Types and Locations:
A. Cylindrial Two-Stage Cartridge (Mechanical- Electrostatic)
B. Cylindrical Backup Filter (Electrostatic)
C. Flat Panel Re-circulation Filter (Electrostatic)
D. Pleated Re-circulation Filter (Electrostatic)

Figure 1 — Roof-mounted retrofitted air-filtration systems.

noncoal operations, these mobile equipment operators and other occupations such as stone cutters, crusher operators and bagging or packing workers commonly exceed the standard due to quartz dust more often than other occupations (Hale, 2002).

Recent surface-mining dust surveys conducted by the National Institute for Occupational Safety and Health (NIOSH) on drills and bulldozers have shown that enclosed cabs can effectively control the operator's dust exposure, but enclosed cab integrity problems still exist (Organiscak and Page, 1999). The enclosed cab protection factors (outside and inside dust concentrations) measured on rotary drills ranged from 2.5 to 84, and those measured on bulldozers ranged from zero to 45. Some of the newer equipment cabs tended to be better sealed and cleaner, while some of the older equipment tended to be more poorly sealed and dirtier. One of the least-protective drill cabs studied had neither heating, air conditioning nor air filtration. There are other older surface mining equipment cabs that have heating but no air conditioning and/or air filtration systems.

NIOSH recently conducted more thorough field studies of upgrading older equipment cabs to improve their dust control effectiveness. These studies encompassed retrofitting older enclosed cabs with air conditioning (AC), heating and air-filtration systems to examine the key factors involved in achieving effective enclosed cab dust control. These field studies were a collaborative effort involving NIOSH, Clean Air Filter®, Red Dot Corp., MSHA and two mining companies[1]. MSHA assisted with finding cooperative mining companies. Red Dot provided the roof-mounted heating and air-conditioning units. Clean Air Filter® provided the filtration and cab enclosure expertise. They designed the air-filtration systems, examined their installation, made air-filtration system modifications and worked on improving the integrity of these cab enclosures. NIOSH was also involved in the system installation and conducted the field dust studies of these retrofitted air-cleaning systems. This paper describes the enclosed cab field studies conducted on a front-end loader and two overburden drill machines.

Retrofitted cab filtration systems

This enclosed cab dust-control research involved retrofitting air-filtration systems on a CAT 980B front-end loader, a Davey M8B rotary drill and a DrillTech DK40 percussive drill. The CAT 980B front-end loader and Davey M8B rotary drill dust-control evaluations were conducted at two surface coal mine sites in Pennsylvania. The DrillTech DK40 percussive-drill dust-control evaluation was conducted at a surface silica mine in West Virginia. As part of this study, dust sampling was conducted before and after the cabs were refurbished and retrofitted with air filtration systems to examine the dust protection changes. The CAT 980B front-end loader and the Davey M8B rotary drill originally did not have any air-conditioning and filtration systems, only floor heaters. The DrillTech DK40 drill had a roof-mounted Red Dot R-9727 air-conditioning unit with an external make-up air filter and also had a separate floor-mounted heater system. The air conditioning external filter housing was damaged and there was no separate external fan to assist with external air filtration and positive cab pressurization.

The retrofitted enclosed-cab air-filtration systems were integrated into a roof-mounted heating and/or air conditioning unit with an additional fan-driven external filtration unit. The heating and/or air conditioning units provide the majority of the enclosed cab air-handling capability and temperature control by recirculating the inside cab air through an inlet filter and heat exchanger. The external filtration unit provides a smaller portion of cleaned outside make-up air that is constantly added into the heating and/or air conditioning unit. This quantity of make-up air added to the cab is positively pushed out through leaks in the cab. Figure 1 shows the basic arrangement of these units with several filter locations that were tested. Table 1 summarizes the cab modifications made

[1]Mention on any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

Table 1 — Summary of enclosed cab modifications and resources allocated.

Machine	Original cab	Modifications: *Resources, Approx. costs and/or Installation Times*
CAT 980 B front-end loader	Floor heater, no A/C or filtration system and a reasonably sound enclosure.	• Added Red Dot R-9757 heating and A/C unit and disconnected floor heater unit: *Red Dot donated unit (~$2,350) and NIOSH contracted unit installation with compressor and parts (one workday, ~$1,600).* • Added external air filtration/pressurizer unit and sealed cab: *Clean Air Filter® donated unit (~$1,000), installed unit and sealed cab enclosure (two Clean Air Filter®people for one-half day or one workday, expenses cost shared with NIOSH).*
Davey M8B rotary drill	Floor heater, no A/C or filtration system and a poor enclosure.	• Added Red Dot R-9757 heating and A/C unit and disconnected floor heater unit: *Red Dot donated unit (~$2,350) and NIOSH contracted unit installation with compressor and parts (one workday, ~$1,300), mine maintenance personnel built steel protective cradle around unit (several work hours).* • Added external air filtration/pressurizer unit and unable to seal existing cab: *Clean Air Filter® donated unit (~$1,000), installed unit and attempted to seal cab (two Clean Air Filter® people for one-half day or one workday, expenses cost shared with NIOSH).*
DrillTech DK40 percussive drill	Floor heater, Red Dot R-9727 AC unit with external filter and a reasonably sound enclosure	• First modification, Period A, added external air filtration/pressurizer unit and sealed cab: *Clean Air Filter® donated unit (~$1,000), mine maintenance personnel installed unit (one workday), and Clean Air Filter® inspected installation and sealed cab (two Clean Air Filter® people for one-half day or one workday, expenses cost shared with NIOSH).* • Second modification, Period B, changed Red Dot R-9727 AC unit to Red Dot R-9777 heating and A/C unit and disconnected floor heater unit: *Red Dot donated unit (~$2,200) and mine maintenance personnel changed units, removed floor heater and built steel protective cradle around unit (several workdays).*

to each mining machine studied and the amount of resources expended on these modifications. The specifics of each cab filtration system installed are described below. Clean Air Filter® made a preliminary visit to each mine site to examine the equipment for the filtration system retrofits, examined the operating parameters of this filtration system design in its laboratory and made a return visit to install its external air filtration/pressurizer unit and to improve the air tightness of the cabs for achieving positive cabin pressure.

CAT 980B front-end loader. A Red Dot R-9757 heater and air conditioner unit with condenser (24 volt) was installed on the cab roof. This unit has two internal centrifugal fans and is designed to recirculate up to 680 m^3/hr (400 cfm) of heated (45,000 Btu/hr or 13,188 W) or cooled (25,000 Btu/hr or 7,327 W) airflow inside the cab. A belt-driven compressor was retrofitted to the engine to operate the roof- mounted air conditioner. The heater hoses from the engine-coolant system were disconnected from the floor heater and reconnected to the roof-mounted heater, so the filtration system could also be used while operating the heater. An external air-filtration/pressurizer unit (24 volt) was also installed in series with the heating and AC unit to provide about 119 m^3/hr (70 cfm) of clean make-up airflow that is added to the recirculated air inside the cab. This unit used two cyclonic inlets to remove very coarse dust before the external dust filter (filter location A in Fig. 1). The filter was a cylindrical two-stage Clean Air Filter® cartridge with a cellulose paper medium for the first stage and a final electrostatic respirator medium for the second stage. The electrostatic media filter performance specifications are at least 99% capture efficiency for 0.1 μm of monodispersed sodium chloride particles, as determined from TSI test method 85 Lpm/dm^2.

Between the external filtration unit fan and the heating and AC unit, 76.2-mm (3-in.) PVC pipe was used. A cylindrical Clean Air Filter® single-stage backup filter (electrostatic respirator medium, filter Location B in Fig. 1) was used inside the pipe on the positive downstream side of the fan before the air entered the heating and AC unit. A threaded plug was used inside the straight end of the PVC pipe to secure and access the backup filter. This filter adds an extra level of protection from outside air leaks around the filter in the pressurizer unit. Finally, Clean Air Filter® installed a flat section of the electrostatic media filter in the inlet of the heating AC unit to remove dust from the recirculated air.

This loader had a reasonably good enclosed cab structure that was effectively sealed to achieve positive interior cab pressure. Cracks, small gaps or holes in the cab were present where parts of the cab were joined together, where control levers were linked with outside components and where the doors closed. Also, a large access opening was present in the floor of the cab underneath the operator seat. The operator seat could be tilted forward to gain access to equipment components underneath the cab. Silicon caulk was used to seal all the observed joint openings in the enclosed cab structure. Closed cell foam tape was placed around the flat adjoining surfaces of adjoining doors and the fold down seat. After sealing the cab, 0.015 in. of positive water gauge pressure (3.7 Pa) was achieved inside the cab with the filtration system operating.

Davey M8B rotary drill. Cab filter system equipment installation was nearly identical to the CAT 980B front-end loader, except that a 12-volt system was used and the cylindrical Clean Air Filter® single-stage backup filter (electrostatic respirator medium, filter Location B in Fig. 1) was not incorporated into the system. This backup filter was omitted because of tight space limitations caused by the articulating drill boom and compressed air hoses that pass along the side external pressurizer ductwork area. The external/pressurizer unit was moved laterally on the roof with respect to the heating

Figure 2 — Floor heater unit.

and AC unit, so the ductwork could be elbowed into the top of the heating and AC unit.

This loader had a reasonably poor enclosed cab structure and could not be effectively sealed to achieve positive internal cab pressure. A large number of cracks, gaps, holes and openings were present in the cab structure. The largest openings were around the front of the cab where mechanical control levers passed through the cab to operate the drill. Many of these openings involved areas of several square inches and would have been very difficult to seal because of a notable amount of control lever linkage travel through these openings in the cab structure. Also, the cab had a bi-fold door on the drill boom side of the cab, which seemed nearly impossible to seal along the bi-fold hinge and bottom of the door. It was generally felt that a major rebuild of this cab structure would be in order to achieve positive pressurization. This effort would have been very time-consuming and expensive. Thus it was decided to test how well an air-filtration system alone would work on a nonpressurized cab.

Drill Tech DK40 percussive drill. This drill had an existing Red Dot R-9727 air conditioner unit with condenser (12 volt) on the cab roof. This unit has two internal centrifugal fans and is designed to recirculate up to 544 m^3/hr (320 cfm) of cooled airflow (22,000 Btu/hr or 6,448 W) inside the cab. The drill also had an external filtration unit (single-stage cylindrical cartridge type) ducted to the AC unit, which allowed the internal recirculation fans to pull some outside make-up air into the air conditioner unit. This external filtration unit did not have a separate pressurizing fan and the filter housing was notably dented.

It was initially decided to try to use the existing roof-mounted Red Dot R-9727 AC unit for the study and replace the existing external filtration unit with the Clean Air Filter® external air filtration/pressurizer unit (12 volt). The pressurizer fan was wired on a separate switch from the AC unit, so it could provide about 119 m^3/hr (70 cfm) of clean make-up air into the cab with or without the AC unit running. This was done so that filtered make-up air could be added into the cab when the small floor heater unit would be used during cold weather (see Fig. 2). The installation of the external air filtration/pressurizer unit was nearly identical to that used on the CAT 980B front-end loader. Between the external filtration unit fan and the AC unit, 76.2-mm (3-in.) PVC pipe was used. A cylindrical Clean Air Filter® single-stage backup filter (electrostatic respirator medium, filter Location B in Fig. 1) was used inside the pipe on the positive downstream side of the fan before the air entered the AC unit. A threaded plug was used inside the straight end of the PVC pipe to secure and access the backup filter.

After testing showed that this system arrangement caused a dust-generation problem with the floor heater in use (Cecala et al., 2001), the R-9727 AC unit was replaced by a newly designed lower profile resin body R-9777 Heating/AC unit (donated by Red Dot) and the floor heater was removed. This R-9777 unit had similar heating and air conditioning capacities of the R-9757 units previously installed on the other two pieces of equipment. In addition to the newer R-9777 unit, a pleated electrostatic recirculation filter was placed inside this newer unit before the heating and AC exchanger core (filter Location D in Fig. 1). This pleated recirculation filter was tried instead of a flat panel filter located at the recirculation inlet (filter Location C in Fig. 1) because it provided more filter area and should be less restrictive on recirculation airflow. The goal of Clean Air Filter® was to maximize filtered recirculation airflow to prevent AC core freeze-ups.

This drill had a reasonably good enclosed cab structure that was effectively sealed to achieve positive interior cab pressure. Cracks, small gaps or holes in the cab were present where parts of the cab were joined together, where control levers were linked with outside components and where the doors closed. Silicon caulk was used to seal all the observed joint openings in the enclosed cab structure. Closed cell foam tape was placed around the flat surfaces of adjoining doors and control levers. After sealing the cab, between 0.07 and 0.12 in. of positive water gauge pressure was achieved inside the cab with the filtration system operating.

Cab filtration system evaluations

Area airborne respirable dust sampling was conducted with personal gravimetric dust samplers inside and outside operator cabs to assess the protection performance of these cabs on the operator dust levels. Three dust samplers were used at each sampling location so that a better representative average of the dust concentration could be measured in the sampling area of the environment. The dust samplers inside the cab were positioned on the inside cab wall near the breathing zone of the operator. Outside the cab, a package of dust samplers was placed near the entrance door on the cab. On the front-end loader, this single package of dust samplers was assumed to be representative of the outside environment of the cab, because the equipment was constantly moving with respect to wind direction during its operation. For the drilling equipment, another package of dust samplers on a tripod was also positioned on the downstream side of the cab and averaged with the samplers placed on the cab. This was done to obtain a more representative area sample around the outside of the stationary drilling operation (Organiscak et al., 2000).

Each gravimetric dust sampler used at the surface coal mines was operated at 2.0 L/min and used a 10-mm Dorr-Oliver nylon cyclone classifier to collect a respirable dust sample corresponding to the coal mine respirable dust sampling parameters as defined by MSHA (U.S. Code of Federal Regulations, 2001). The respirable dust was deposited on a 37-mm MSA (Mine Safety Appliance Co., Pittsburgh, Pennsylvania) coal mine dust filter cassette and the dust concentrations determined were not adjusted to be an MRE equivalent. Each personal dust sampler used at the surface silica mine was operated at 1.7 L/min and used a 10-mm Dorr-Oliver nylon cyclone classifier to collect a respirable dust sample, corresponding to the metal/nonmetal mine respirable dust-sampling parameters as defined by MSHA (U.S. Code of Federal Regulations, 2001). The respirable dust was deposited on a 37-mm two-piece compression filter cassette. All the filters were pre- and post-weighed to the nearest 0.001 mg on a microbalance. Gravimetric dust sampling was normally conducted during a majority of the working shift with about two-thirds of the gravimetric sampling periods exceeding 5 hrs. The other gravimetric sampling periods (nearly all exceeding 3 hrs) were made shorter because of operational downtime or high dust loading.

Dust sampling was conducted before and after any cab modifications were made. Multiple dust sampling shifts were conducted for each cab condition to determine the dust concentration average and variation. Dust sampling was usually conducted over multiple shifts, intermittently spaced out over several months. For the CAT 980B front-end loader, three shifts of baseline dust samples were collected during the months of March and April; six shifts of modified cab dust samples were collected during the months of August, Sept, and October. For the Davey M8B rotary rock drill, four baseline shifts of dust samples were collected during the months of March and April; four shifts of modified cab dust samples were collected during the months of August and October. For the Drill Tech DK40 percussive rock drill, four baseline shifts of dust samples were collected during the month of May; five shifts of dust samples for the first cab modification were collected during the months of November and January; seven shifts of dust samples for the second cab modification were collected during the months of March, April, October and November. Before the modified cab dust sampling shifts, cab filters were checked and cleaned and the inside cab static air pressure was measured with either a magnehelic or velometer.

Instantaneous GRIMM optical particle counters (Model 1.106, Grimm Laborotek, Ainring, Germany) were also used during one of the modified cab sampling shifts for each piece of equipment in order to examine the cabs' filtration effectiveness with respect to particle size. This cab performance evaluation was conducted over a several-hour period and was similar to agricultural cab testing procedures (Heitbrink et al., 1998). GRIMM sampling was simultaneously conducted inside and outside the cab during a portion of the shift with the instruments alternated between these positions to remove any instrumental bias from the outside and inside particle counting. GRIMM particle counting measurements were made during Day 1 of post-testing the CAT 980B front-end loader, during Day 2 of post-testing the Davey M8B rotary drill, and on a different day between Days 2 and 3 of post-testing (period B) the Drill Tech DK40 percussive drill. The GRIMM particle size count data was used to determine the percentage and size of dust particle penetration into the enclosed cab systems.

The cab performance field data were examined by relative measures (relative comparisons of outside to inside cab dust concentrations) and by statistical measures of dust concentration changes (mean, standard deviation, analysis of variance) with respect to cab modifications. Relative measures of cab dust control performance commonly used include protection factor, efficiency and penetration. These relative measures are shown and defined as

$$PF = \frac{C_O}{C_I}; \quad \eta = \frac{C_O - C_I}{C_O}; \quad Pen = 1 - \eta \qquad (1)$$

where

PF is the protection factor (ratio),

η is the efficiency (fractional or percent),

Pen is the penetration (fractional or percent),

C_O is the outside cab concentration (mass or counts per unit volume), and

C_I is the inside cab concentration (mass or counts per unit volume).

All of these measures are related by

$$PF = \frac{C_O}{C_I} = \frac{1}{1-\eta} = \frac{1}{Pen} \qquad (2)$$

Statistical measures determine the mean and variation of dust concentrations for each cab condition and the certainty of these differences through unexplained data variance. Because frequency distributions of environmental dust data have the tendency to be asymmetrically skewed towards the upper limit (skewed to the right or positive skewness), both the arithmetic and geometric means and standard deviations have been determined and examined for this field study data (Willeke and Baron, 1993).

An Analysis of Variance (ANOVA) was also conducted on each cab to determine the level of significance of the changes made and the variance measured. The ANOVA analysis was conducted with the assumption that the data are either normally or log-normally distributed. ANOVA analysis assumes normality, so the concentration data are used for the normal distribution assumption, whereas a natural log transformation of the concentration data are used for the log-normal distribution assumption. The inside cab dust concentration was the dependent variable with the cab modification being the main effect or change and the outside dust concentration being an uncontrolled covariate. The CAT 980B front-end loader and Davey M8B rotary drill had two test levels of cab control (Level 1 – existing and Level 2 – modified). The DrillTech DK40 percussive drill had three levels of cab controls (Level 1 – existing, Level 2 – first modification, and Level 3 – second modification, described above).

Cab evaluation results

Figure 3 shows the day-to-day cab protection factors measured for the CAT 980B front-end loader, Davey M8B rotary drill, and DrillTech DK40 percussive drill. Table 2 shows the summary statistics determined for the dust concentrations measured inside and outside the cab for each test condition. Table 3 shows both the normal and log-normal ANOVA analysis results of the respirable dust concentrations for each cab before and after the above modifications were made. The log-normal results are shown as italicized numbers in parentheses in the table. Figure 4 shows the particle-size penetration for the finalized cab systems measured with the GRIMM optical particle counters.

The dust concentration statistics shown in Table 2 indicate that a large variation in outside cab dust concentrations was experienced during these field evaluations, making the protection factors quite variable even for the same enclosed cab test configurations as shown in Fig. 3. The minimum and maximum outside dust concentration values sometimes differed by an order of magnitude, with the standard deviation (arithmetic) near or exceeding the mean (arithmetic). Several suspected reasons for some of these large day-to-day variations include: early morning rain suppressed outside dust on two days of post- testing the modified CAT 980B loader cab (Organiscak et al., 2000); higher wind velocities during three

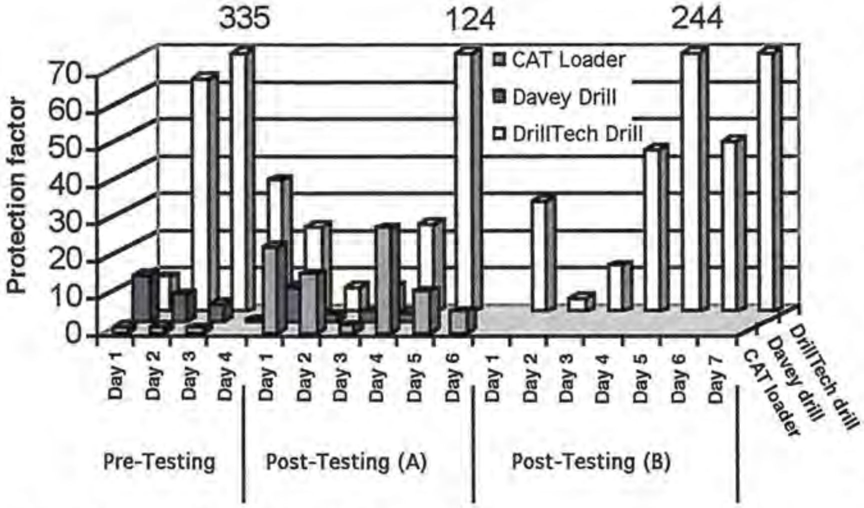

Figure 3 — Day-to-day protection measured.

dence level or 0.05 significance level. Thus, retrofitting the cab with an air filtration system and sealing the cab to achieve some positive cab pressurization (0.015-in. of water gauge or 3.7 Pa) appeared to significantly lower inside cab dust levels while increasing the relative cab protection factor.

The dust summary statistics and ANOVA analysis (shown in Tables 2 and 3) for the Davey M8B rotary drill indicate that no significant improvement was achieved with the enclosed cab modifications. The mean inside cab dust concentration was only slightly reduced from 0.14 mg/m^3 with the existing cab to 0.08 mg/m^3 with a filtration system and unsealed cab (no positive pressure achieved). When considering the different dust concentration means measured during the testing periods, the overall cab protection factor was slightly reduced from 5.1 to 2.8. ANOVA analysis (assuming normal or log-normal) of the inside dust concentration data with respect to the cab modification effect and outside cab dust concentrations indicates that both of these factors had a small effect on the inside cab dust levels at the 95% confidence level or 0.05 significance level. Thus, retrofitting this drill cab with an air filtration system and not achieving positive cab pressurization appeared to make very little difference in reducing inside cab dust levels and cab protection factor performance.

The dust summary statistics and ANOVA analysis (shown in Tables 2 and 3) for the DrillTech DK40 percussive drill indicate that the floor heater used during post-testing Period A was a significant source of inside cab dust. The overall cab protection factor decreased from 63 to 31 for the first cab modification, with the pretesting conducted during the use of the roof-mounted air conditioner in May vs. post-testing Period A conducted during the use of the floor heater in November and January. The mean inside cab dust concentration increased from 0.04 to 0.68 mg/m^3 from the pretesting to the post-testing Period A, respectively. To confirm that the floor heater was the dust source, GRIMM optical particle counters were used inside the cab and outside the cab when the drill was in the shop for maintenance. Dust levels notably increased from 0.03 mg/m^3 when the roof-mounted air filtration unit was operated to 0.26 mg/m^3 when the floor heater was turned on (Cecala et al., 2001). In fact, the floor heater made dust levels inside the cab higher than the outside dust levels in the shop area.

Further testing the DrillTech DK40 percussive drill after removing the floor heater and replacing the roof-mounted AC unit (Red Dot R-9727) with a combination heating and AC unit (Red Dot R-9777) with an internal recirculation filter (as described above) showed an improvement in year around (all season) enclosed cab performance. Post-testing (Period B) of this modification was conducted over a range of heating and AC months, and showed a mean inside cab concentration of 0.07 mg/m^3 with an overall cab protection factor of 89. Inside cab pressure remained between 0.07 and 0.12 in. of water gauge (17.4 and 29.9 Pa) for both modified cab systems tested. ANOVA analysis (assuming normal or log-normal) of the inside dust concentration data with respect to all the cab modifications and outside dust concentrations shows that these factors significantly affected the inside cab dust levels at

days of pretesting the Davey M8B drill cab increased drilling dust emissions (Organiscak et al., 2000); different drill hole lengths, reduced winter water usage and different operating pit locations changed the drill dust emissions throughout the Drill Tech DK40 testing. These wide variations in outside dust concentrations largely influenced the large day-to-day variations in relative cab protection factors shown in Fig. 3. A smaller amount of variation in the inside cab dust concentrations were measured and were influenced by the effectiveness of the cab enclosure system, outside dust concentrations, and other unexplained variations (such as operator practices, cab cleanliness and door opening frequency). Thus, the statistical measures for multiple days of test data should provide a better cab performance assessment.

The summary statistics also show that the arithmetic mean is commonly higher than the geometric mean, indicating that the dust concentration frequency distributions are asymmetrically skewed toward the higher levels of dust concentration measurements (positive skewness). The difference between the arithmetic and geometric (an indicator of skewness) is slight for the CAT 980 B loader, while it is more pronounced for the Drill Tech DK40 drill. However, because the sample sizes are small for each testing period (3 to 7 shifts), distribution fitting this data can be ambiguous. The Kolmogorov-Smirnov (KS) test does permit distribution fitting for small sample sizes (Emory, 1985), but does not clearly reject either the normal and log-normal frequency distributions for this data at the 0.05 significance level. Thus, the ANOVA analysis was conducted assuming both the normal and log-normal distribution of the data.

The dust summary statistics and ANOVA analysis (shown in Tables 2 and 3) for the CAT 980B front-end loader indicate that the enclosed cab modifications significantly lowered the inside cab dust concentrations by improving the cab's protection factor performance. The mean inside cab dust concentration was reduced from 0.55 mg/m^3 with the existing cab to 0.03 mg/m^3 with the filtration system and a sealed cab. When considering the different outside cab dust concentrations measured during the testing periods, the overall cab protection factor improved from 1.1 to 10. ANOVA analysis (assuming normal or log-normal) of the inside dust concentration data with respect to the cab modification effect and outside cab dust concentrations indicates that both of these factors significantly affected the inside cab dust levels at the 95% confi-

Table 2 — Summary statistics of dust concentrations measured in mg/m^3.

Cab evaluation Sampling location (*n* = sampling shifts)	Data range Min.	 Max.	Arithmetic Mean	 Std. deviation	Geometric Mean	 Std. deviation.
Pretesting CAT 980B loader						
Outside Cab (*n*=3)	0.41	0.75	0.63	0.19	0.61	1.41
Inside Cab (*n*=3)	0.32	0.75	0.55	0.22	0.52	1.55
Post-testing CAT 980B loader						
Outside Cab (*n*=6)	0.09	0.47	0.30	0.17	0.25	2.10
Inside Cab (*n*=6)	0.01	0.07	0.03	0.02	0.02	2.25
Pretesting Davey M8B drill						
Outside Cab (*n*=4)	0.10	1.13	0.72	0.46	0.52	3.07
Inside Cab (*n*=4)	0.09	0.19	0.14	0.04	0.13	1.36
Post-testing Davey M8B drill						
Outside Cab (*n*=4)	0.12	0.46	0.22	0.16	0.19	1.85
Inside Cab (*n*=4)	0.02	0.17	0.08	0.07	0.06	2.41
Pretesting DrillTech DK40 drill						
Outside Cab (*n*=4)	0.71	6.70	2.52	2.84	1.62	2.85
Inside Cab (*n*=4)	0.02	0.08	0.04	0.03	0.03	1.92
Post-testing A DrillTech DK40 drill						
Outside Cab (*n*=5)	3.92	66.73	20.85	26.08	12.51	2.92
Inside Cab (*n*=5)	0.38	1.16	0.68	0.30	0.63	1.51
Post-testing B DrillTech DK40 drill						
Outside Cab (*n*=7)	0.25	31.77	6.25	11.34	2.07	4.59
Inside Cab (*n*=7)	0.02	0.13	0.07	0.04	0.06	1.98

Table 3 — ANOVA analysis of each cab modification assuming normal or log-normal data distribution.

Cab evaluation Inside dust *(Log$_e$ inside dust)*	**Main effect** Level of cab Modification	**Covariate** Outside dust *(Log$_e$ Outside Dust)*	**Residual**	**Total**
CAT 980B loader	**1 *d.f.***	**1 *d.f.***	**6 *d.f.***	**8 *d.f.***
Sum of squares	0.1662 *(12.052)*	0.3995 *(8.170)*	0.0713 *(4.780)*	0.6370 *(25.003)*
F-Ratio	13.991 *(15.127)*	33.628 *(10.255)*		
Significance level	0.0096 *(0.0081)*	0.0012 *(0.0185)*		
Davey M8B drill	**1 *d.f.***	**1 *d.f.***	**5 *d.f***	**7 *d.f.***
Sum of squares	0.0066 *(0.8225)*	0.0008 *(0.3771)*	0.0172 *(2.287)*	0.0246 *(3.487)*
F-Ratio	1.924 *(1.798)*	0.241 *(0.825)*		
Significance level	0.2241 *(0.2376)*	0.6492 *(0.4147)*		
DrillTech DK40 drill	**2 *d.f.***	**1 *d.f.***	**12 *d.f.***	**15 *d.f.***
Sum of squares	1.1354 *(13.383)*	0.1816 *(10.843)*	0.3549 *(4.472)*	1.6719 *(28.697)*
F-Ratio	19.196 *(17.956)*	6.141 *(29.096)*		
Significance level	0.0002 *(0.0002)*	0.0291 *(0.0002)*		

the 95% confidence level or 0.05 significance level. The inside cab mean dust concentrations show no notable difference between the original system tested during AC use only (pretesting) and the final system with both heating and AC use (post-testing B). Floor heater use showed a noticeable difference for the inside cab mean dust concentration as compared to heating and air conditioning from the roof. Thus, when retrofitting the cab with a positive cab pressurizing air filtration system, having the heating and AC discharge points high up at the cab ceiling appeared to make a significant improvement in cab protection factor performance and significantly lowered the inside cab dust levels.

The GRIMM particle counting size penetration results measured these modified cab filtration systems are shown in Fig. 4. Because penetration is just the reciprocal of the protection factor, a 10 and 100 protection factor would be

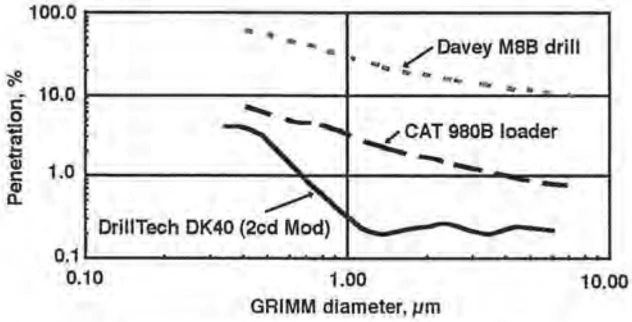

Figure 4 — Grimm optical particle counter data.

equivalent to 10% (0.10) and 1% (0.01) penetration, respectively. The GRIMM sampling results show similar cab performance measures as determined by average gravimetric results for multiple shifts. The poorest cab was the Davey M8B rotary drill, with more than 10% dust penetration across the respirable size range. The CAT 980B front-end loader had less than 10% dust penetration across the respirable size range. The best cab was the Drill Tech DK40 percussive drill, with less than 3% dust penetration across the respirable size range. These results also show that a relatively high percentage of particulate penetration occurs for all the cabs in the smaller size ranges. The GRIMM data collected provided good performance measures for a several-hour time period because of the relatively large and consistent difference in particle counts (one to two orders of magnitude difference) measured outside and inside the cab, even for the low mass concentrations that were measured gravimetrically. However, cleaner ambient air away from mining operations could also yield variable and unreliable relative cab performance measures if outside cab particle counts are too low to show measurable differences as compared to those inside the cab (Heitbrink et al., 1998).

Conclusions

Relative measures of enclosed cab performance from field data can be quite variable or unreliable if the outside dust mass or count concentrations vary significantly between low and high measurements. During the day-to-day cab field sampling, outside cab dust concentrations varied widely over several orders of magnitude. This made the day-to-day protection factors vary notably as compared to the more stable inside cab concentrations. Statistical measures had to be used to determine the significance of cab system changes and outside dust concentration variation on the average inside cab dust concentration. The GRIMM optical particle counters were able to more reliably measure the relative performance over a much shorter time period at these mining operations, because a large number of respirable dust particles were available at low mass concentrations. However, particle counting can yield unreliable performance measurements given low enough particle counts. One to two orders of magnitude between the outside and inside cab concentrations (mass or counts) are needed to reliably determine a relative performance measure for an enclosed cab.

A better than 90% respirable dust reduction, or a protection factor greater than 10, was demonstrated on two of the three retrofitted cab filtration systems. The two elements that appeared to be important for this kind of performance were an efficient filtration system and an enclosed cab that could be effectively sealed to achieve positive inside cab pressure with quality filtered airflow. A floor heater used in one of the two positively pressurized cabs was found to be a notable inside cab dust source by reducing the recirculation airflow quality. Upon removing the floor heater and adding an improved recirculation filter, the enclosed cab protection factor was significantly improved. The least significant cab performance improvement was measured on one of the three retrofitted cab filtration systems, where positive inside cab pressure was not achieved.

References

Cecala, A., Organiscak, J., and Heitbrink, W., 2001, "Dust underfoot: Enclosed cab-floor heaters can significantly increase operator's respirable dust exposure," *Rock Products*, Vol. 104, No. 4, pp. 39-44.

Emory, W.C., 1985, *Business Research Methods*, Third Edition, Irwin, Homewood, Illinois.

Hale, J., 2002, NIOSH's Division of Respiratory Disease Studies informational analysis of MSHA's dust sampling database.

Heitbrink, W.A., Hall, R.M., Reed, L.D., and Gibbons, D., 1998, "Review of ambient aerosol test procedures in ASAE Standard S525," *Journal of Agricultural Safety and Health*, 4(4), pp. 255-266.

National Institute for Occupational Safety and Health, 1994, *NIOSH Manual of Analytical Methods*, Fourth Ed., DHHS (NIOSH) Pub. No. 94-113, NIOSH, Cincinnati, Ohio.

National Institute for Occupational Safety and Health, 1983, *Collaborative Tests of Two Methods for Determining Free Silica in Airborne Dust*, DHHS (NIOSH) Pub. No. 83-124, NIOSH, Cincinnati, Ohio.

Organiscak, J.A., Cecala, A.B., Heitbrink, W.A., Thimons, E.D., Schmitz, M., and Ahrenholtz, E., 2000, "Field assessment of retrofitting surface coal mine equipment cabs with air filtration systems," *Proceedings of the Thirty-First Annual Institute on Mining Health, Safety and Research*, August 27-30, Roanoke, Virginia, pp. 57-68.

Organiscak, J.A., and Page, S.J., 1999, "Field assessment of control techniques and long-term dust variability for surface coal mine rock drills and bulldozers," *International Journal of Surface Mining and Reclamation and Environment*, Vol. 13, No. 4, pp. 165-172.

Parobeck, P.S., and Tomb, T.F., 2000, "MSHA's programs to quantify the crystalline silica content of respirable mine dust samples," Presented at the 2000 SME Annual Meeting and Exhibit, February 28-March 1, Salt Lake City, Utah, Pre-P No. 00-159, 5 pp.

Tomb, T.F., Gero, A.J., and Kogut, J., 1995, "Analysis of quartz exposure data obtained from underground and surface coal mining operations," *Appl. Occup. Environ. Hyg.*, 10(12), December, pp. 1019-1026.

U.S. Code of Federal Regulations, 2001, Title 30-Mineral Resources; Chapter I-Mine Safety and Health Administration, Dep. Labor; Subchapter K- Metal and Nonmetal Mine Safety and Health, Parts 56 through 58; Subchapter O-Coal Mine Safety and Health, Parts 70 through 74," U.S. Gov. Printing Office, Office of Federal Regulations, July 1, 2001.

Willeke, K., and Baron, P.A., 1993, *Aerosol Measurement Principles Techniques and Applications*, Van Nostrand Reinhold, New York, New York.