Long-term evaluation of cab particulate filtration and pressurization performance

A.B. Cecala, J.A. Organiscak and J.D. Noll
National Institute for Occupational Safety and Health, Pittsburgh, PA

Abstract

Over the past decade, a substantial effort has been made to improve the air quality inside enclosed cabs of both underground and surface mobile mining equipment to reduce respirable dust exposures by the equipment operators. As part of this effort, the U.S. National Institute for Occupational Safety and Health, (NIOSH) completed a comprehensive laboratory study that determined the significant factors for cab filtration and pressurization systems. From this information, a major underground mining equipment manufacturer designed a filtration and pressurization system that was incorporated into the enclosed cabs of its equipment. A long-term evaluation was performed on the effectiveness of this filtration and pressurization system to improve the air quality in the enclosed cabs of two different pieces of equipment, a face drill and a roof-bolter machine, at an underground limestone mine. This long-term evaluation demonstrated a significant reduction in dust levels between outside-to-inside cab respirable dust concentrations. During this evaluation, a modification to remove one of the filters on the roof-bolter machine simplified the design without sacrificing the system's efficiency. Tests using particle count instruments performed during nonproduction time periods on both pieces of equipment indicated protection factors greater than 100 when comparing respirable-sized dust particles inside the enclosed cab relative to outside.

Key words: Dust control, Silica, Health and safety

2012 *Transactions of the Society for Mining, Metallurgy, and Exploration*, Vol. 332, pp. 521-531.

Introduction

The goal of the U.S. National Institute for Occupational Safety and Health (NIOSH), as well as many other health and safety professionals working within the U.S. mining industry, is to improve the working environment for all workers within mining. A significant health concern was identified in a study performed in 1996 and 1997 in the surface coal mines in central Pennsylvania, which found an alarming prevalence of silicosis among these workers. This study was a multi-agency effort performed by the Mine Safety and Health Administration (MSHA), the Pennsylvania Department of Health, the Department of Health Evaluation Sciences of Pennsylvania State University College of Medicine and the Centers for Disease Control and Prevention's NIOSH. In this study, 1,236 miners were screened for lung disease at eight different surface coal mines, and based on chest X-rays, 6.7% of these workers were diagnosed with silicosis. In one particular county, 16% of the 213 participants were classified with the disease (Centers for Disease Control, 2000). Surface drill operators had the greatest number of cases of silicosis, although workers with other types of mechanized equipment, including dozers, loaders and haul trucks, were also being overexposed to crystalline silica and respirable dust. One alarming aspect was that in a number of cases, relatively young workers with relatively little mining experience were being diagnosed with the disease.

This CDC study was the impetus for a concentrated research effort to control the dust generated from these types of mechanized mobile equipment in order to minimize worker exposure to silica and other respirable dusts and contaminants. NIOSH, as well as other federal agencies, mining companies and health and safety professionals, launched research studies in this area. Because of the identification of older mining equipment being a potential contributor to these silicosis cases, NIOSH's efforts concentrated on taking older equipment and evaluating the effectiveness of retrofitting the enclosed cabs with new filtration and pressurization systems. Over the past decade, great strides have been made to improve the air quality inside of enclosed cabs by lowering the dust exposure of equipment operators through the implementation of improved filtration and pressurization systems.

The ultimate goal with this, or any area of research when completed and proven to be effective, is to be adopted and implemented by the industry. In this case, J.H. Fletcher & Company used the information published on improving the air quality in enclosed cabs to design a new filtration and pressurization system for cabs on its underground metal/nonmetal mining equipment. Once its design was completed, Douglas Hardman, president of J.H. Fletcher & Company, approached NIOSH and asked for comments and feedback on their design. It was through this interaction that a cooperative study was initiated to perform a long-term evaluation of this newly designed filtration and pressurization system in an underground mine. It was believed this long-term study would benefit the entire mining industry through the information and knowledge gained. From this, as well as other cooperative research studies with equipment manufacturers, filtration and pressur-

Paper number TP-11-047. Original manuscript submitted December 2011. Revised manuscript accepted for publication April 2012. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to Sept. 30, 2013.

ization manufacturers, and the mining industry, changes and modifications implemented to improve the air quality in the enclosed cabs of mobile mining equipment will have an impact on improving the health of these workers and will contribute towards the ultimate goal of the elimination of silicosis and other debilitating lung diseases from this industry.

Background

Enclosed cabs in mobile mining equipment have been used for many years to isolate workers from the work environment. Workers in these enclosed cabs are surrounded by dynamic working conditions that have highly variable dust sources. These cabs create a microenvironment for the workers, where they can be either more protected or more vulnerable to respirable dust. Workers can be more vulnerable to in-cab dust sources (floor heaters, dirt on floors/walls or on operator clothing, etc.) that are trapped within the enclosure. If not properly addressed, these sources can, in some instances, expose the worker to higher dust concentrations than outside the enclosed cab (Cecala et al., 2007; Cecala et al., 2001).

Over the past decade, a number of studies were performed in which new filtration and pressurization systems were installed on older pieces of mining equipment in an attempt to improve the air quality inside the enclosed cabs. The results of a few of these studies can be seen in Appendix A, listed in ascending order of effectiveness (Organiscak et al., 2004; Chekan and Colinet, 2003; Cecala et al., 2005; Cecala et al., 2004). The protection factor for an enclosed cab is determined by dividing the outside cab dust concentration by that of the inside.

These studies highlighted some very important factors relevant to improving the air quality in enclosed cabs and ultimately protecting the workers. Cab integrity, and the related ability to achieve positive pressurization, was found to be one of the key factors. As seen in the first two studies listed in Appendix A, when there was little to no cab pressure detected, the results showed minimal improvement in the cab's air quality. In fact, similar filtration and pressurization systems were installed on the rotary drill and front-end loader listed as items 1 and 3 in Appendix A, with a protection factor (PF) of 2.8 and 10, respectively. One notable difference between these two systems was that a small amount of pressurization was achieved in the front-end loader, whereas it was not possible to achieve any pressurization in the rotary drill.

Another critical factor was the quality and effectiveness of the filtration system. The various studies presented in Appendix A indicate substantial improvement in the interior air quality from effectively removing the dust particles from the outside air and delivering this clean filtered air into the enclosed cab. When sufficient pressurization was achieved, along with an effective filtration system, very good air quality was obtained in these cabs as indicated by significant protection factors.

Along with these field studies, NIOSH performed a detailed laboratory study at its Pittsburgh location in an effort to identify the significant factors for an effective enclosed cab filtration and pressurization system. During this laboratory study, filtration system operating factors were experimentally investigated with respect to the protection factor performance of a physically modeled enclosed cab test apparatus. The results of this study indicated that intake filter efficiency, along with the use of a recirculation filter, were the two greatest factors in improving the air quality in the enclosed cab. When considering the use of an intake air filter, the addition of the recirculation component significantly improved the air quality due to the repeated filtration of the cab's interior air. The addition of an intake pressurizer fan to the filtration system increased both intake airflow and cab pressure significantly. The cab air quality was also affected by intake filter loading and air leakage (Organiscak and Cecala, 2008a, b; Organiscak and Cecala, 2009).

In the course of the laboratory study, the significance of the filtration system parameters was evaluated and the following mathematical model was developed. Equation (1)[1] was formulated from a basic time-dependent mass balance model of airborne substances within a control volume with steady state conditions. The equation determines the protection factor in terms of intake air filter efficiency, intake air quantity, intake air leakage, recirculation filter efficiency, recirculation filter quantity and outside wind quantity infiltration into the cab.

$$PF = \frac{C_o}{C_i} = \frac{Q_I + Q_R\eta_R}{Q_I(1-\eta_I + l\eta_I) + Q_W} \quad (1)$$

PF = Protection factor, C_o/C_i
C_o = outside cab concentration
C_i = inside cab concentration
η_I = intake filter efficiency, fractional
Q_I = intake air quantity
Q_L = leakage air quantity
l = intake air leakage, Q_L/Q_I;
η_R = recirculation filter efficiency, fractional
Q_R = recirculation air quantity
Q_W = wind quantity infiltration
V_C = cab volume

Equation (1) allows for a comparison of how changes in the various parameters and components in the system impact the protection factor. The wind quantity infiltration (Q_w) can be assumed to be zero if the cab pressure exceeds the wind velocity pressure. By using Eq. (1), operators have the ability to determine the parameters necessary to systematically achieve a desired protection factor in their enclosed cab to improve the air quality to safe levels and to ultimately protect their workers.

Protection factor is the term used by NIOSH that provides a quantified value to evaluate and compare the effectiveness of a filtration and pressurization system on an enclosed cab for protecting the worker. It must be noted that protection factor is a relative value that does not predict exposure. On a comparative basis, the higher the value for protection factor achieved, the better the air quality is inside the enclosed cab relative to the outside air quality. Because of this, the value for protection factor can vary significantly based on the outside dust concentration. As an example, if there was a 0.1 mg/m^3 respirable dust concentration inside the enclosed cab, but the outside concentration varied from 1 to 10 and to 100 mg/m^3, the protection factor would be a value of 10, 100 and 1,000, respectively. This could lead one to believe that the worker in the enclosed cab of the third scenario with a PF of 1,000 was much more protected than the worker in the first case with the PF of 10, when in reality, both workers were exposed to the same respirable dust concentration inside the cab, 0.1 mg/m^3.

After the completion of the laboratory study discussed above, another field study was performed to determine if a unidirectional filtration and pressurization airflow pattern

[1] This equation is dimensionless; therefore, air quantities used must be in equivalent units. Also, filter efficiencies and intake air leakage must be fractional values (not percentage values).

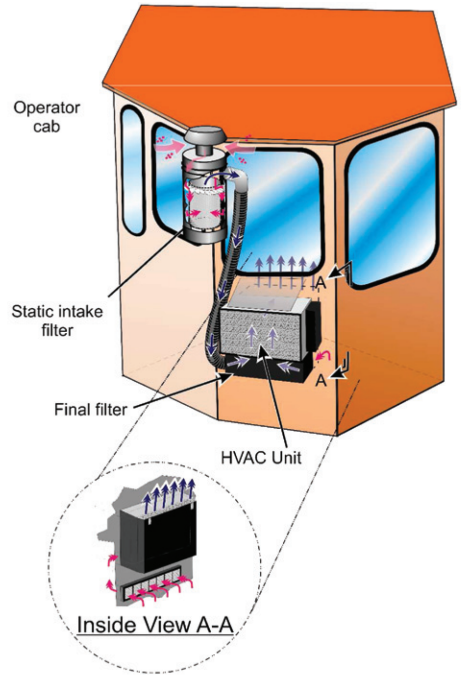

Figure 1 — Face drill filtration and pressurization system.

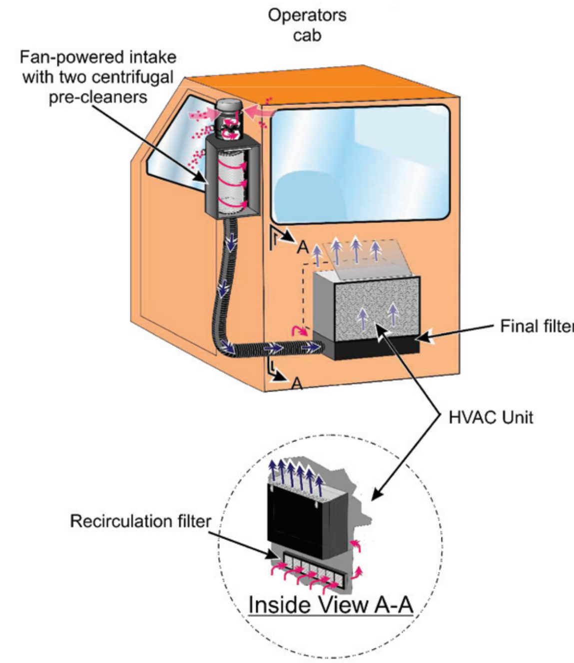

Figure 2 — Roof-bolter filtration and pressurization system.

was the optimal design for these systems. In the past, most recirculation systems had the intake and discharge air vents located at the roof of the enclosed cab. In theory, this design has two shortcomings. First, some of the clean air discharged is immediately short-circuited right back into the recirculation vent (intake) without ever flowing through the enclosed cab. Second, dust-laden air from the operator's clothing, the inner walls of the cab, and the cab floor, is drawn up through the operator's breathing zone as it travels into the recirculation duct at the roof of the enclosed cab. By having all the clean filtered air brought in at or near the roof of the cab, while withdrawing the recirculated air near the floor of the cab, a one-direction or unidirectional flow pattern would be established.

In this recent NIOSH cooperative study, a new unidirectional filtration and pressurization system was installed in an older drill at a surface mining aggregate operation. During baseline testing on a nonunidirectional system on this drill, respirable dust concentrations inside the enclosed cab ranged from an average of 0.43 to 0.95 mg/m^3 for the three days of testing. In the final post-evaluation, the average respirable dust concentration ranged from 0.09 to 0.14 mg/m^3 for the two days of testing (Cecala et al., 2009). There were two sampling locations inside this enclosed cab, one high in the cab and the other near the floor of the cab, to determine if there were differences in the dust at these two levels. The results of this testing showed that there was not a significant statistical difference between the two in-cab sampling locations, although it was believed that the cab door being opened for a substantial time period throughout the workday had a significant impact on these results.

The filtration and pressurization system designed by J.H. Fletcher & Company for its enclosed cab uses a modified unidirectional design. The clean filtered air is discharged into the enclosed cab at the midlevel of the cab and is directed upwards toward the roof or the ceiling of the cab, while the recirculation pickup point is near the floor of the cab. This should create a circular airflow pattern to maintain clean filtered air at the top of the cab, and in the breathing zone of the equipment operator, while any dust-laden air is being picked up at the recirculation intake near the floor of the cab, thus being a modified unidirectional airflow design.

System design

In the study to evaluate the newly designed filtration and pressurization system on J. H. Fletcher & Company's mining equipment, two different pieces of equipment, a face drill and roof-bolter, were chosen and evaluated at the Sidwell underground limestone mine near Zanesville, OH. The filtration and pressurization system on both pieces of equipment were almost identical units, as seen in Figs. 1 and 2. Makeup air was drawn into the system from the outside and filtered (intake filter). This filtered air then flowed down into the main heating, ventilation and air-conditioning unit (HVAC), located on the outside wall of the enclosed cab. Simultaneously, air was being drawn through the recirculation filter. Once the in-cab air flowed through the recirculation filter, it was combined with the intake air in the main HVAC unit of the system and was conditioned with either heat or cooling if necessary. This conditioned air flowed through the final filter and was then blown into the enclosed cab. The recirculation and final filter were identical on both the face drill and roof-bolter machines. The recirculation filter was 7.6 cm (3 in.) wide, 40.6 cm (16 in.) long, 5.1 cm (2 in.) deep and used filter media with a dust capture efficiency similar to the American Society of Heating Refrigeration and Air Conditioning Engineer's (ASHRAE) minimum reporting value (MERV) between 8 and 9, see Appendix B. The final filter was 28.89 cm (11.38 in.) wide, 44.45 cm (17.5 in.) long and 9.53 cm (3.75 in.) deep and had a MERV 16 filter rating.

The one aspect that was different between the filtration and pressurization unit on the face drill and roof-bolter was the intake filtering unit. Although both intake filters were rated at the MERV 16 filter efficiency level, the intake unit on the face drill was a Donaldson system, which uses a non-fan-powered filter housing referred to in this report as a static filter unit. For this design, the outside air was drawn through the intake filter (33.0 cm/ 10 in. long, 20.3 cm/ 8 in. in diameter), by the main fan on the HVAC unit. Because of this, the amount of intake airflow was completely dependent on the pressure and filter loading components of the entire system, which are the intake, recirculation and final filters.

The intake unit of the roof-bolter was a Sy-Klone International RESPA unit, which is a fan-powered unit. The RESPA unit uses a design that brings the outside air into the unit and causes it to travel through two parallel powered air pre-cleaners. Each precleaner unit delivered approximately 1.13 m^3/min (40 cfm) of air, making the potential makeup air quantity total roughly 2.27 m^3/min (80 cfm). These precleaners use a centrifugal design to spin off the larger dust particles (> 5.0 microns). After the centrifugal precleaner units, the air then passes through a canister filtering cartridge 33.0 cm (13 in.) long and 20.3 cm (8 in.) in diameter. The centrifugal precleaning technique reduces the amount of dust loading on the intake filter, potentially increasing the lifespan of the filter. Once the air passes through the intake canister filter, the air then combines with the recirculation air at the main HVAC unit. This is the same as on the face drill unit.

Testing

The objective of this research study was to determine the improvement in the air quality inside the enclosed cab on two pieces of mobile equipment with the newly designed filtration and pressurization system. To properly evaluate this system, airflow, dust and pressure monitoring needed to be performed. The following are the sampling procedures used in this long-term evaluation of the newly designed filtration and pressurization system on the face drill and roof-bolter machines at the Sidwell limestone mine.

Air volume measurements. In order to evaluate the effects of filter dust buildup/cake, airflow readings were taken for the intake and recirculation component on the filtration and pressurization system on both the face drill and roof-bolter units. These airflow measurements were taken with two different measuring devices. For the intake airflow, the measurements were taken with a Velocicalc air velocity meter, model 9555 (TSI Incorporated, Shoreview, MN). This instrument has the capability to input the duct type and size and then record one-minute averages. Three separate one-minute averages were taken to determine a consistent value, and then these three values were averaged together for the final intake air volume. For the recirculation component, measurements were taken with a vane anemometer (Davis Instruments, Vernon Hills, IL). A stopwatch was used to take one-minute averages and, once again, three one-minute readings were averaged together to obtain the final value. Since this was a manual reading with the vane anemometer, the average air velocity value was then multiplied by the area of the recirculation filter (0.00935 m^3 (0.33 ft^2)) through which the in-cab air was drawn to determine the recirculated air volume.

Particle count measurement testing. In order to determine the effectiveness of the cab to eliminate dust as the filters became loaded with dust and diesel particulate, nonproduction stationary machine cab testing (referred to in this report as static cab testing) was performed during each field survey using particle count instruments. This static testing was performed outside the underground limestone mine, using an unoccupied cab with the machinery idling. The filtration and pressurization system was on and the fan speed was set to "high." Two 30-min tests were performed on each cab. In the first test, one particle count instrument was located inside the enclosed cab and the other was located on the outside of the cab. One-min averages for both particle count instruments were recorded. After the 30-min run, the instruments were switched and the test was repeated. The Protection Factor results presented for each cab were determined by averaging the last 15 min of the inside and outside cab concentration data collected with both instruments from the two 30-min test runs. The first 15 min of run test data was excluded to ensure that inside cab particle count concentrations reached a stable equilibrium condition after the door was closed. The particle count instruments used for this study were ARTI HHPC-6 particle counting instruments (Hach Ultra Analytics, Grants Pass, OR). These instruments have six different particle count ranges as follows: 0.3-0.5 μm, 0.5-0.7 μm, 0.7-1.0 μm, 1.0-3.0 μm, 3.0-5.0 μm and > 5.0 μm. The values for each of these six different ranges are stored in the instrument's internal datalogger and then downloaded to a laptop computer for each day of testing. The 0.3-1.0 μm size range was used for the protection factor calculations, because most of the ambient air particles resided in this size range and thus provided the most accurate analysis.

Respirable dust testing. To determine the reduction in respirable dust levels inside the enclosed cab with the newly designed filtration and pressurization system, the following sampling setup was used. Two dust sampling locations were monitored, one inside the enclosed cab and the other on the outside of the cab. Obviously, the inside location would provide the respirable dust exposure for the equipment operator. This would then be compared to the respirable dust concentration on the outside of the enclosed cab. All dust sampling instrumentation was placed on a sampling rack for each sampling location. Both of these sampling racks were composed of three gravimetric samplers and an instantaneous respirable dust monitor.

The three gravimetric samplers were located side-by-side on the sampling rack to provide an average respirable dust concentration using this technique at both sampling locations. Escort Elf (Zefon International Inc., Ocala, FL) sampling pumps were used 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 industry (Mine Safety and Health Administration, 1990). Dust samples were collected with a 10-mm (0.4-in.) Dorr-Oliver cyclone, which classifies the respirable portion of dust, then deposited on a polyvinylchloride 37-mm (1.5-in.) filter (SKC Inc., Eighty-Four, PA). Filters were pre- and postweighed to the nearest 0.001 mg on a microbalance in a temperature/humidity controlled weighing room at NIOSH's Pittsburgh location. All sampling pumps were also postcalibrated to ensure that an acceptable flow rate of 1.7 L/min (+/- 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, which was then applied to all field gravimetric measurements.

All instantaneous respirable dust measurements were taken with personal Data RAM (pDR 1000) instruments (Thermo Fisher Scientific Corp., Waltham, MA). This is a real-time aerosol monitor that measures the respirable dust concentration based upon the light scatter of particles that are drawn in and travel through an internal sensing chamber. The respirable dust levels are recorded on an internal data logger every 10 seconds and were downloaded to a laptop computer at the end of each day of testing. All pDR-1000 units were operated in the passive mode, in which dust particles flow through the sampling chamber by exterior airflow currents.

The average respirable dust concentration measured by the three gravimetric samplers was compared to the instantaneous respirable dust concentration, as measured by the pDR monitor for the exact sampling time period. A correction factor was then calculated by dividing the pDR average concentration value into the gravimetric value. This calculated correction factor was then multiplied by all the individual dust measurements taken with the pDR device in an Excel spreadsheet. Using both types of respirable dust monitoring equipment provided a good profile of the dust concentrations throughout testing, as well as variations and changes in respirable dust concentrations throughout each day.

Pressure measurements. All cab pressure measurements were taken with DP-CALC Micromanometers, Model 5825 (TSI, Incorporated, Shoreview, MN). These pressure measurements were taken every minute and recorded on the unit's internal datalogger. After each day of testing, this information was downloaded to a laptop computer and stored as an Excel data file. This pressure measurement provided the necessary data to determine when the door on the enclosed cab was opened for any significant time period. Obviously, during the times when the door is open, dust and contaminants from the mine are able to enter the enclosed cab and cause higher respirable dust readings. When this occurs, it does not provide an accurate indication of the effectiveness of the filtration and pressurization system.

Test plan. When this study was initiated in November 2010, new intake, recirculation and final filters were placed in the filtration system of both the face drill and roof-bolter machines. Airflow and particle count measurements were taken on both pieces of equipment before they were taken underground and exposed to any dust. Then, three consecutive days of underground testing were performed in which both dust and pressure data were obtained. After these three days of testing were completed, airflow measurements on both filtration and pressurization systems were taken again. Regular return trips were scheduled to the mine to perform additional tests to evaluate changes in the filtration and pressurization systems as they loaded with dust and diesel particulate.

For each of these return tests, the first task was to perform airflow and particle count measurements under static testing conditions. For this static testing, the machines were located either outside the mine or in the shop area, depending on weather conditions. During this testing, the machines' engines would be idling, with the filtration and pressurization unit fan on the "high" fan speed. Particle count measurements were taken on one of the cabs, while the airflow measurements were being made on the other cab. At this point, the engine hours on both pieces of machinery were recorded. The engine hours is an important factor when considering the degradation in airflow as the filters load with dust and diesel contaminants, because it provides a measure of the amount of use for each piece of equipment. After the static testing was completed, the following day was comprised of a full shift of testing in the underground limestone mine.

This test sequence continued through July 2011 with the time between tests varying between three and six weeks, based on the scheduling and availability of the researchers. During any return test, if it was determined that the air volume had decreased to an unacceptable level, new filter(s) would be added to the filtration and pressurization system and the analysis continued.

Results

The results of this study were evaluated using different instrumentation and techniques. Seventeen different tests were performed that spanned a nine-month time period from November 2010 through July 2011. This time span provided for the entire spectrum of temperature extremes for seasonal variation, including both winter and summer test conditions.

The first static test performed in November 2010 provided airflow baseline values, since the system contained all new system filters (intake, recirculation and final). The filtering efficiency is not normally as high with new filters compared to subsequent tests, when the filters are loaded with dust and diesel contaminants. Figure 3 provides the values obtained for this static testing for the face drill and roof-bolter machines, respectively. Particle count testing was not performed at the 174- and 726-hour operating time periods for the face drill, and at the 106-hour operating time period for the roof-bolter, due to various operational factors. When viewing this graph, the first point that is obvious is the substantial protection factors achieved by the filtration and pressurization system on both pieces of equipment. Protection factors were determined from the cumulative 0.3 to 1.0 μm particle size range data, which is a good representative size range of respirable dust and diesel particles reaching the inner regions of the lungs, and thus harmful to a worker's health. As speculated, the lowest protection factor values obtained for the entire test period were the values of 132 and 72 for the face drill and roof-bolter machine, respectively, and were collected on the first day of testing, when all the filters were new.

It is interesting to note that after only eight hours of use on the face drill, the protection factor went up to 367. Similarly, the roof-bolter machine's protection factor increased to 451 within 18 hours of use. For the entire test period, the protection factor values varied somewhat, but always remained at high values. It can also be noted that the average value for both the face drill and roof-bolter machine was a protection factor of over 1,000. Again, it must be remembered that these values were obtained at optimum steady-state conditions without any disruptions to the system, which is not the case when testing with an equipment operator in an underground environment.

The *x* axis on both graphs in Fig. 3 represents the hours of use for each piece of equipment for each test. Obviously, this is a very important factor to consider, because it provides an indication of the amount of dust loading on the filters based upon how much the equipment was used. At the end of testing, this value showed that the face drill was used significantly more than the roof-bolter machine with 1,132 hours of use for the face drill, as compared to 841 hours for the roof-bolter machine. The limestone mine had another wire cable roof-bolter machine, periodically used in place of the roof-bolter machine used for this study, and this was the main factor that accounted for the approximate 300-hour difference between the two pieces of equipment.

One point to note for both the face drill and roof-bolter machine is the rapid decline in recirculation airflow shortly after testing began. When evaluating the airflow for both filtration and pressurization systems, it is best to consider each piece of equipment separately. Since the face drill and roof-bolter had different intake unit filtering systems, as previously discussed in the system design section, this significantly impacted the intake airflow as the test progressed and filters loaded with dust, as well as the airflow for the entire filtration and pressurization system.

When the recirculation airflow decreased into the 0.85-to-

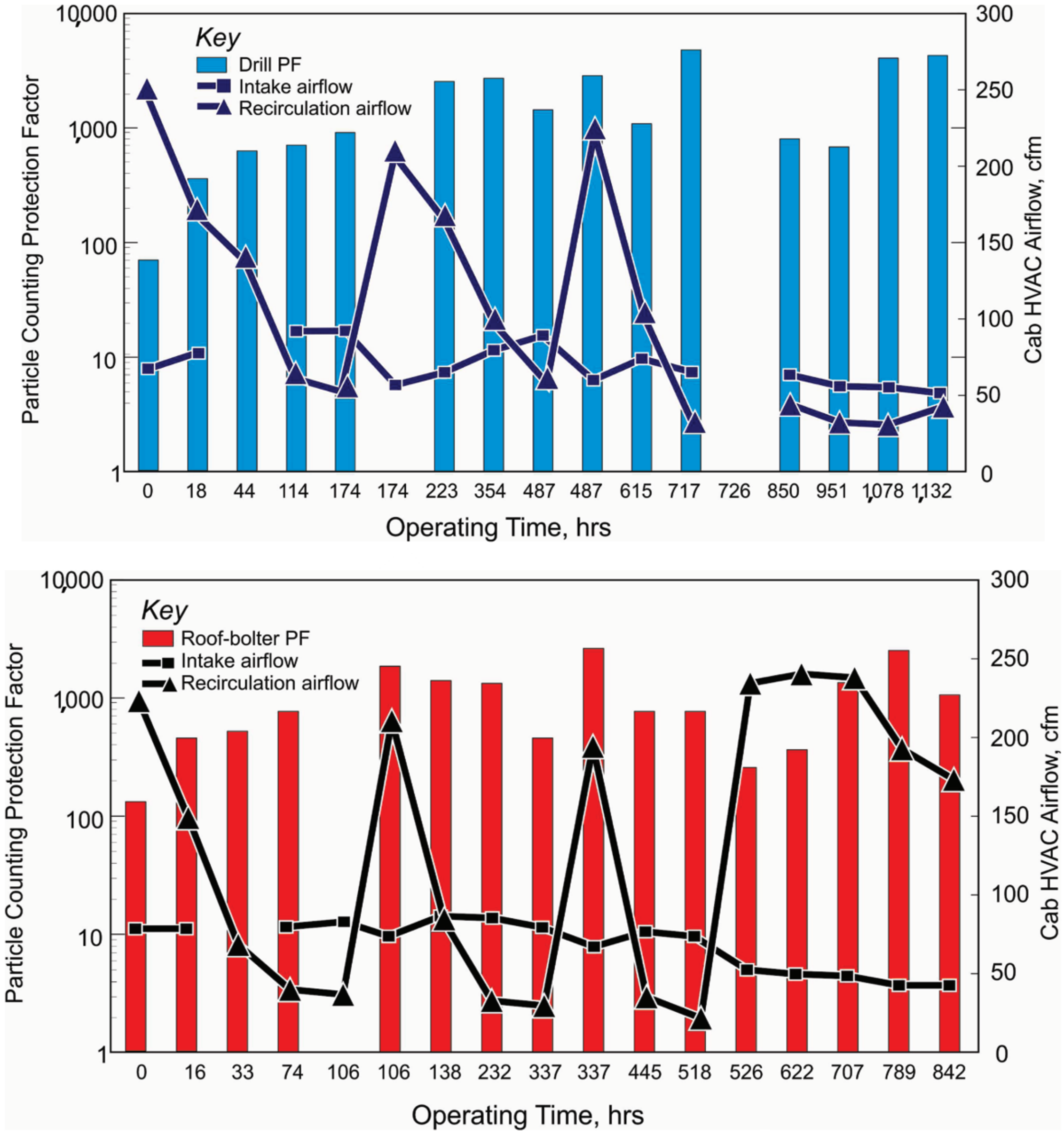

Figure 3 — Protection factor obtained with particle count instruments, as well as intake and recirculation airflow for the filtration and pressurization system on the face drill and roof-bolter machines.

1.70 m^3/min (30-to-60 cfm) range, a new recirculation filter was installed without changing the intake or final filters. This first occurred at the 174- and 106-hour mark for the face drill and roof-bolter machines, respectively. When the new recirculation filters were installed, both systems' airflow returned very close to the initial levels seen with all (three) new filters. Since only the recirculation filter was changed, this indicated very little loading impact on the intake and final filters. One would assume there would be insignificant loading on the final filter, since it functions as a backup filter within the system's design. This cycle quickly repeated itself, with the recirculation airflow dropping off rapidly and then being replaced again at the 447- and 337-hour mark for the face drill and roof-bolter machines, respectively.

At this point, another approach was tried. Since it appeared that only the recirculation filter was loading quickly and needed to be changed, the recirculation filter was removed from the system to determine the effect. This was thought to be a viable option because any dust or diesel contaminant in the enclosed cab from the door being opened or from any potential leakage points would ultimately be removed as the recirculated air flowed through the final filter before being delivered back into the enclosed cab. In theory, there should not be a substantial amount of contaminants inside the enclosed cab, although it was surprising how quickly the recirculation filter became restricted, causing the airflow to drop off. This modification was discussed with both J.H. Fletcher & Company and the Sidwell limestone mine and then tried at the 726- and 526-hour mark for the face drill and roof-bolter machines, respectively.

During this modification, the recirculation filter was removed from both filtration and pressurization systems, and new intake and final filters were installed. The modification was made on the roof-bolter system without any problem. This system had a powered intake air circuit so removing the recirculation filter did not create a condition where air was preferentially drawn through the recirculation duct. Airflow measurement

Table 1 — Average respirable dust concentrations inside and outside the enclosed cab, and the corresponding protection factor for the face drill and roof-bolter machines for each test.

Face drill				Roof-bolter			
Hours of use	Outside concentration, mg/m³	Inside concentration, mg/m³	Protection factor	Hours of use	Outside concentration, mg/m³	Inside concentration, mg/m³	Protection factor
0	2.18	0.11	20	0	0.45	0.06	8
9	1.12	0.04	28	8	1.61	0.12	13
18	5.43	0.60	9	16	1.70	0.18	9
44	4.05	0.21	19	33	1.18	0.09	13
114	0.91	0.45	2	74	NA	NA	NA
174	2.21	0.47	5	106	1.25	0.20	6
223	0.65	0.32	2	138	0.16	0.05	3
354	0.71	0.10	7	232	0.27	0.04	6
487	0.93	0.14	7	337	0.43	0.14	3
615	1.95	0.32	6	445	1.27	0.15	8
726	3.63	0.07	52	518	0.51	0.05	10
730	3.98	0.05	80	526	1.60	0.18	9
733	5.54	0.08	69	542	0.57	0.05	11
850	3.25	0.05	65	622	1.42	0.31	5
951	2.82	0.05	56	707	0.78	0.09	9
1078	0.74	0.15	5	789	NA	NA	NA
1132	1.16	0.03	39	842	0.63	0.11	6
Average	**2.43**	**0.19**	**28**	**Average**	**0.92**	**0.12**	**8**

and particle count testing was once again performed before the machine was tested in the underground environment, identical to the start of the test. When the modification was performed on the face drill, it was determined from the air measurements that there was not a sufficient intake air quantity being delivered and the modification was abandoned.

The modification of removing the recirculation filter on the roof-bolter unit was possible because the system used a powered intake unit. This intake unit had two parallel powered air precleaners, to centrifugally spin off oversized dust particles greater than 5.0 μm. Our calculations indicated that of the air brought into the unit, approximately 50% was discharged back into the atmosphere with the oversized dust particles and the remaining air then blown into the intake filtering unit. Although a wide range of different efficiency filters were available, from a mid-MERV rating all the way to a HEPA-level filter, for this testing it was decided to go with a MERV 16 efficiency filter, Appendix B. As seen in Fig. 3, the intake airflow was consistent for the entire test period and ranged from 1.13 to 2.44 m^3/min (40 to 86 cfm), with the average value being 1.93 m^3/min (68 cfm). Even after the modification to remove the recirculation filter at the 526-hour test, the intake airflow only dropped marginally for the four additional tests, which accounted for 316 hours of use. An additional benefit with this change was the increase in the recirculation airflow. The recirculation airflow prior to the change was at 0.59 m^3/min (21 cfm) and this increased to 6.66 m^3/min (235-cfm) after the modification. For the four subsequent tests, the recirculation airflow was 6.80, 6.80, 5.47 and 4.90 m^3/min (240, 240, 193 and 173 cfm), respectively. As shown in the NIOSH laboratory study, a substantial amount of recirculation airflow is a great benefit to any filtration and pressurization system (Organiscak and Cecala, 2008a, b).

Similar to the start of testing, the initial protection factor on the roof-bolter machine for this modified test was 250, as determined with particle count instruments for the 0.3-to-1.0 micron range. Once again, this was the lowest protection factor for measurement with the modification, and subsequent tests indicated protection factors ranging from 350 to more than 1,000, as the filters loaded with particulate and became more efficient. The original test on the roof-bolter was performed for five months with 526 hours of use on the machine. After the modification, testing was performed for another four months, which accounted for an additional 316 hours of use on the unit.

When the modification was performed on the face drill at the 726-hour mark, the average intake airflow decreased to slightly less than 0.57 m^3/min (20-cfm). In any ventilation system, air is drawn from the point(s) of least resistance, and this modification caused the overwhelming majority of air to be drawn from the recirculation entry area within the cab, as there was less resistance with the recirculation filter removed. A certain level of intake/outside air is necessary to replace the carbon monoxide exhaled from a worker; thus, from a safety standpoint, it was determined that a passive intake air system on the face drill machine was not capable of handling this modification. Since 0.57 m^3/min (20-cfm) was not an acceptable nor a safe amount of outside intake air being brought into the enclosed cab, the modified test had to be abandoned on the face drill and the unit was returned to its original state.

Although the protection factors obtained for the face drill and roof-bolter machines during static testing with the particle count instruments indicated substantial levels, determining the results during actual mining is the level realized by the equipment operators. Table 1 provides the average respirable dust concentrations inside and outside of the enclosed cab for both pieces of equipment for each day of testing through the entire evaluation using both gravimetric dust sampling instruments. This table also provides the calculated protection factor, so that these values can be compared with the static testing.

When comparing these protection factor values for static versus in-mine testing for both the face drill and roof-bolter machines, the in-mine values are substantially lower. This is to be expected, because for the static testing there were absolutely no disturbances after the particle counting instruments were placed inside the enclosed cab and the door was closed. For the in-mine testing, numerous factors affected the dust concentrations inside the enclosed cab. It is believed that the greatest factor was the cab door being opened and closed with the ingress and egress of the equipment operator in the enclosed cab. In addition, there were also times when the researchers performing this study would enter the enclosed cab to check on the sampling equipment or when the cab door would be opened by the equipment operator to communicate with others outside the mobile equipment.

In addition to the door being opened and allowing dust to enter the cab, there are also in-cab dust sources. The most common in-cab dust sources are dust on the cab walls, on the cab floor and on the operator's chair or seat. This dust can become liberated and dispersed by the equipment operator and from the vibration of the equipment. One other common in-cab dust source is from dust on the equipment operator's clothing, which can be liberated from normal movement of the equipment operator performing his work duties. Dust allowed to enter the enclosed cab from the door being opened or from the in-cab dust sources validates the importance of filtering the cab air, and thus, the recirculation component to any filtration and pressurization system. Even though the in-mine protection factor values were much lower than the static values, they still indicated the protection that was provided to both the face drill and roof-bolter operator from this newly designed filtration and pressurization system.

Discussion

For this long-term evaluation on the new filtration and pressurization system, the most accurate method to determine the ultimate effectiveness of the system was the static testing performed with the particle count instruments. Obviously, these particle count measurements of the protection factor are under ideal steady-state test conditions without any changes or disruptions to the filtration and pressurization system or to the enclosed cabs (door remained closed). Once the door was closed, the system should come to a steady-state condition relatively quickly.

When the weather permitted, this testing was performed in natural outside conditions at a location that was relatively close to the entrance to the limestone mine. For a number of winter months (December 2010 through March 2011), this particle count testing was performed inside the mine's maintenance shop areas after the completion of the daylight shift, when all the maintenance workers had departed for the day. As seen in Fig. 3, the protection factors obtained for both the face drill and the roof-bolter were extremely high and ranged from near 100 to well over 1,000. These particle count measurements also allowed for the analysis of the system's effectiveness in a number of different size distribution ranges. This provides the most accurate indication of improvement in air quality inside the enclosed cab from the filtration and pressurization system. When the machinery was outside for this testing, it is possible that some dust may have been blown inside the enclosed cab from the wind and this could account for some of the fluctuations in the protection factor values. Even with the fluctuations, these particle count measurements definitely show the effectiveness of the filtration and pressurization systems on both pieces of equipment to lower respirable dust levels inside the enclosed cab, and, thus, the potential to protect the equipment operators under ideal conditions.

The in-mine testing results also showed substantial protection factor values, but these values were significantly lower than those for the static testing. This is to be expected during actual testing underground, when various factors and conditions occur that allow dust to enter or to be liberated inside the enclosed cab. This was most evident on a day when a new roof-bolt operator was being trained. During this training, the cab door was left open for significant periods of time so that the trainee, who was inside the cab, and the trainer, who was standing outside, could communicate.

Another notable situation occurred on the test day of the 615-engine-hour mark for the face drill, when one of the NIOSH researchers entered the enclosed cab and determined that the pressure monitor was reading 0.0 inches static pressure. Upon a quick analysis of the situation, it was determined that the filtration and pressurization system was not operating. The researcher turned the HVAC/filtration and pressurization unit on and immediately noticed the cab pressure increased to normal operating pressure levels. At the end of the day, the researcher informed the equipment operator of the situation and instructed him that he needed to ensure that the unit was operating, because he would be exposed to outside respirable dust concentrations without the unit running. The operator was instructed to control the fan speed between the three operating conditions (high, medium and low), as well as controlling the temperature setting in order to obtain cooling or heating. Again, the face drill operator was informed that he needed to at least have the fan setting on low, or the filtration and pressurization would not be operating, and he would not be provided with clean filtered air. From this test forward, in-cab respirable dust levels on the face drill were significantly lower and remained at levels that were 50% or more lower than the in-cab dust values for this day of testing. It is possible that before this time the face drill was being operated for time periods without the filtration and pressurization system operating.

The situation of the filtration and pressurization not being turned on by the face drill operator indicated a critical flaw in the system. After this occurred, this situation was discussed with J.H. Fletcher & Company and a modification was performed on both the face drill and roof-bolter to start the filtration and pressurization system when the machinery was started. It should be noted that any filtration and pressurization system should operate automatically as soon as the machinery is started. The equipment operator should not have the ability to turn off a system that is designed to improve the air quality and, thus, protect the health of the worker. The only aspects that the operator should have the ability to control are the fan speed setting and the temperature control setting. It is anticipated that J.H. Fletcher & Company will incorporate this modification in all future systems placed in its machinery.

As mentioned in the system design section regarding variations in the protection factor based upon the outside dust concentration, the most important factor to consider is the actual air quality, or dust concentration that the equipment operator is exposed to inside the enclosed cab. Figure 4 shows the average respirable dust concentration inside the enclosed cab for the face drill and roof-bolter machines for the 17 different sampling days. This figure shows some variation in these respirable dust levels, but all levels remained below 0.62 mg/m^3, with the average inside respirable dust concentration being 0.19 and 0.12 mg/m^3 for the face drill and roof-bolter, respectively. This provides the truest indication of the protection

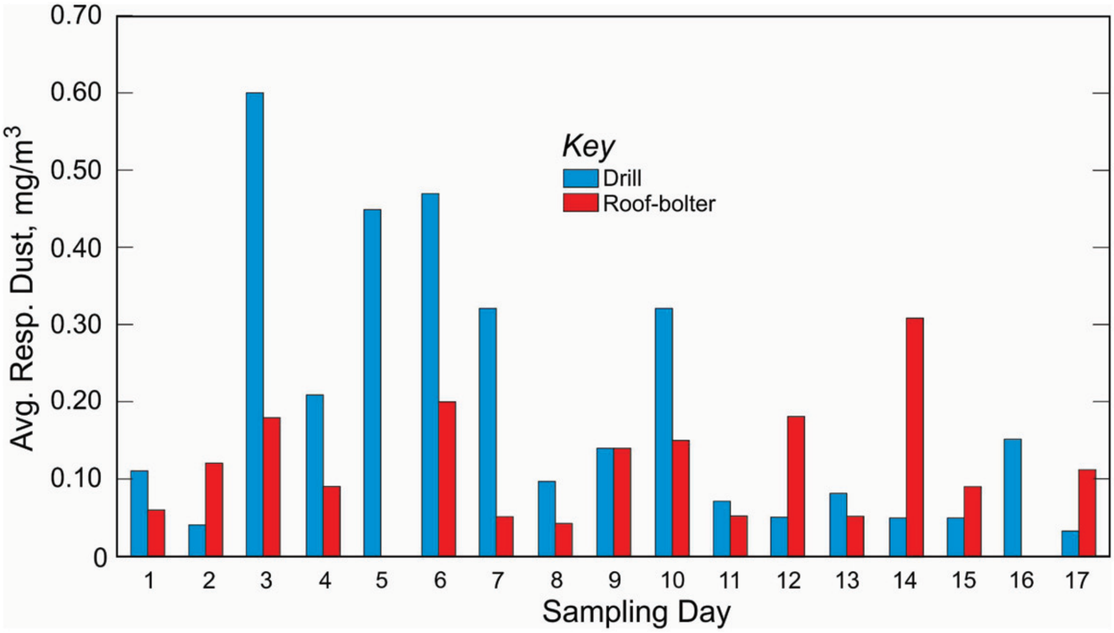

Figure 4 — Average respirable dust concentration inside the enclosed cab for both the face drill and roof-bolter machines for each day of testing.

to the equipment operators while working inside the enclosed cab during actual mining conditions.

As stated in the test setup section, an electronic micromanometer pressure instrument was located in both the face drill and roof-bolter machines to provide the cab pressure with the filtration and pressurization system. The positive port on the pressure instrument was open to the inside of the cab, while a section of tygon tubing extended from outside the enclosed cab to the negative port on the instrument located on the inside. The micromanometer instrument then provided a visual display, as well as recorded one-minute averages of the cab pressure. This cab pressure provided a record of when the cab door was closed and the inside pressure was positive, as well as when the door was open and the pressure went to zero. By identifying the time periods when the pressure was positive and zero, the respirable dust concentrations measured with the pDR1000 instruments were able to be time-weighted averaged for those time periods when the door was open or closed.

Table 2 shows the calculated results for the average respirable dust concentrations from the face drill and roof-bolter when the cab door was open and closed for each day of testing. Obviously, there are substantial variations for both the face drill and the roof-bolter on each of the test days, but in every case, the respirable dust concentrations inside the enclosed cab when the door was closed were significantly lower than when the door was opened. There is a possibility that the majority of time when the door was open, the machinery was not even being operated, and thus not generating dust. However, this further shows the importance and protection of an effective filtration and pressurization on the enclosed cab. The respirable dust concentration for the face drill and roof-bolter averaged 0.05 and 0.08 mg/m^3, respectively, when the cab door was closed, thus further showing the tremendous reduction in the respirable dust levels with

Table 2 — Average respirable dust concentration for the face drill and roof-bolter for each day of testing for time periods when the cab door was open and when it was closed.

Test	Face drill		Roof-bolter	
	Open, mg/m^3	Closed, mg/m^3	Open, mg/m^3	Closed, mg/m^3
1	0.14	0.02	0.09	0.03
2	0.81	0.29	0.13	0.00
3	0.36	0.01	0.23	0.12
4	0.29	0.10	0.12	0.00
5	0.51	0.03	NA	NA
6	0.32	0.04	0.22	0.12
7	0.43	0.00	0.05	0.04
8	0.24	0.01	0.05	0.03
9	1.03	0.04	0.18	0.11
10	0.23	0.13	0.11	0.06
11	0.33	0.05	0.05	NA
12	0.20	0.01	0.45	0.34
13	0.23	0.02	0.05	NA
14	0.41	0.02	0.19	0.05
15	0.05	0.02	0.08	0.04
16	0.09	0.08	NA	NA
17	0.02	0.02	0.04	0.03
Average	**0.33**	**0.05**	**0.14**	**0.08**

Figure 5 — Top picture shows final filter damaged during installation; bottom picture shows screening placed over filter media which eliminated filter damage during installation.

the filtration and pressurization system and providing an even closer indication of the effectiveness determined by the particle count instruments under static test conditions.

Throughout the course of any research effort into new control technology or systems, there are always areas that can be identified for improvement. One area identified early on in this research effort was how easily the final filters were damaged during installation. The filter housing unit for the final filter was designed to provide a tight fit to minimize any air leakage around the filter. Because of this tight fit, several new filters were damaged during installation, with holes observed through the filter media. Obviously, any time there is a hole in the filter, this would provide a path of least resistance for dust particles to travel directly through the hole without being filtered. When this situation was brought to the attention of the J.H. Fletcher & Company, the company contacted its filter manufacturer and had screening placed over the filter. Figure 5 shows an example of a final filter damaged sometime during installation, and an improved filter design with screening over the filter media, which eliminated damage occurring during installation. All subsequent testing showed that the screening eliminated damage to the filter during installation and quickly corrected this problem.

Another area identified during this testing that would be beneficial to this or any filtration and pressurization system is some type of cab pressure indicator to inform the operator when there is a problem with the system. As previously discussed, during one day of testing, the equipment operator was operating the equipment, but did not realize that the filtration and pressurization system was not operating because of noise occurring in the underground environment. The following is a list of potential occurrences that could significantly impact a filtration and pressurization system's ability to provide clean filtered air to an enclosed cab and protect the equipment operator:

- The filtration and pressurization system is not operating.
- Either the intake or the recirculation component of the system is not operating properly.
- The HVAC component of the system is not operating properly.
- Either the intake, recirculation or final filter is clogged and needs to be replaced.
- The intake, recirculation or final filter has been damaged and is not filtering properly.

If some type of pressure monitoring device could be implemented in enclosed cabs of machinery that have a filtration and pressurization system, and that device could provide a visual indication to the equipment operator of a potential problem with the system, it would be of great benefit for ensuring the long-term effectiveness of these systems.

Conclusions

A long-term study was performed to evaluate the effectiveness of a newly designed filtration and pressurization system for underground mobile mining equipment. This study was performed on a face drill and a roof-bolter machine and showed that the system significantly lowered respirable dust concentrations inside the enclosed cabs, thus improving the air quality for the equipment operators. The evaluation demonstrated a significant reduction in dust levels when comparing outside to inside cab respirable dust concentrations for both static and in-mine testing. For static testing, protection factor values were always greater than 100, and, in many cases, they were in the 1,000 range, indicating a tremendous improvement in the cab air quality. During underground in-mine testing, respirable dust measurements also indicated substantial improvements, but the protection factor levels were significantly lower than the static testing values.

When evaluating the dust levels in the enclosed cabs during periods when the cab door was closed and positive cab pressure was achieved, the average respirable dust concentrations for the entire evaluation averaged 0.05 and 0.08 mg/m^3 for the face drill and the roof-bolter, respectively. These low respirable dust concentrations also indicate the effectiveness of the newly designed filtration and pressurization system during actual mining operations.

One area that was identified for improvement on the system was that the recirculation filter loaded much too quickly and needs to be resized to significantly increase the surface area. Alternatively, the filter could be eliminated when used with a powered intake air system, to ensure that an acceptable amount of outside/intake air is always entering the enclosed cab. The latter modification was tried for a four-month trial and appeared to be a viable solution.

This long-term study showed that the newly designed filtration and pressurization system significantly reduced respirable dust levels in the enclosed cabs of the face drill and roof-bolter machines used in this testing, significantly improving the air quality, and thus having the potential to improve the health of all miners working in enclosed cabs of mobile mining equipment with these systems.

Disclaimer

Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Acknowledgments

We would like to acknowledge Doug Hardman, president, J.H. Fletcher & Company for his initiation of this cooperative research study. We would also like to acknowledge and thank Sean Farrell, product engineer, and Ward Morrison, product manager, Rock & Industrial Mineral Products, J.H. Fletcher & Company, and Ted DiNardo, mine manager, Jay White, roof-bolter operator, and Jerry Siddle, drill operator, with Sidwell Mining Equipment Company, for their cooperation and assistance during this research effort. Their cooperation and dedication was instrumental in the success of this study.

References

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

Cecala, A.B., Organiscak, J.A., Heitbrink, W.A., Zimmer, J.A., Fisher, T., Gresh, R.E., and Ashley, J.D. II, 2004, "Reducing enclosed cab drill operator's respirable dust exposure at surface coal operations with a retrofitted filtration and pressurization system," *2003 Transactions*, Vol. 314, Society for Mining, Metallurgy, and Exploration, Inc., pp. 31–36.

Cecala, A.B., Organiscak, J.A., Zimmer, J.A., Heitbrink, W.A., Moyer, E.S., Schmitz, M., Ahrenholtz, E., Coppock, C.C., and Andrews, E.H. 2005, "Reducing enclosed cab drill operator's respirable dust exposure with effective filtration and pressurization techniques," *Journal of Occupational and Environmental Hygiene*, Vol. 2, pp. 54-63.

Cecala, A.B., Organiscak, J.A., Zimmer, J.A., Moredock, D., and Hillis, M.S. 2007, "Closing the door to dust when adding drill steels," *Rock Products*, Vol. 110, No. 10, pp.: 29-32.

Cecala, A.B., Organiscak, J.A., Zimmer, J.A., Hillis, M.S., and Moredock, D., 2009, "Maximizing air quality inside enclosed cabs with a unidirectional filtration and pressurization system," *2009 Transactions*, Vol. 326,Society for Mining, Metallurgy, and Exploration, pp.71-78.

Centers for Disease Control, 2000, "Silicosis screening in surface coal mines – Pennsylvania, 1996-1997," *Morbidity and Mortality Weekly Report*, July 12, 2000, Vol. 49, No. 27, pp. 612–615.

Chekan, G.J., and Colinet, J.F., 2003, "Retrofit options for better dust control cab filtration, pressurization systems prove effective in reducing silica dust exposures in older trucks," *Aggregates Manager*, Vol. 8, No. 9, pp. 9-12.

Mine Safety and Health Administration (MSHA), 1990, Metal, *Nonmetal Health Procedures Manual* (PH90-IV4), Chapter D, Arlington, VA.

Organiscak, J.A., and Cecala, A.B., 2008a, "Laboratory investigation of enclosed cab filtration system performance factors," *Mining Engineering*, Vol. 60, No. 12, pp.74-80.

Organiscak, J.A., and Cecala, A.B. 2008b, "Key design factors of enclosed cab dust filtration systems," Report of Investigation 9677, National Institute for Occupational Safety and Health.

Organiscak, J.A., and Cecala, A.B., 2009, "Doing the Math–The effectiveness of enclosed-cab air–cleaning methods can be spelled out in mathematical equations," *Rock Products*, October, pp. 20–22.

Organiscak, J.A., Cecala, A.B., Thimons, E.D., Heitbrink, W.A., Schmitz, M., and Ahrenholtz, E., 2004, "NIOSH/Industry collaborative efforts show improved mining equipment cab dust protection," *2003 Transactions*, Vol. 314, Society of Mining, Metallurgy and Exploration, Inc., pp. 145–152.

Appendix A — Summary of results of field studies evaluating upgraded cabs (Organiscak et al., 2004; Chekan and Colinet, 2003; Cecala et al., 2005; Cecala et al., 2004).

Cab being evaluated	Cab pressure, inches, wg	Average inside cab dust level, mg/m^3	Average outside cab dust level, mg/m^3	Protection factor, out/in
1. Rotary drill	None detected	0.08	0.22	2.8
2. Haul truck	0.01	0.32	1.01	3.2
3. Front-end loader	0.015	0.03	0.30	10.0
4. Rotary drill	0.20 to 0.40	0.05	2.80	56.0
5. Rotary drill	0.07 to 0.12	0.07	6.25	89.3

Appendix B — MERV rating efficiency values for three size range dust particles. Minimum efficiency reporting values (MERV) according to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Group	MERV rating	Average particle size efficiency (PSE) 0.3 - 1.0 microns	Average particle size efficiency (PSE) 1.0 - 3.0 microns	Average particle size efficiency (PSE) 3.0 - 10.0 microns
1	1			< 20%
	2			< 20%
	3			< 20%
	4			< 20%
2	5			20 - 34.9%
	6			35 - 49.9%
	7			50 - 69.9%
	8			70 - 84.9%
3	9		< 50%	≥ 85%
	10		50 - 64.9%	≥ 85%
	11		65 - 79.9%	≥ 85%
	12		80 - 89.9%	≥ 90%
4	13	< 75%	≥ 90%	≥ 90%
	14	75 - 84.9%	≥ 90%	≥ 90%
	15	85 - 94.9%	≥ 90%	≥ 90%
	16	≥ 95%	≥ 95%	≥ 95%