Reducing Enclosed Cab Drill Operator's Respirable Dust Exposure with Effective Filtration and Pressurization Techniques

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Many different types of surface mining equipment use enclosed cabs to protect equipment operators from health and safety hazards. The overburden removal and mining process can be extremely dusty and can cause excessive dust exposure. To study this issue, a cooperative research effort was established between the National Institute for Occupational Safety and Health, U.S. Silica Co., Clean Air Filter Co., and Red Dot Corp. in an effort to lower respirable dust levels in an enclosed cab on an older surface drill at a silica sand operation. Throughout this research effort, a number of modifications were incorporated into the drill's filtration and pressurization system, as well as in other areas, to improve its design and performance. An average cab efficiency of 93.4% was determined with gravimetric sampling instruments when comparing the outside with the inside cab dust levels on the final design. Although this study considered just one operation, the goal was to identify cost-effective improvements that could be implemented on all types of enclosed cabs to lower respirable dust concentrations. Two critical components for an effective enclosed cab system are having a properly designed, installed, and maintained filtration and pressurization system, along with a method for maintaining structural cab integrity, which allows the cab to be positively pressurized. Another important component is maintaining cab cleanliness. Although this research was originally directed toward the mining industry, it is also applicable to agricultural or construction equipment.

Keywords dust control, dust exposure, enclosed cab, filtration and pressurization system, respirable dust, silicosis

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INTRODUCTION

This research addresses the health component of enclosed cabs to determine whether acceptable air quality can be provided to operators while the equipment is being used in extremely dusty environments. The issue becomes even more critical when this equipment is operated in an environment where silica dust is present. The serious health effects to workers breathing respirable silica dust and the potential for subsequently developing silicosis have been known for decades.[1–5] The concern with this dust has been further complicated by Monograph 68, published by the International Agency for Research on Cancer in 1997, which states that inhaled crystalline silica from occupational sources is considered a (Group 1) human carcinogen.[6]

Worker exposure to respirable silica dust is common in surface metal/nonmetal and coal mining operations in the United States, since a significant portion of the overburden material contains high silica-bearing strata. This study evaluated a surface drill at a silica sand operation where the majority of ore being drilled had a very high silica or quartz content.

A multitask research effort has been under way to evaluate the air quality delivered to enclosed cabs on many different types of heavy equipment. Acceptable air quality being provided to workers in enclosed cabs is based on many different factors, but the most critical one is the cab's filtration and pressurization system. Since a significant portion of surface mining equipment in the United States is old, the cabs may not be providing acceptable air quality to the equipment operators. While visiting many operations over the past few years, we have observed a wide spectrum of effectiveness of various filtration and pressurization systems being used in the mining and agricultural industries. Some enclosed cabs had effective filtration and pressurization systems that provided acceptable air quality to the operator, while others were poorly maintained and provided marginal or unacceptable air quality. A major factor in the degradation of these systems was the aging and wear of many of the components on the enclosed cabs. As cabs get older, gaskets and seals commonly deteriorate to a point where they no longer provide adequate closure or sealing, and positive pressurization cannot be achieved. Other cabs were observed with poorly designed filtration and pressurization systems not capable of providing acceptable air quality. Such design flaws have even been identified on some new equipment.

In an effort to minimize workers' respirable dust exposures, this and other similar studies were concurrently performed to evaluate and improve the effectiveness of the air quality provided to workers operating heavy equipment inside enclosed cabs.[7–10] The National Institute for Occupational Safety and Health (NIOSH) entered into a verbal agreement with U.S. Silica Co. to determine the respirable dust exposure to the operators of a surface drill and then to subsequently implement cost-effective methods to optimize the air quality in the enclosed cab. Initially, this effort focused on making improvements to the existing filtration system and improving the pressurization by installing an add-on system. In addition, the integrity of the cab was also improved by replacing gaskets and seals, and by sealing holes and cracks. Eventually, a completely new filtration/pressurization system was installed to determine the level of improvement in air quality that could be achieved with a new prototype system. Results from this study can be applied to other types of enclosed cabs on different equipment across various industries.

METHODS

The objective of this research was to initially determine the air quality in the enclosed cab of the drill and then compare it as modifications were implemented to improve the cab's filtration and pressurization system. The sampling strategy provided a quantitative analysis of respirable dust levels inside and outside the enclosed cab on this drill. Data collected included gravimetric and instantaneous respirable dust monitoring measurements, instantaneous particle counting measurements, weather conditions (wind speed, direction, temperature, and relative humidity), and documentation of equipment operation.

Sampling Strategy

Three main sampling locations were used for this evaluation: (1) inside the enclosed cab, (2) outside the enclosed cab, and (3) outside the cab on a movable sample tripod positioned downwind in the dust cloud. The inside sample location was used to determine the air quality inside the cab, which represents the drill operator's respirable dust exposure during the time spent inside the enclosed cab over the workday. All sampling instrumentation was located on a sampling rack positioned directly behind the drill operator's chair. This sampling rack normally comprised three gravimetric samplers and an instantaneous respirable dust monitor.

The outside sampling location also used a sampling rack that was attached to the drill cab directly under the window where the operator views the drilling process. This sampling unit also comprised three gravimetric samplers and an instantaneous respirable dust monitor. Cascade impactors and temperature recording devices were used at the inside and outside sample locations, but that data will not be presented here.

The tripod sample location used three gravimetric samplers and was manually moved by test personnel to always be positioned downwind of drilling. This sample location normally represented the worst-case dust exposure potential, since it was always located in the dust cloud even if the wind was blowing the dust away from the enclosed cab.

Respirable dust measurements using gravimetric samplers were normally taken by three individual units located side by side on the sampling rack. MSA Escort Elf (MSA, Pittsburgh, Pa.) sampling pumps were used in this study and calibrated to a flow rate of 1.7 L/min before each field survey, which is the required flow rate as established by the American Conference of Governmental Industrial Hygienists (ACGIH®) for the metal/nonmetal mining industry.[11] Dust samples were collected with a 10-mm Dorr-Oliver cyclone, which classifies the respirable portion of dust, and then deposited on a 37-mm MSA filter. Filters were pre- and postweighed to the nearest 0.001 mg on a microbalance in a temperature/humidity controlled weighing room. All sampling pumps were also post-calibrated to ensure that an acceptable flow rate of 1.7 L/min ($\pm$0.015 L/min) was maintained throughout testing. For every 10 gravimetric filters used in the field, a blank cassette was used to determine a correction factor for the filter weighing process that was then applied to all the field gravimetric measurements.

Airborne respirable dust measurements inside and outside the enclosed cab location were taken with Personal DataRAM (PDR) instruments (model 1200, Thermo Andersen, Smyrna, Ga.). The PDR instruments were operated in the active sampling mode, which involved the use of the same sampling setup as previously described for the gravimetric instruments. After the filter was postweighed and a correction factor calculated, it was applied to all dust data concentrations for that day of testing with the PDR.

Two different types of particle counting instruments were used for short evaluations during this research. These were the Pacific Scientific Met One model 227B hand-held particle counting instruments and Grimm PDM model 1108 optical particle counters. The Met One instrument is a laser-based sensor that was used in the manual mode to record 1-min measurements for 0.3 and 3.0 μm particles. The Grimm particle count instruments were used to measure aerosol concentrations with an omnidirectional sampling inlet in 15 different ranges from 0.3 to 15 μm.

A number of different instruments were used to determine environmental conditions during testing. Since this drill operates outside during a wide range of weather conditions throughout the year, environmental factors such as wind velocity, wind direction, temperature, and relative humidity levels were monitored during each test. Periodically throughout each day of testing, a 9-inch (22.9-cm) sling psychrometer was used to verify temperature and relative humidity measurements. The drill location and orientation were manually recorded by work personnel to provide a wind profile for the drill that was used for data analysis calculations. Baseline testing included two different 2-day series that were slightly over a week apart (May 10 and 11, and May 19 and 20, 1999).

Pressurization and Filtration Effectiveness Descriptors

When evaluating a pressurization and filtration system (comparing outside with inside respirable dust concentrations), a number of different descriptors or measures provide a numerical value to describe the system's effectiveness. The following three measures can all be used:

$$\text{Protection factor (PF)} = C_o/C_i \text{ (ratio)}$$
$$\text{Efficiency } (\eta) = (C_o - C_i/C_o) \text{ (fraction—or multiplied by “100” for percent)}$$
$$\text{Penetration (Pen)} = 1 - \eta \text{ (fraction)}$$

where C_o = outside respirable dust concentration, C_i = inside cab respirable dust concentration.

$$\text{Comparison} \quad PF = C_o/C_i = 1/1 - \eta = 1/\text{Pen}$$

Drill Description

The drill evaluated in this study was a DrilTech D40Kii rotary percussion drill approximately 20 years old, operated by a drill operator and drill helper. The drill was driven into place by the drill helper from a driver's compartment located in the left front of the drill rig. When the drill was moved at this operation, the drill operator would exit the drill cab and stand outside on the driver's side of the drill rig, providing hand motions to the drill helper to position the drill in place for the next hole. The driller operated the drill from the enclosed cab located on the right back of the drill. This drill cab had a Red Dot R-9727 12-volt air-conditioning unit located on the roof of the cab. This unit had two internal fans that moved approximately 320 ft^3/min (9.1 m^3/min) of air to the enclosed cab, but there was no filtering of this air. The only dust filtering performed for this system was from an external filter housing that brought outside air into the system. At the time of testing, the filter housing unit was substantially dented and the general condition of the unit was poor, although this is typical in the mining industry.

Postmodification A

A Clean Air Filter Co. cab pressurization system was added to the existing system, providing approximately 70 ft^3/min (2.0 m^3/min) of makeup air to the system. Since the volume of the enclosed cab was approximately 45 ft^3 (1.3 m^3), this new system provided approximately 1 $^1/_2$ filtered air changes to the enclosed cab every minute. This system was composed of a prefilter, a blower, and a respirator-medium secondary filter (Figure 1). The prefilter was a two-stage media type filter in a steel housing located on the negative side of the fan and was used to remove the larger particles (greater than 20 μm). The final filter was on the positive side of the fan housed in a 3-inch (7.6-cm) cylindrical chamber. This filter was a near-respiratory quality electrostatic media with a rating of 97% efficiency at 0.3 μm. After the pressurization system was installed, the cab static pressure was measured at 0.01 in. H_2O.

Another significant modification was improving the sealing effectiveness of the enclosed cab. New door gaskets were installed, and all small cracks and holes in the shell of the cab were plugged with silicon caulking. All control levers had rubber boots placed around them to provide the highest quality seal possible. A tenfold increase in the cab pressurization was achieved through these numerous efforts and resulted in a cab pressure of approximately 0.1 in. H_2O. Achieving this level of pressurization is important because it prevents moderate wind velocities from forcing dust-laden air into the cab.[12] Testing these improvements consisted of 2$^1/_2$ days in November 1999 and 2 days of testing in January 2000.

Postmodification B

A newly designed low-profile plastic body Red Dot Corp. R-9777 system was installed on the enclosed cab that offered improved sealing capacity over the traditional metal unit. The new system located the fan before the heater core and the

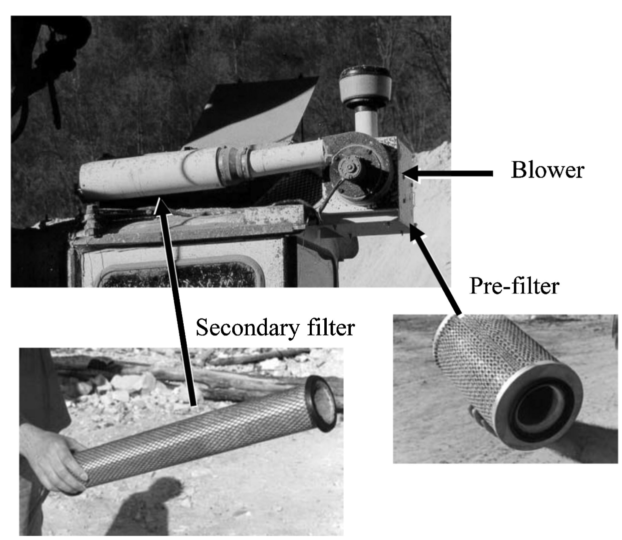

FIGURE 1. Cab filtration and pressurization system

air-conditioner evaporator to minimize the negative pressure area within the unit. The floor heater was removed since the overhead unit provided heating capabilities. Clean Air Filter Co. also developed a high-efficiency pleated recirculation filter that was placed inside this unit and located immediately before the heating and air-conditioner core. This filter medium was rated at 97% efficiency at 0.3 μm particles. It was an electrostatic filter medium because it provided less restriction per unit area of filtering when compared with a standard mechanical type filter. One goal was to maximize the amount of recirculated air within the cab to increase the efficiency of the heater and air-conditioner by minimizing the amount of fresh air that needed to be conditioned. The cab was once again sealed of all possible leak areas. After all of these modifications, a positive cab pressure of between 0.07 and 0.12 in. H_2O was achieved. A full range of temperature conditions were achieved for the 7 days of testing from April 2001 to March 2002 to evaluate this test condition.

Statistical Analysis

A statistical analysis was performed on the inside cab respirable dust concentrations to examine the enclosed cab modification significance level, given the day-to-day variation of outside dust concentrations. An analysis of covariance (ANCOVA) statistical technique was deemed suitable for this cab modification effect examination because it combined the features of analysis of variance (ANOVA) and regression.(13) The ANCOVA technique augments an ANOVA model of the qualitative effect of cab modification with the regression of the quantitative variable (or covariance) of outside cab dust concentration, both anticipated to influence the day-to-day inside cab dust concentrations during the study. This method is a special type of regression analysis used to determine the level of influence or significance of the variables (qualitative and quantitative) on the inside cab dust concentrations.

RESULTS

Baseline

The first part of Table I indicates the respirable dust concentrations determined at all three monitoring locations using gravimetric dust sampling equipment. Average outside respirable dust concentrations ranged from 0.71 to 6.71 mg/m^3 as compared with 0.02 to 0.08 mg/m^3 for levels inside the operator's cab. For all 4 days of testing, the outside cab respirable dust concentrations were higher than for the tripod sample location because the primary wind direction was from the drill hole to the enclosed cab.

Pressure measurements taken inside the cab indicated that there was very minimal cab pressurization at approximately 0.005 in. H_2O. Despite the poor visual conditions of the filtration system and the poor structural integrity of the cab, respirable dust levels measured inside the cab during baseline testing were much lower than expected. Since the air-conditioning unit was being used for a substantial part of each day of testing, it was believed that a significant portion of dust

TABLE I. Gravimetric Dust Sampling on Surface Drill for Various Phases of Research

Date	Outside Cab Dust Conc. (mg/m^3)	Outside Tripod Dust Conc. (mg/m^3)	Average Outside Dust Conc. (mg/m^3)	Inside Cab Dust Conc. (mg/m^3)	Protection Factor	Efficiency (%)	Penetration
			Baseline				
5/10/1999	0.97	0.54	0.76	0.08	9.4	89.4	0.11
5/11/1999	2.21	1.57	1.89	0.03	63.0	98.4	0.02
5/19/1999	12.88	0.53	6.71	0.02	335.3	99.7	0.00
5/20/1999	0.91	0.51	0.71	0.02	35.5	97.2	0.03
			Postmodification A				
11/16/1999	2.74	14.74	8.74	0.38	23.0	95.7	0.04
11/17/1999	2.47	5.38	3.93	0.58	6.8	85.2	0.15
11/18/1999	11.07	4.82	7.95	1.16	6.8	85.4	0.15
1/25/2000	14.09	19.88	16.99	0.72	23.6	95.8	0.04
1/26/2000	73.33	60.09	66.71	0.54	123.5	99.2	0.01
			Postmodification B				
4/24/2001	3.01	1.14	2.08	0.07	29.6	96.6	0.03
4/25/2001	0.28	0.52	0.40	0.11	3.6	72.5	0.28
10/16/2001	0.31	0.14	0.23	0.02	11.3	91.1	0.09
11/1/2001	6.06	2.65	4.36	0.10	43.6	97.7	0.02
11/2/2001	29.91	36.78	31.85	0.13	245.0	99.6	0.00
3/27/2002	1.95	1.74	1.85	0.04	46.1	97.8	0.02
3/28/2002	3.83	2.3	3.07	0.04	76.6	98.7	0.01

was removed as the air moved through the evaporator unit, thus increasing the filtering efficiency of the system.

After baseline testing was completed, a number of modifications were made to further improve the filtration efficiency and pressurization of the enclosed cab. Since the R-9727 roof-mounted unit appeared to be in poor working order, a maintenance overhaul and cleaning was performed on it. One problem with the current design was that the filtration unit was under negative pressure; thus, any leak in the system would allow dust to enter the unit and be blown directly into the enclosed cab.

Postmodification A

To correct the problems identified, the drill was modified with a new pressurization system, and the cab integrity and cab pressurization were improved (postmodification A). After the implementation of these changes, the identical dust analysis performed during baseline testing was repeated (Table I). Originally it was anticipated that dust levels would decrease because of the modifications and improvements made to the filtration and pressurization system on the enclosed cab; instead, respirable dust levels inside the enclosed cab increased seventeenfold from an average concentration of 0.04 mg/m^3 (baseline) to 0.68 mg/m^3 in posttesting.

In trying to determine the reason for this significant increase in respirable dust levels, the researchers examined all the parameters that changed from baseline to postmodifications. Since postmodification A testing took place in winter conditions with low outside air temperatures, a radiator-type floor heater with a fan was used in the cab (Figure 2). This type of heater is commonly used in heavy equipment during the winter months and is well liked by equipment operators because it keeps their feet warm. After considering all the factors in this analysis, it was hypothesized that the floor heater in the cab was the primary cause of the increased dust concentrations. It was believed that dust was being generated from the drill operator's boots grinding and stirring up material on the floor and from dust being blown off the operator's clothing.

In an effort to verify the effects of using the floor heater, the drill was taken into the maintenance shop and tested using two Grimm particle-counting instruments. The first sequence was to monitor particle levels inside and outside the enclosed cab with the filtration and pressurization system operating along with the recirculation system, which was the postmodification A setup. The next sequence was to operate only the recirculation system. The third and final sequence was with both units operating in conjunction with the floor heater. Once this test series was completed, the Grimm instruments were switched to minimize any instrument bias effects, and the test series was repeated. Figure 3 shows the results from this testing. The lowest levels recorded in the cab resulted from sequence #1 (0.01 mg/m^3), which was with the improvements to the air filtration and pressurization system. For test sequence #2, pretest conditions averaged a respirable dust concentration of 0.03 mg/m^3, while test sequence #3 (both units operating with the floor heater) recorded the highest average respirable dust concentration at 0.26 mg/m^3. This represents a ninefold increase over pretest conditions (sequence #2) and a twenty-sevenfold increase over postmodification A conditions (sequence #1). Outside respirable dust levels remained relatively constant throughout this testing.[14]

Postmodification B

After completing the floor heater testing, it was decided to make additional changes on the drill in an effort to further improve the air quality in the enclosed cab—postmodification B. When the drill became available after being out of production for 14 months, testing was performed to evaluate the new filtration and pressurization system's ability to improve the air quality in the enclosed cab (postmodification B). Seven different days of testing were performed over an 11-month period to evaluate the effectiveness of the system during a range of weather conditions when either the heater or the air conditioner was used.

Table I shows the results for all testing performed. In addition to dust concentrations inside and outside the cab, the table presents the protection factor, efficiency, and penetration for

FIGURE 2. Floor heater inside enclosed cab

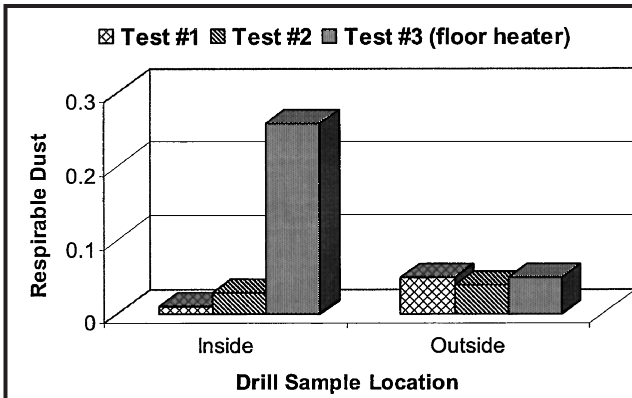

FIGURE 3. Shop testing to determine increase in respirable dust levels inside cab with floor heater

TABLE II. Cab/Filtering Performance Measures Using Met One Particle Counting Instruments

Date	μm Size	Outside Count	Inside Count	Protection Factor	Efficiency	Penetration
5/11/2001	0.3	48,465	2531	19	0.95	0.05
	0.5	15,953	431	37	0.97	0.03
10/17/2001	0.3	233,220[A]	30,942	8	0.87	0.13
	3.0	533	2	267	0.99	0.00
11/1/2001	0.3	849,382[A]	892	952	0.99	0.00
	3.0	1744	2	872	0.99	0.00
11/2/2001	0.3	908,221[A]	437	2078	0.99	0.00
	3.0	2558	1	2558	0.99	0.00
3/27/2002	0.3	320,412[A]	3287	97	0.99	0.01
	3.0	157	11	14	0.93	0.07

Note: All testing performed under postmodification B testing.
[A] Particle concentrations exceed the manufacturers 5% concentration level criteria of 200,000 particles/min.

each day of testing, which indicate that the cab effectiveness measures are strongly influenced by the relative changes in outside dust concentrations. An example of this is for the last 2 days of testing on March 27 and 28, 2002, when the inside respirable dust concentration was 0.04 mg/m^3 for both days, but the outside concentration averaged 1.85 and 3.07 mg/m^3, respectively. The effect of the outside dust concentration caused the protection factor to go from 46.1 to 77.6, the efficiency from 97.8 to 98.7, and penetration from 0.02 to 0.1. This also indicates the changes to each of the descriptors on a relative basis. The point to note is that a system could have extremely low inside dust concentrations but with high outside levels, the performance values for protection factor efficiency, and penetration may not appear to be significant.

Met One Cab Filtering Performance—Postmodification B

During the course of this research effort, Met One particle counter instruments were used to evaluate cab performance effectiveness. An initial analysis was performed on May 11, 2001, to verify that the Met One instrument provided particle count values comparable to the Grimm instruments. For this comparison, 0.3 and 0.5 μm particle sizes were used and indicated that similar values were obtained with both instruments. After this initial test, all other tests used the 0.3 and 3.0 μm levels since the large particle size is more significant in the respirable size range. All of the subsequent tests using the Met One instruments were static, nonproduction tests performed during off-shift production times (testing during production time periods would have overloaded the instrument). Table II lists the results from this testing.

When comparing the results from the Met One and gravimetric sampling instruments, it can be seen that the Met One cab/filtering performance measures (protection factor, efficiency, and penetration) normally are higher than for gravimetric sampling. However, the Met One performance measures are static tests under ideal performance conditions. In contrast, gravimetric testing is performed continuously throughout the workday and includes periods when the drill operator is going into and out of the enclosed cab and may include periods when the cab door is left open. Dust enters the cab when the door is open and thus lowers the performance measures for gravimetric sampling relative to the Met One instrument.

Statistical Analysis

An ANCOVA was performed for the cab data shown in Table I to determine the significance level of the enclosed cab changes with respect to the variation of outside dust concentrations. A natural log-transformation of the dust concentrations was conducted to meet the ANCOVA assumptions of normality and equal variances between treatment groups.[13] For this statistical analysis, the inside cab dust concentration was the dependent variable, the cab modification was the treatment effect (main factor effect), and the outside dust concentration was considered the uncontrolled independent covariate. Table III shows the summary statistics of the dust data for the three different cab test conditions studied and indicates which

TABLE III. Summary Statistics of Dust Concentrations Measured

Summary Statistics of Field Testing Dust Data				
	Data Range		Arithmetic	Std.
	Min	Max	Mean	Dev.
Baseline				
Outside cab (n = 4)	0.71	6.70	2.52	2.84
Inside cab (n = 4)	0.02	0.08	0.04	0.03
Postmodification A (floor heater)				
Outside cab (n = 5)	3.92	66.73	20.85	26.08
Inside cab (n = 5)	0.38	1.16	0.68[A]	0.03
Postmodification B (new units)				
Outside cab (n = 7)	0.25	31.77	6.25	11.34
Inside cab (n = 7)	0.02	0.13	0.07	0.04

[A] ANCOVA analysis of the $\log_e$ transformed dust data showed that the postmodification A inside cab concentrations were significantly higher than the other two periods at the 95% confidence level.

average cab dust concentration was significantly different (at the 95% confidence level) from the others.

Results from ANCOVA analysis showed that some of the cab modifications, along with outside dust concentrations, were significantly associated with dust concentrations measured inside the cab. Table III indicates that a significant difference in respirable dust concentrations were measured inside the cab between the baseline and postmodification A testing. In this case, floor heater use and increased outside dust concentrations were both significantly associated with the increase of inside cab dust concentrations from 0.04 mg/m^3 to 0.68 mg/m^3. A second evaluation comparing postmodification A with postmodification B indicated that postmodification B was significantly associated with reducing the enclosed dust concentrations from 0.68 mg to 0.07 mg/m^3. Postmodification B removed the floor heater and heated the cab from the ceiling. The third analysis compared baseline levels with postmodification B, which indicated that there was not a significant difference for inside cab dust concentrations between these two field studies when the floor heater was not used.

DISCUSSION

While performing this research, a number of issues were identified that affected the air quality inside the enclosed cab. Cab cleanliness is one such area that was brought to light by the floor heater issue. The shop testing showed a seventeenfold increase in dust levels inside the enclosed cab from the heater stirring up dust on the floor of the cab and from the operator's clothing. Although floor heaters are no longer recommended for use within enclosed cabs, the magnitude of this problem was exacerbated by the amount of product on the floor in this cab. Walls and floors of cabs should be cleaned by equipment operators on a daily basis to ensure that dust is constantly removed from the cab interior. This work also stresses the significance of the operator having clean work clothing.

Another outcome from the floor heater analysis is the importance of providing effective filtering of recirculated air within the enclosed cab. When dust is generated within a cab from items such as the floor heater or contaminated work clothing, the only method available to remove this dust is through the use of a recirculation filter. Many roof-mounted filtration and pressurization systems have inferior recirculation filters that are incapable of removing the respirable fraction of dust. This is a primary reason that a number of additional modifications (postmodification B) were performed on the drill cab after the shop testing was completed.

Another notable finding is the loss of filter efficiency for electrostatic filter media over time, even without the filter in use. The filter in question is the final filter on the pressurizer system. Loss of filter efficiency was clearly noted during the Met One particle count testing. May 11, 2001, was the first day of testing with the Met One instruments, and these results were used as a baseline. The drill had a major mechanical failure shortly after this test and was out of service for the following 4 months. Shortly after the drill was repaired, Met One testing was performed on the drill on October 17. The inside 0.3 μm particle count was very high and averaged a twelvefold increase, even though the outside change was under a fivefold increase. Despite this loss of efficiency, the filter had minimal use between these two tests. For the testing on November 1 and 2 the following month, a new filter was installed and levels once again were low, in the 0.3 μm range. When testing was performed 4 months later, the loss of efficiency in the 0.3 μm range became evident once again. Similar findings regarding the loss of efficiency over time with electrostatic filter medium have been noted by other researchers.[15–17]

In light of these findings, if an electrostatic filter is used on enclosed cab filtering systems, it needs to be changed on a scheduled time basis whether or not the filter is used or visually shows signs of dust loading. In an effort to improve the filter design, Clean Air Filter Co. is now fabricating an "absolute" design. This incorporates a 95% efficiency mechanical filter medium for 0.3 μm particles, with an electrostatic filter media wrapped around the mechanical filter.

Another important finding during this research was the impact of the drill cab door being opened throughout the day. It was noted on many occasions that the drill operator left the enclosed cab door open when the drill was being moved and repositioned, as well as during some nonproduction periods, such as lunch, which allowed outside dust to enter the cab. The impact of this can be seen in Figure 4 for a particular day of testing when this situation occurred frequently. This graph provides respirable dust levels inside and outside the cab taken with PDR instantaneous dust monitors. The inside cab dust levels are designated as both production (drilling) and nonproduction time periods (nondrilling). As shown, the highest respirable dust levels recorded inside the cab were during the nonproduction time periods. The graph also shows slightly higher dust levels inside the cab during the lunch break, from 11:33 a.m. to approximately 12:45 p.m., in comparison with outside dust levels.

In light of these findings, we recommend that the drill cab door remain closed whenever possible. We also recommend that the drill operator remain in the drill cab as much as possible when the drill is being repositioned to the next drill hole. The drill operator could easily communicate with the drill helper through radio communications to position the drill over the next hole without ever leaving the cab. This would decrease the drill operator's dust and noise exposure, as well as reduce the amount of dust entering into and contaminating the interior of the enclosed cab.

Sweep Compound Testing

After acknowledging the problem created by the floor heater and that cab floors are commonly very soiled from the equipment operators tracking dirt inside the cabs on their work shoes, a test was performed to determine whether dust levels in the enclosed cab could be lowered by using a floor sweep compound. The goal of the sweep compound is to keep agglomerate dirt and dust on the floor from becoming aerosolized. Prior

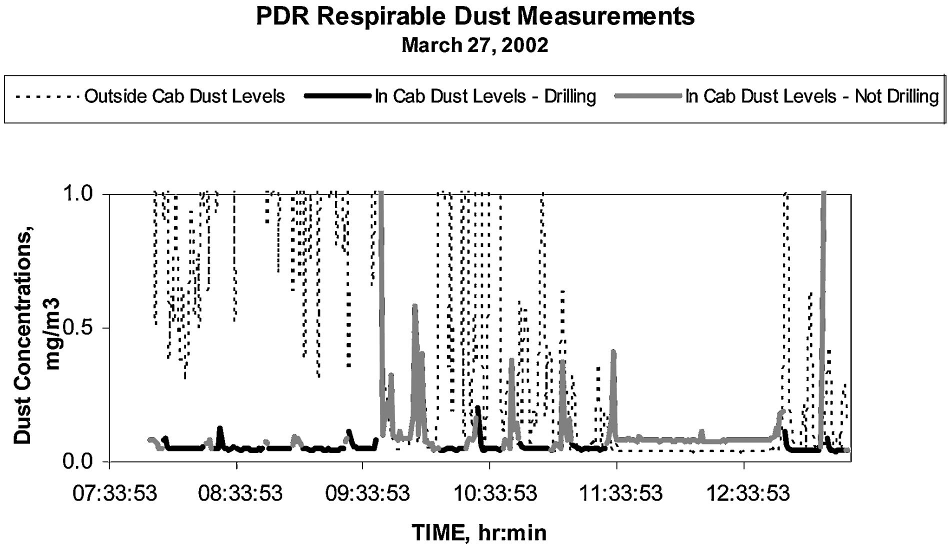

FIGURE 4. Impact of respirable dust levels inside enclosed cab when door is left open

to this testing, a number of different sweep compounds were evaluated. For this testing, it was decided to use a canola oil-based sweeping compound, which is preferable to a petroleum-based compound because of problems associated with using the petroleum product in a closed environment.

Presweep dust levels were already determined by using the postmodification A dust levels. For the 5 days of testing, the average respirable dust concentration was 0.68 mg/m^3. A $\frac{1}{4}$ inch to $\frac{1}{2}$ inch (0.64 to 1.3 cm) thick layer of canola oil sweeping compound was applied on the floor of the drill cab, then 3 days of posttesting was performed. Testing showed that this sweeping compound had a positive effect on suppressing dust from the soiled work floor in this cab. The 3 days of posttesting averaged a respirable dust concentration of 0.11 mg/m^3, which accounted for an 84% reduction in dust levels. Despite these positive results, it must be noted that in two similar studies performed in another drill and a dozer, the floor sweep did not provide similar reductions as obtained in this study.(18) However, both of these studies indicate the need to maintain a clean cab and floor area and the potential that a floor sweep compound can have in lowering dust levels by agglomerating dust and dirt on the floor and keeping it from becoming airborne.

System Cost

A primary concern regarding any modification or change to equipment is cost. The following is an approximate cost for the various equipment installed during this phase of the research: (1) an R-9777 heater and air-conditioner system donated by Red Dot Corp. (approximate cost: $2200); (2) an external air filtration and pressurization system donated by Clean Air Filter Co. (approximate cost $1000). It took approximately 40 man-hours to complete the installation of components 1 and 2, the removal of the floor heater, and the inspection and sealing of the enclosed cab.

CONCLUSIONS

Results from this study can be applied to other types of equipment that use enclosed cabs, that is, in mining, agriculture, and construction. An older surface drill at a silica sand operation was initially evaluated to determine the air quality delivered to the enclosed cab from the existing filtration system. After this testing was completed, a number of modifications were implemented in an effort to improve air quality. This research shows that there are two key components necessary for an enclosed cab to be effective from a dust control standpoint: effective filtration and cab integrity.

Filtration System

An effective filtration system should be composed of both a recirculation and outside (makeup) air system. The majority of air inside an enclosed cab should be recirculated through a high-quality filter medium. This allows air to be heated or cooled to the cab operator's comfort without the major air changes that would significantly affect the size and capability requirements and, ultimately, the cost for conditioning the cab air.

A major component in an effective system is to have the makeup air positively pressurize the enclosed cab. This results in any system leakage from inside of the cab to outside, preventing dusty air from entering the cab. It is also highly recommended that the makeup air be positively pressurized after being filtered to eliminate any possibility of dust-laden air being drawn into the system. Additionally, the optimal location for the makeup air inlet on the cab would be the farthest location from the dust sources.(19) This reduces the amount of loading on the filters and increases the time between cleaning or replacement. Finally, the makeup discharge vent into an enclosed cab should be located high in the enclosure, preferably at the roof, which allows the clean air to be blown

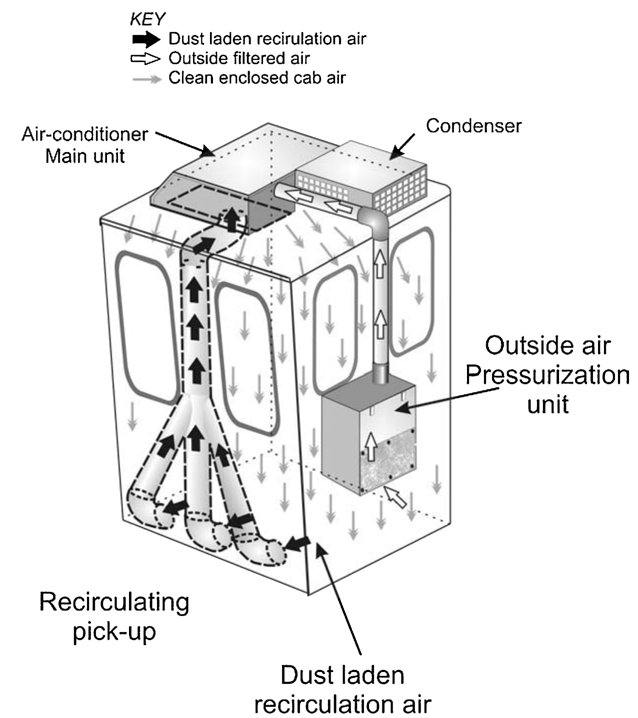

FIGURE 5. Ideal schematic for effective filtration and pressurization system

down over the equipment operator's breathing zone without becoming contaminated by any in-cab dust sources.

One last design criterion is for the filtration component to use a top-down approach to the clean air flow pattern. In this study, as well as in most other systems, the intake and discharge for the recirculation air is located in the roof of the cab. Although this is acceptable, we believe the most beneficial design would be to draw the recirculated air from the bottom of the cab instead of at the roof of the enclosure. This allows the dust-laden air to be drawn out of the cab near the worker's feet and away from the breathing zone. Again, the clean air would be blown in at the roof of the enclosure and the dust-laden recirculated air would be withdrawn from the floor of the cab. We strongly recommend against the discharge of clean air low in a cab wall because, as we observed, this can entrain a significant amount of dust from soiled work clothes, boots, and a dirty floor. Figure 5 represents our ideal schematic for an effective filtration and pressurization system on an enclosed drill cab.

Cab Integrity

Cab integrity is necessary to achieve some level of pressurization. Field testing has shown that installing new door gaskets and plugging and sealing cracks and holes in the shell of the cab have a major impact on increasing cab pressurization. To prevent dust-laden air from infiltrating into the cab, the cab's static pressure must be higher than the wind's velocity pressure. Although higher static pressure requirements help overcome outside wind speeds, a major drawback is that this necessitates more air being delivered by the outside air unit, causing more loading on the filters. Higher airflows through filters increases particle penetration and decreases the filter's efficiency by allowing more contaminants to flow through the filter media. Another drawback to higher airflows is that they create more air-conditioning (heating and cooling) requirements for operator comfort, which increases the size and cost of the unit. The key to an effective retrofit enclosed cab filtration and pressurization system is to balance the various factors and components discussed in this report.

Finally, because of the significant increase in dust levels with the use of floor heaters, it is recommended that they not be used in their present form. If needed, they should be repositioned to a higher area in the cab where they are less prone to recirculate dust from the floor and the operator's clothes. Probably the best solution would be to install a heating and air-conditioning unit into the clean air and pressurization system.

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