Published in final edited form as:
Min Eng. 2014 February ; 66(2): 45–52.

Effects of MERV 16 filters and routine work practices on enclosed cabs for reducing respirable dust and DPM exposures in an underground limestone mine

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Abstract

An effective technique to minimize miners' respirable dust and diesel exposure on mobile mining equipment is to place mine operators in enclosed cabs with designed filtration and pressurization systems. Many factors affect the performance of these enclosed cab systems, and one of the most significant factors is the effectiveness of the filtration system. High-efficiency particulate air (HEPA)-type filters are typically used because they are highly efficient at capturing all types and sizes of particles, including those in the submicron range such as diesel particulate matter (DPM). However, in laboratory tests, minimum efficiency reporting value (MERV) 16 filters have proven to be highly efficient for capturing DPM and respirable dust. Also, MERV 16 filters can be less restrictive to cab airflow and less expensive than HEPA filters. To verify their effectiveness in the field, MERV 16 filters were used in the enclosed cab filtration system on a face drill and roof bolting mining machine and tested at an underground limestone mine. Test results showed that DPM and respirable dust concentrations were reduced by more than 90% when the cabs were properly sealed. However, when the cab door was opened periodically throughout the shift, the reduction efficiency of the MERV 16 filters was reduced to 80% on average.

Introduction

A goal of the U.S. National Institute for Occupational Safety and Health (NIOSH) is to reduce respirable dust and diesel particulate matter (DPM) exposures for mine workers, since both substances can cause adverse health effects (CDC, 2000; Colinet et al., 2010; NIOSH, 1988; EPA, 2002; Pope et al., 2002; Ris, 2007; Kahn et al., 1988; Wade and Newman, 1993). Respirable dust containing silica, present in many mines, has been linked to the development of silicosis and lung cancer (CDC, 2000; Colinet et al., 2010), and DPM has been classified as a potential occupational carcinogen by the U.S National Institute for Occupational Safety and Health (NIOSH) and as likely to be carcinogenic to humans by the U.S Environmental Protection Agency (EPA) (NIOSH, 1988; EPA, 2002; Pope et al., 2002;

Disclosure
Mention of a company name or product does not constitute an 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.

Ris, 2007). This can be a real concern for underground miners since they are exposed to some of the highest levels of DPM of any workers in the country (EPA, 2002; Watts, 1995; MSHA, 2001; MSHA, 2006).

One method for reducing miners' exposures to dust and DPM is to use enclosed cabs with filtration and pressurization systems in mobile mining equipment (Cecala et al., 2001, 2003, 2005, 2007, 2009, 2012; Chekan and Colinet, 2003; Organiscak and Cecala, 2008a, 2008b, 2009; Organiscak et al., 2004; Noll et al., 2012). These enclosed cabs create a microenvironment that protects workers from mine aerosol contaminants. In a properly functioning cab, a fan induces positive cab pressure and moves outside air through a filtration system where particles are collected, resulting in clean air inside the compartment where the miner is located. However, studies have shown that, in some cab systems, the workers can be exposed to elevated concentrations of dust, which can be even higher than outside the enclosed cab (Cecala et al., 2001, 2007). Some factors contributing to this phenomenon include the re-entrainment of dust from the floor and from miners' clothes inside the cab, the effectiveness of the filtration system and work practices (Cecala et al., 2001, 2007). Dust re-entrainment can be reduced with the use of a recirculation filter inside the cab (Cecala et al., 2001, 2007). When using a recirculation filter, some researchers have reported that a unidirectional filtration and pressurization airflow pattern, where the clean filtered air is brought in at or near the roof of the cab while withdrawing the recirculated air near the floor of the cab, seems to be the optimal design (Cecala et al., 2009).

HEPA (high-efficiency particulate air)-type filters are typically used in these systems because they are highly efficient at capturing all types and sizes of particles, including those in the submicron range. However, in laboratory tests, MERV (minimum efficiency reporting value, as defined by the American Society of Heating, Refrigerating and Air Conditioning Engineers) 16 filters have also proven to be highly efficient (about 96%) for capturing respirable dust and DPM. They can also be less restrictive to cab airflow and less expensive than HEPA filters (Noll et al., 2012).

This paper describes a research study investigating the effectiveness of MERV 16 filters in the field by determining the reduction of respirable dust and DPM in an enclosed cab with a unidirectional airflow design equipped with MERV 16 filters at a limestone mine. Respirable dust and DPM were measured because they possess different chemical compositions and particle sizes (more than 90% of dust particles are greater than 1 μm, while more than 90% of DPM particles are less than 1 μm). These differences can result in different capture efficiencies for a particular filter (Bugarski et al., 2011).

In addition to the filter evaluation, this paper discusses the effects of routine work practices on respirable dust and DPM concentrations inside the cab. Previous studies have shown that work practices such as opening and closing windows and doors may influence the concentration of DPM and dust inside the cabs, possibly causing some DPM concentrations to rise above the U.S. Mine Safety and Health Administration (MSHA) permissible exposure limit (PEL) of 160 $\mu g/m^3$ total carbon (*TC*) (Colinet et al., 2010; MSHA, 2001, 2006; Cecala et al., 2009, 2012; Noll et al., 2008, 2012). However, these studies did not confirm or quantify the influence of these work practices.

Methods

General procedure

The respirable dust and DPM concentrations (average over the entire shift and real-time) inside and outside of two cabs were measured while the vehicles were operating in a limestone mine. Samples were collected on 17 days over a nine-month period with sampling at least once a month. The pressure inside the cab was also monitored to determine when the cab doors were opened. A positive pressure indicated the cab was sealed (the door was closed), while a pressure reading of zero indicated the cab door was open.

The average concentrations inside and outside of the cab over the entire shift were used to calculate the total percentage of respirable dust and DPM reduced by the cab system (reduction efficiency). This total reduction efficiency could be influenced by the opening of a cab door periodically throughout the day. Therefore, the real-time data for concentrations inside and outside of the cab when positive cab pressure existed were averaged and used to determine the reduction efficiency when the cab was sealed. Both types of reduction efficiencies were compared to evaluate the influence of work practices on the concentration of dust and DPM inside the cab. In addition, the concentrations of respirable dust and DPM inside the cab were measured to determine the operators’ exposure level while performing their routine work practices.

Cab systems

In this study, face drill and roof bolter mining machines were equipped with newly designed filtration and pressurization systems as shown in Fig. 1 and evaluated at an underground limestone mine. Air was drawn into the system from the outside and filtered (intake filter). This filtered air flowed down into the main HVAC unit, located on the outside wall of the enclosed cab. Simultaneously, air was drawn through the recirculation filter and was combined with the intake air in the main HVAC unit. This conditioned air flowed through the final filter and was circulated into the enclosed cab. The recirculation and final filter were identical on the face drill and roof bolter machines. The recirculation filter had the following dimensions: 7.6 cm (3 in.) width, 40.6 cm (16 in.) length, 5.1 cm (2 in.) depth, and used filter media with a dust capture efficiency similar to the American Society of Heating, Refrigerating and Air-Conditioning Engineer's (ASHRAE) MERV between 8 and 9. The final filter was 29.9 cm (11.375 in.) wide, 44.45 cm (17.5 in.) long, 9.53 cm (3.75 in.) deep, and had a MERV 16 filter rating. Both vehicles were relatively new, with good cab integrity (good gaskets, good molding around door, etc.).

The only difference between the filtration and pressurization unit on the drill and the one on the roof bolter was the intake filtering unit. The intake unit on the face drill was a Donaldson system, which used 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 by the main fan on the HVAC unit, which can be operated at three different fan speeds. Because of this, the amount of intake airflow was completely dependent on the pressure and filter loading components of the entire system, which consisted of the intake, recirculation and final filters.

The intake unit of the roof bolter was a fan-powered Sy-Klone International RESPA-SD unit. The RESPA-SD unit uses a design that brings the outside air into the unit and causes it to travel through two powered air precleaners in series. Each precleaner unit delivers approximately 1.13 m^3/min (40 cfm) of air, making the total makeup air quantity about 2.27 m^3/min (80 cfm). These precleaners use a centrifugal design to spin off the larger dust particles (> 5.0 μm). After going through the centrifugal precleaner units, the air then passes through a canister filtering cartridge 33 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 time between filter changes. Once the intake air passes through the intake canister filter (MERV 16), the air then combines with the recirculated air at the main HVAC unit, as with the face drill unit.

DPM samplers

For DPM measurements, a sampling package was inserted inside the cabs of the roof bolter and face drill mining machines with an identical sampling package placed outside of the cabs. The sampling package contained three SKC DPM cassettes with quartz fiber filters for elemental carbon (*EC*) and total carbon (*TC*) analysis and an *EC* monitor developed by NIOSH (either the NIOSH prototype or the FLIR Airtec (Bugarski et al., 2011)) attached to a submicron impactor for real-time *EC* measurement. The flow rates of all pumps and instruments were checked and recorded. The SKC DPM cassettes were attached to 10-mm Dorr-Oliver cyclones with tubing extending from the cassette to MSA Elf pumps operated at 1.7 L/min (0.06 cfm). The SKC DPM cassette is the standard method for collecting DPM (MSHA, 2001; Noll et al., 2007) and retrieves particulate at a 0.8-μm cut point at 1.7 L/min (0.06 cfm) onto quartz fiber filters to collect DPM in the presence of dust. This sample is used to determine *EC* and *TC* concentrations via NIOSH method 5040 (Birch, 2004). The *EC* monitor measures real-time *EC* concentrations via laser absorption (Noll and Janisko, 2007).

EC and *TC* were measured since they are both used as surrogates for determining DPM exposures in underground mines (MSHA, 2001, 2006; Noll et al., 2006). In fact, for compliance sampling, MSHA first uses *TC* concentrations taken from a personal sample for determining DPM exposures (MSHA, 2001, 2006). However, *TC* can be prone to interferences from sampling artifacts, cigarette smoke and oil mist (Noll et al., 2006). A dynamic blank, as described by Noll and Birch (2008), can be used to correct for some sampling artifacts and is part of the SKC DPM cassette. However, the influence of cigarette smoke and oil mist cannot be corrected for with a dynamic blank and cannot always be avoided in the mine environment. Contrary to *TC*, *EC* is not prone to these interferences and is still a major portion of the DPM sample. Therefore, in addition to measuring *TC* from a personal sample, MSHA also uses the *EC* portion of the sample for compliance purposes. *EC* is converted to equivalent *TC* concentrations with a conversion factor as described by MSHA's Program Policy Letter No. P08-IV-01 (MSHA, 2008).

Since *EC* is not prone to interference and can be measured in real time, it was used to determine reduction efficiencies of the cab systems. *TC* measurements inside the cab were collected to determine the potential exposure of miners to DPM, since the final PEL is expressed as *TC*. *TC* concentrations were determined in two ways: (1) the *TC* from the NIOSH method 5040 sample was used after being dynamic blank corrected and, (2), the *EC* concentration was multiplied by a conversion factor of 1.3, since this factor is commonly observed in underground metal/nonmetal mines (Noll et al., 2007).

Respirable dust samplers

Determining the difference in respirable dust levels in the operator cabs was accomplished by monitoring two sampling locations, one inside the enclosed cab and the other on the outside of the cab, using standard respirable dust measurement techniques as described by Colinet et al. 2010. The inside location provides the potential dust exposure levels of the equipment operator and is compared to the dust concentrations measured outside the enclosed cab.

All sampling instrumentation was placed on a sampling rack for each sampling location. Three gravimetric samplers located side-by-side on the sampling rack provided an average respirable dust concentration at each of the sampling locations. Escort Elf (Zefon International Inc., Ocala, FL) sampling pumps were used and calibrated to a flow rate of 1.7 L/min (0.06 cfm) before each field survey (the required flow rate established by the American Conference of Governmental Industrial Hygienists for the metal/nonmetal industry (MSHA, 1990)). Respirable dust samples were drawn through a 10-mm (0.4-in.) Dorr-Oliver cyclone, which classifies the respirable portion of dust and, then, were deposited on a polyvinyl-chloride 37-mm (1.5-in.) filter (SKC Inc., Eighty-Four, PA). Filters were pre- and post-weighed to the nearest 0.001 mg on a microbalance in a temperature/humidity-controlled weighing room at NIOSH's laboratory in Pittsburgh, PA. All sampling pumps were post-calibrated to ensure that an acceptable flow rate of 1.7 L/min (+/− 0.015 L/min) (0.06 cfm) 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 applied to all the field gravimetric measurements.

Instantaneous respirable dust measurements were taken with personal Data RAM (pDR 1000) instruments (Thermo Fisher Scientific Corp., Waltham, MA). This real-time dust monitor measures the respirable aerosol concentration based upon the light scatter of particles that pass through an internal sensing chamber. This instrument usually requires a correction factor using a gravimetric sampler for acceptable accuracy (Colinet et al., 2010), which was accomplished by first comparing the average respirable dust concentrations measured by the three gravimetric samplers to the pDR's instantaneous respirable dust concentration for a defined 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 of the individual aerosol measurements taken with the pDR instrument and recorded in an Excel spreadsheet.

Pressure measurements

All cab pressure measurements were taken with DP-CALC micromanometers, Model 5825 (TSI Inc., Shoreview, MN). These pressure measurements were taken every minute and recorded on the unit's internal datalogger. After each day of testing, the data was downloaded to a laptop computer and stored as an Excel data file. The pressure measurement provided the necessary data to determine when the door on the enclosed cab was opened for any significant time period.

Testing

The samplers were turned on before the miners had to begin their shift so that setting up the experiment did not delay the miners' work. At the end of the shift, the samplers were turned off and removed from the vehicles. The quartz filters from the SKC DPM cassettes were analyzed for *EC* and *TC* at the NIOSH laboratory in Pittsburgh, PA using NIOSH method 5040 (Birch, 2004). The gravimetric filters were sealed and weighed at NIOSH, Pittsburgh, PA. Data from the *EC* real-time monitors were downloaded each day. A data point was collected every minute and used to calculate an eight-hour time-weighted average (TWA) along with 5-, 10- or 15-minute rolling average concentrations. The real-time respirable aerosol levels were recorded on an internal data logger every 10 seconds and were downloaded to a laptop computer at the end of each day of testing. This procedure was repeated for 17 days throughout a nine-month test period, with an attempt to test at least once a month to obtain a long-term evaluation.

Unfortunately, there was not a complete data set for each day; instrument malfunctions occurred with the pressure monitor on one day when evaluating the drill and on four days when evaluating the bolter. Six data sets from the *EC* monitors (some of which were prototypes) had issues with tubing, kinked line and/or damage occurring during sampling. These problems prohibited the calculation of the efficiency of the cab system when the cab was sealed, since it could not be obtained without pressure and real-time data. Also, on some days, only one vehicle was operating, which limited the number of data points for each vehicle.

Data analysis and experimental error

In this study, NIOSH method 5040 *EC* results using Eq. (1) were used to determine the reduction efficiency of the cab system for DPM:

$$\text{Reduction efficiency}=\frac{EC_{outside}-EC_{inside}}{EC_{outside}}\times 100 \quad (1)$$

where $EC_{outside}$ = the *EC* concentration measured by NIOSH method 5040 outside of the cab, and EC_{inside} = the *EC* concentration measured by NIOSH method 5040 inside of the cab.

Triplicate samples were collected inside and outside of the cab, but due to pump error on some days of testing, only duplicate *EC* samples were available for analysis. These multiple samples were used to calculate replicate efficiencies for each experiment. This was accomplished by inserting the data for the highest concentration outside the cab and the lowest concentration inside the cab into Eq. (1). The next reduction efficiency was calculated using the lowest concentration outside the cab and the highest concentration inside the cab. When triplicate samples were analyzed, the samples left were used to determine the third efficiency. This method for determining efficiencies ensures the largest standard deviation between efficiencies. If the *EC* concentration inside the cab was below the limit of detection (*LOD*), the *LOD* value was inserted as the *EC* inside concentration in Eq. (1). The reduction efficiency was then recorded as being greater than the calculated value. The two or three replicate reduction efficiencies calculated for each experiment were averaged to obtain the overall value for that cab on that day. The same procedure and equation were used to calculate the respirable dust reduction efficiencies, but the gravimetric data outside and inside the cab were used instead of the *EC* values.

The experimental error for measuring reduction efficiencies was determined by calculating the relative standard deviation (RSD) of the reduction efficiencies for each experiment. Instead of determining a confidence interval for each set of measurements, the RSDs from each day for each cab were pooled to achieve a much stronger statistical determination of error, since each experiment only possessed two to three data points. The pooled RSD was multiplied by the 95% confidence student *t* factor (1.96 with the degrees of freedom in this case) to obtain the error of this analysis at the 95% confidence level.

The respirable dust results using gravimetric analysis and *EC* results using NIOSH method 5040 provided information on the efficiency of the cab system for the entire shift and were affected by the opening of the cab doors. Therefore, in order to determine an efficiency when the cab was sealed, the reduction efficiency was calculated by first averaging the real-time concentrations of the Airtec and pDR at the times of the day when the cab door was closed (shown by the pressure data). These concentrations were then used in Eq. (1) to determine the reduction efficiency of the cab for DPM and respirable dust. On some of the sampling, the concentrations measured with the pDRs outside of the cab when the door was closed were low (less than or equal to 0.21 mg/m^3), and an accurate efficiency of the cab system for respirable dust when the cab was sealed could not be determined with these data points. In fact, at these concentrations, the measurements could be strongly influenced by other aerosols such as DPM and, since the pDRs are not calibrated for these aerosol particle sizes, erroneous results from the pDRs could result.

An RSD could not be calculated for the efficiencies when using the pDRs and Airtecs, since only single measurements were taken. However, the gravimetric data was used to calibrate the pDR results, and the Airtecs have been shown to be equivalent to NIOSH method 5040 (Noll and Janisko, 2007). Therefore, RSDs similar to the gravimetric and NIOSH method 5040 samples would be expected when determining the efficiencies with these instruments.

The RSDs of the duplicate or triplicate *TC* measurements inside the cab for each day were pooled as discussed for the *EC* measurements above and, then, multiplied by the 95% confidence student *t* factor to determine the experimental precision for the *TC* measurements.

Results and discussion

Reduction efficiency for DPM and respirable dust with the MERV 16 filter

As seen in Table 1, the enclosed cab systems in the face drill and roof bolter mining machines reduced DPM between 46% and 95% under normal operating conditions. A large range of efficiencies were evident because the reduction efficiency depended upon the amount of time the cab door was open for that test. This can be substantiated by the concentration of *EC* inside the cabs being above 39 µg/m^3 only when the pressure was near zero, indicating the cab door was open (see an example of this in Fig. 2). In addition, the range of reduction efficiencies was much tighter when the influence of the open door was eliminated. The reduction efficiency was primarily more than 90% (Table 2) when a positive pressure existed in the cab. Even though there were some days that data was not collected, at least six days of sampling per cab were achieved, resulting in 13 data points between the two cabs. This number of samples is not extensive, but is enough to provide valuable information on the characteristics of the cabs.

The reduction efficiency for respirable dust was similar to the reduction efficiency for DPM with these enclosed cabs. As can be seen in Table 3, a large range (51-99%) of reduction efficiencies for respirable dust were observed, which was probably due to the influence of the operator's opening and closing of the door. As seen in Fig. 3, the concentration of respirable aerosols did not exceed 0.4 mg/m^3, unless the pressure was zero, indicating that the door was open. As with the DPM results, the reduction efficiencies were tighter when evaluating the pDR only when the cab was sealed, always resulting in reduction efficiencies above 91%, and above 95% for most days of testing. The tests results indicate that cab systems with a MERV 16 rated filter can reduce DPM and dust in real mining conditions by more than 90% when sealed. Even though there were some days that data was not collected, at least seven days of sampling per cab were achieved, resulting in 21 data points between the two cabs. Again, this number of samples is not extensive, but is enough to provide valuable information on the characteristics of the cabs.

These DPM and dust reduction efficiencies with the unidirectional designed cab system and the MERV 16 filter were similar to results observed when using a HEPA filter in other field studies of cab systems, even though the HEPA was shown to be slightly more efficient than the MERV 16 filter in laboratory tests (more than 99% efficient for capturing DPM with the HEPA filters compared to 96% with the MERV 16) (Noll et al., 2012, 2008). This similarity could be due to the MERV 16 filters providing equivalent protection from DPM and dust as the HEPA when employed in the cab systems under real mining conditions. In other words, the MERV 16 and HEPA filters provide enough protection (more than 96%) so that the filtration system is no longer a limiting factor to the reduction efficiency of the cab system. Instead, other factors such as cab integrity and pressurization are limiting the reduction efficiency of the cab system operating in the mine.

Another scenario that could cause similarities is that the cab systems tested with the HEPA filters were not as effective as the cabs tested in this current study, resulting in the newly designed cabs providing the same protection with slightly less efficient filters. The cab systems tested with the HEPA filters could have had more leaks, less pressurizations or some other flaw not present in the cabs tested in the current study. At this time, it is not known which scenario is correct, offering an opportunity for future studies.

Effects of work practices

As seen in Tables 1-3 and discussed earlier, the opening of the cab door on average reduced the reduction efficiencies of DPM and respirable dust from more than 90% to about 80%. In fact, for most samples (about 47 out of 58), the reduction efficiencies were at or above 80% for DPM and dust. The other 11 samples had reduction efficiencies as low as approximately 46%. It is not known why the door was open for longer periods for the days with the lower reduction efficiencies.

Even though opening the door can have a major effect on reduction efficiencies, routine work practices dictate that the opening of the cab door will continue to occur periodically throughout the day. However, minimizing the time the door is open will enhance the protection of the miner. Since 80% reduction efficiency was achieved for most days, miners may be able to adapt their work practices to achieve at least this efficiency for every day. At the mining operation where this study occurred, an 80% and greater efficiency resulted in DPM concentrations inside the cab of less than or equal to 117 $\mu g/m^3$ *TC* (see Table 1) and, as shown in a previous publication, less than 0.6 mg/m^3 respirable dust concentrations (Cecala et al., 2012).

Conclusion

The filtration and pressurization system evaluated in this study with MERV 16 filters provided more than 90% reduction in DPM and respirable dust when the cab doors were closed and positive pressurization was achieved. In some cases, routine work practices required the opening of doors in the cabs, resulting in lower reduction efficiencies. In fact, these types of work practices can cause the reduction efficiencies to decrease from more than 90% to below 50% , as shown in this study. However, for the majority of the days during this study, there was an 80% reduction even considering the current work practices of the cab operators. The results from this test and others should be used to convey to miners the importance of keeping operator compartments’ doors and windows closed as much as possible in order to maintain the highest possible air quality.

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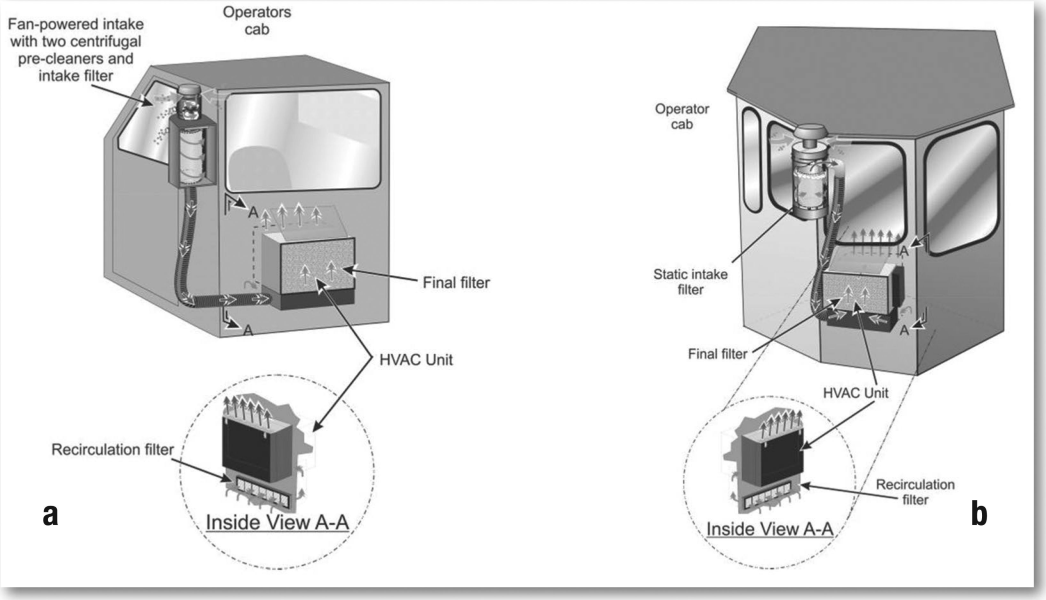

Figure 1.

The unidirectional cab design used in the bolter (a) and the unidirectional cab design used in the drill (b).

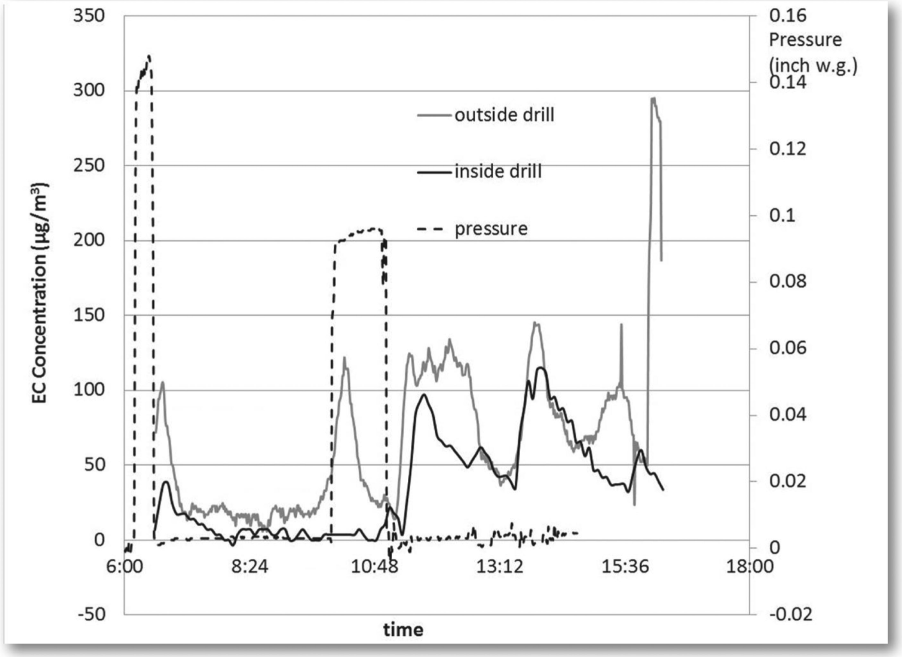

Figure 2.

Example of how *EC* concentrations increased significantly during periods when the cab door was open, creating a cab pressure of zero.

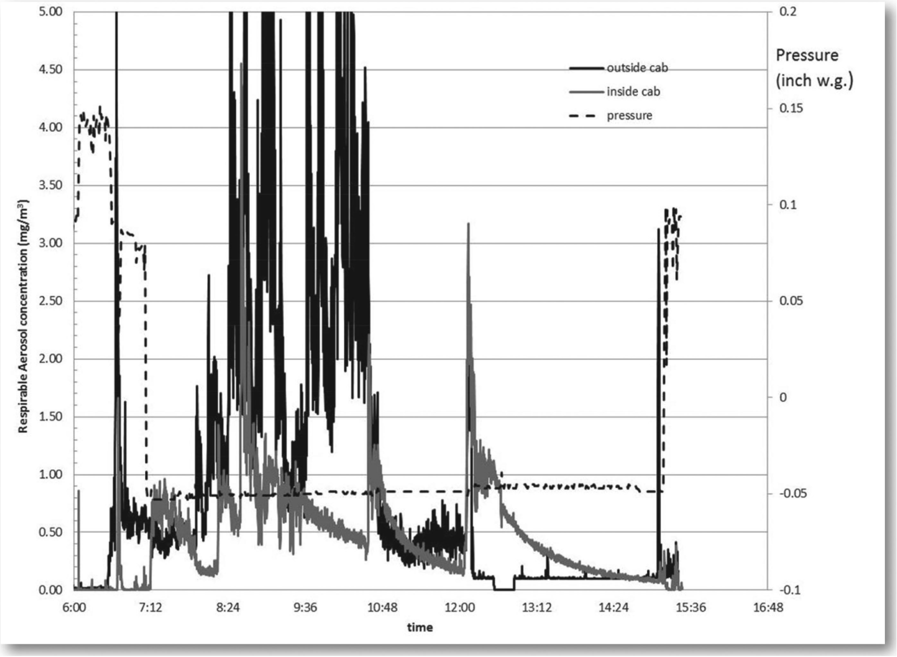

Figure 3.

Example showing how the average respirable dust concentrations in the cab were not above 0.4 mg/m^3 unless the pressure was at zero, indicating that a window or door was opened.

Table 1

DPM reduction efficiencies for enclosed cabs.

Roof bolter				**Jumbo drill**			
Date	**Reduction efficiency using NIOSH method 5040 *EC* (%)**	**8-hr TWA *TC* inside cab (μg/m^3)**	**8-hr TWA *TC* inside cab determined by *EC* × 1.3 (μg/m^3)**	**Date**	**Reduction efficiency using NIOSH method 5040 *EC* (%)**	**8-hr TWA *TC* inside cab (μg/m^3)**	**8-hr TWA *TC* inside cab determined by *EC* × 1.3 (μg/m^3)**
11/9/10	84	48	42	**11/9/10**	92	22	17
11/10/10	>86	<10	<13	**11/10/10**	>90	<10	<13
11/11/10	87	49	46	**11/11/10**	73	28	25
11/17/10	91	39	18	**11/17/10**	86	75	68
12/9/10	50	57	65	**12/9/10**	67	43	49
1/13/11	76	32	21	**12/16/10**	46	53	55
2/3/11	90	15	16	**1/13/11**	84	37	18
3/2/11	90	78	43	**2/3/11**	91	23	<13
3/22/11	89	26	26	**3/22/11**	95	18	18
3/23/11	86	117	95	**5/5/11**	95	10	<13
3/24/11	83	23	27	**7/12/11**	92	25	<13
4/14/11	64	130	140				
5/5/11	82	54	55				
6/16/11	92	10	<13				
7/12/11	80	96	104				

RSD at 95% confidence level for efficiencies: 10%.

RSD at 95% confidence level for *TC* concentrations: 30%.

Table 2

Reduction efficiencies for enclosed cabs when doors and windows were closed.

Reduction in DPM				Reduction in respirable dust			
Vehicle	**Date**	**Reduction efficiency using NIOSH method 5040 *EC* (%)**	**Reduction efficiency using real-time *EC* when door was closed (%)**	**Vehicle**	**Date**	**Reduction efficiency gravimetric data (%)**	**Reduction efficiency PDR data when door was closed (%)**
Roof bolter	11/9/10	84	91	**Roof bolter**	11/9/10	87	95
Roof bolter	11/17/10	91	>97	**Roof bolter**	11/11/10	89	94
Roof bolter	12/9/10	50	>92	**Roof bolter**	12/9/10	84	91
Roof bolter	3/23/11	86	91	**Roof bolter**	3/23/11	89	95
Roof bolter	5/5/11	82	90	**Roof bolter**	4/14/11	78	94
Roof bolter	7/12/11	80	92	**Roof bolter**	5/5/11	88	96
Jumbo drill	11/11/10	73	>85	**Roof bolter**	7/12/11	92	>93
Jumbo drill	11/17/10	86	96	**Jumbo drill**	11/9/10	95	99
Jumbo drill	12/16/10	46	>91	**Jumbo drill**	11/11/10	89	99
Jumbo drill	2/3/11	91	>93	**Jumbo drill**	11/17/10	95	98
Jumbo drill	3/22/11	95	96	**Jumbo drill**	12/1/10	51	91
Jumbo drill	5/5/11	95	>95	**Jumbo drill**	12/9/10	79	96
Jumbo drill	7/12/11	92	>93	**Jumbo drill**	1/13/11	86	93
				Jumbo drill	2/3/11	85	94
				Jumbo drill	3/22/11	98	99
				Jumbo drill	3/23/11	99	99
				Jumbo drill	3/24/11	99	99
				Jumbo drill	4/14/11	98	99
				Jumbo drill	5/5/11	98	99
				Jumbo drill	6/16/11	80	92
				Jumbo drill	7/12/11	97	99

RSD at 95% confidence level for efficiencies: 10%.

Table 3

Respirable dust reduction efficiencies for enclosed cabs.

Roof Bolter		**Jumbo Drill**	
Date	**Reduction efficiency gravimetric data (%)**	**Date**	**Reduction efficiency gravimetric data (%)**
11/9/10	87	**11/9/10**	95
11/10/10	93	**11/10/10**	96
11/11/10	89	**11/11/10**	89
11/17/10	92	**11/17/10**	95
12/9/10	84	**12/1/10**	51
12/16/10	69	**12/9/10**	79
1/13/11	84	**12/16/10**	51
2/3/11	67	**1/13/11**	86
3/2/11	88	**2/3/11**	85
3/22/11	90	**3/22/11**	98
3/23/11	89	**3/23/11**	99
3/24/11	91	**3/24/11**	99
4/14/11	78	**4/14/11**	98
5/5/11	88	**5/5/11**	98
7/12/11	83	**6/16/11**	80
		7/12/11	97

RSD at 95% confidence level for efficiencies: 10%.