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COMPARING THE AIR QUALITY INSIDE ENCLOSED CABS OF UNDERGROUND MINING EQUIPMENT WITH MERV 16 AND HEPA FILTERS

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ABSTRACT

In recent years, significant strides have been made to optimize the design of filtration and pressurization systems used on enclosed cabs of mobile mining equipment to reduce respirable dust and other contaminants and provide the best air quality to the equipment operators. This synergetic effort has involved original equipment manufacturers building mining equipment, manufacturers of heating, ventilation, and air conditioning systems for mobile equipment, filtration and pressurization system manufacturing companies, as well as the National Institute for Occupational Safety and Health, and other government organizations. Considering all the advances made in this area over the last decade, one aspect that NIOSH still needs to assess is the longevity of optimal cab performance with respect to the quality (filtering efficiency) of the filters used in filtration and pressurization systems. In today's culture, most health and safety professionals automatically believe that HEPA quality filters need to be used to provide the greatest level of protection to workers. Researchers at the Office of Mine Safety and Health Research for NIOSH hypothesized that HEPA quality filters may not be optimal for the mining industry and speculated that MERV 16 rated filters would be more appropriate in most cases. In order to test this hypothesis, NIOSH performed a two-year study comparing both HEPA and MERV 16 quality filters on two pieces of underground limestone mining equipment, being a roof-bolter and face drill machine. Testing showed at the 95 pct. confidence level that there was no statistical difference between the two efficiency filters on both pieces of mining equipment. Since the MERV 16 rated filters were less restrictive and provided greater cab pressure, and since they did not have to be replaced as often as the HEPA quality filters, researchers concluded the MERV 16 filters were the optimal choice for both pieces of mining equipment in this case study comparative analysis.

INTRODUCTION

When most health and safety professionals today think about filtration efficiencies and their correlation with protecting workers' health, the normal assumption is the higher the efficiency of a filter, the greater the protection afforded to the workers. The next logical step is to believe that HEPA filters deliver the greatest protection for workers because they provide the highest filtering efficiency. Obviously high-efficiency intake filters are a necessity for an effective cab filtration and pressurization system on mobile mining equipment, but what is the optimal filter efficiency rating for achieving high levels of cab protection factor performance over the service life of filters? To address this question, the National Institute for Occupational Safety and Health (NIOSH) has performed an in-depth laboratory research study over the years simultaneously with numerous field studies to retrofit used enclosed cabs on mobile mining equipment with newer and more effective filtration and pressurization systems.

Table 1 shows a summary of the different MERV ratings and the filtration efficiency values that correspond with three different size ranges of dust/contaminant particles with each filter type. This table was obtained from the American Society of Heating, Refrigerating and Air-Conditioning Engineers Handbook (1) with the exception of the bottom row which was added to also provide the HEPA efficiency rating.

Table 1. MERV rating efficiency values for 3 size ranges of dust particles.

Minimum efficiency reporting values (MERV) according to the 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%
HEPA		≥ 99.97%	≥ 99.97%	≥ 99.97%

The "Minimum Efficiency Reporting Value," commonly known as a MERV rating, is a comparative value designated by ASHRAE to compare the effectiveness of different air filters. In some cases, there are tables that extend the MERV ratings up to a value of 20, but typically the 17 through 20 ratings are not part of the standard specifications. The ratings of 17 through 20 typically relate to extremely fine contaminants such as carbon dust, virus, and smoke-sized particles, and are typically used in the electronics and pharmaceutical cleanroom type applications. There are numerous articles showcasing the effectiveness of HEPA filtration in these types of applications (2-5).

"HEPA" is the most common filtration term known today and stands for "High-Efficiency Particulate Arrestance." Sometimes the "Arrestance" term can be substituted with either "Arresting" or "Air." To be rated as HEPA quality, filters must meet specifications set forth by the United States Department of Energy (DOE) and must be capable of 99.97% filtering efficiency at 0.3-micron particles. As seen in Table 1, there is a considerable jump in the filtering efficiency from the MERV 16 to HEPA quality filters which increases from $\geq$ 95 pct. to $\geq$ 99.97 pct. efficiency at the 0.3-micron particle size range, respectively.

To achieve a high MERV or HEPA filter efficiency rating, the contaminant particles are filtered by interception, impaction, diffusion, or electrostatic collection. Distinctions among these capture processes are as follows:

Interception – occurs when smaller-sized particles follow the airstream flow lines and come within one radius of the fabric fiber, then adhere to the fabric.

Impaction – occurs when larger particles that are not able to stay on airstream flow contours travel through the filter media and then become embedded into one of the fibers directly.

Diffusion – occurs when the smallest dust particles collide with gas molecules, especially those smaller than 0.1 micron, and then alter their flow path so that they are captured by either interception or impaction.

Electrostatic collection – makes use of a filter fabric made from a material or media that is able to sustain an electrical charge. Because dust particles also have an electrical charge, as these dust particles pass through the filter fabric, they are attracted to and adhere to the electrically charged fabric material.

Filter fabrics are constructed of either natural or man-made fibrous material and are either woven or nonwoven. Both woven and nonwoven are usually identified by a weight per unit area, but nonwoven also include a filter thickness classification (6).

Based upon the results of a previous NIOSH lab study using diesel particulate, NIOSH has hypothesized that for the majority of enclosed cabs for mining applications, it was believed that a MERV 16 intake filter using a mechanical filter media would be the optimal design for use in these applications (7-9). When using a mechanical filter media, the filter becomes more efficient as it loads with dust and develops a filter cake. A new (non-loaded) MERV 16 media would have a greater than 95% filtering efficiency on particles in the respirable size range of 0.3-1.0 microns. Non-rated used (loaded) filters achieved over 98 pct. capture efficiency on 0.3-1.0 micron particles as compared to 23 pct. when new (non-loaded) (10). In a prior NIOSH laboratory study which focused on diesel particulate, a comparison study was performed on a MERV 8, MERV 16, and two different HEPA quality filters. The results of this study indicated a 50 pct., a 96–98 pct., and over a 99 pct. collection efficiency for the MERV 8, MERV 16, and HEPA quality filters, respectively (9). In this study as the filter media loaded with dust, it became more efficient at removing particles from the intake airflow as expected.

The term “HEPA” is the filtering efficiency most known today and is even a common term among most non-health and safety professionals. Along with the term’s recognition is the mentality that HEPA quality filters should be used in almost all applications. However, these filters are more costly and restrictive than the MERV 16, placing additional demands on the entire filtering system including the intake fan. Because of the increased restriction and pressure drop across the HEPA filters, this ultimately decreases the intake airflow and subsequently lowers the level of positive pressure within the cab, both of which are detrimental to the overall system performance. In addition, this situation also creates a greater likelihood of leakage around the filter if the design and construction of the filter housing has minor imperfections. When one is dealing with mobile equipment used in the mining and construction industries, because of the constant movement, vibration, and stress placed on the enclosed cab over years of use, the likelihood of stress cracks and leakage points in the HVAC and filtration system becomes more of an issue.

When this research attempting to improve the air quality in the enclosed cabs of mobile equipment was started approximately 15 years ago, the analysis method used by the Office of Mine Safety and Health Research (OMSHR) for NIOSH was to perform gravimetric sampling along with the use of light-scattering nephelometer instruments to obtain instantaneous measurements both inside and outside of the enclosed cab during in-mine testing. Three gravimetric samplers were used and averaged together to determine a respirable dust concentration over the sampling period at both the inside and outside sampling locations. This average value was then used to calculate a correction factor for both light-scattering respirable dust instruments, and the values were corrected before the data was analyzed. This data was then used to determine a protection factor (PF) for each enclosed cab for each day of testing. This sampling process was very time consuming as well as complicated because it would include time periods when the equipment operator would be entering and exiting the cab which allowed dust and contaminants to enter. In addition, the equipment operator’s movement while performing his or her work duties would generate and liberate dust and contaminants from dust on the inside cab surfaces, from dust on the worker’s clothing, and from material on the cab floor and the worker’s boots moving and grinding the material.

Although there were previous studies using the particle count instruments to evaluate enclosed cabs in both mining and agricultural environments, these instruments were expensive, difficult to use, and not viewed as field-worthy for most field study situations (11,12). Over the last number of years, particle count instruments continue to advance in many different ways, having become more economical and simplified, and have improved the accuracy of the testing performed on this research area. This current comparative filter study was effectively performed using particle count instruments during non-production time periods while the roof-bolter and face drill machines were located outside the mine. The researchers believe these static conditions provide a much more reliable, as well as the most favorable and comparable PF values for each enclosed cab. It is believed that this study is the first of its kind attempting to compare HEPA and MERV 16 quality filters in the same enclosed cabs of mining machinery being used in the industry.

BACKGROUND

Over the past fifteen years, NIOSH OMSHR has partnered with many companies including original equipment manufacturers building mining equipment, manufacturers of heating, ventilation, and air conditioning systems for mobile mining equipment, filtration and pressurization system manufacturers, as well as other government organizations wanting to improve the health of miners working inside enclosed cabs of mobile mining equipment (13-18). Initially, enclosed cabs were mainly used for the safety concerns of protecting the equipment operators from falling ore and material and for temperature controls of providing operator comfort. Then health issues became more of a focus and cabs were sealed in an effort to provide greater protection for the workers, but initially this appeared to be more related to noise protection than for air quality issues. As time progressed and some efforts were initiated on basic systems to provide some filtration, many times these systems were not maintained or supported and in certain instances they actually made the air quality inside the enclosed cabs worse than without the system. Figure 1 shows extremely poor conditions of two air conditioning and filtration systems taken out of equipment before a new retrofit system was installed during a NIOSH cooperative study. The photo of the air filter shown in the upper right hand corner of the figure shows the lack of maintenance and concern for this critical component of removing the dust and improving the air quality inside enclosed cabs. Since the cab creates a microenvironment for workers, they can be either more protected or more vulnerable to respirable dust. One documented instance shows how dust generated from a floor heater unit used in low temperatures to provide heat to the equipment operator significantly increased the operator’s respirable dust exposure (19).

The key impetus for focusing on the air quality inside enclosed cabs was the published results from a multi-agency cooperative study performed in 1996 and 1997 at eight different surface coal mines, where 1,238 miners were screened for lung disease. This study identified that 6.7 pct. of these miners had silicosis based upon the results of chest X-rays. In one particular county in central Pennsylvania identified in this study, 16 pct. of the 213 participants were classified with the disease. The alarming aspect of this NIOSH report, published in July of 2000, was the relatively young age and the relatively short time that many of the miners being diagnosed with silicosis had been employed in the mining industry (20).

This study was the impetus for a new research area from NIOSH OMSHR to investigate engineering controls to improve the air quality in enclosed cabs. The first mine site visited in this new research effort was a surface coal operation in central Pennsylvania, located in the county identified in this study with the highest silicosis cases. This study identified a number of considerations for filtration and pressurization systems but one very important factor was the ability of the system to achieve positive pressure inside the enclosed cab. With the installation of the exact same filtration unit on two pieces of mobile mining equipment at a surface coal mine site, being a drill and a front-end loader, only the front-end loader was able to be sealed to a level where a 0.015-inches wg positive pressure was achieved. Despite all the efforts on the drill, it was not possible to achieve any positive cab pressure. This resulted in a minimal improvement in air quality with the surface drill corresponding to a protection factor of 2.8, compared to a significant improvement in air quality in the front-end loader enclosed cab with a protection factor of 10.0 (17). The protection factors for these enclosed cabs were determined by dividing the outside cab respirable dust concentration by that of the inside. This was the first of many studies in which new filtration and pressurization systems were installed on older pieces of mining equipment, attempting to improve the air quality inside of the enclosed cabs (13,15,16,18,21,22).

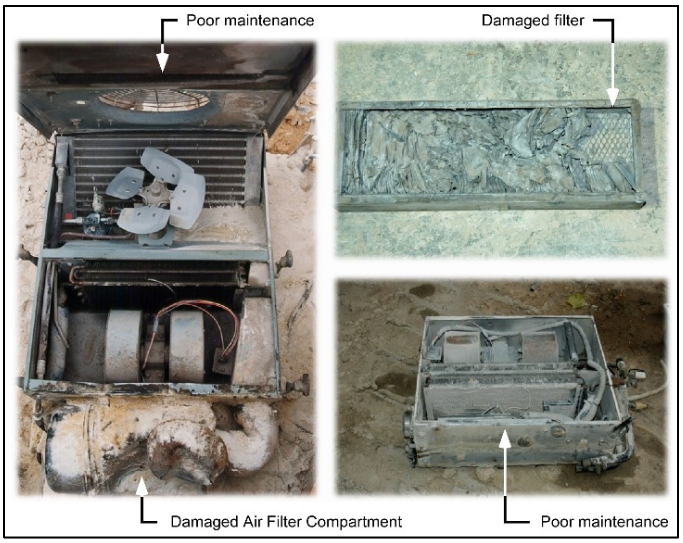

Figure 1. Examples of the poor quality and lack of maintenance on HVAC filtration and pressurization systems removed from mining machinery during various field research efforts. Photo in upper right corner shows the deterioration of a filter found in one of these units.

Concurrent with these multiple field research retrofit filtration and pressurization studies, NIOSH performed a long-term in-depth laboratory study and has published multiple reports documenting the progress of these efforts (23,24). Initially the focus was supporting the results obtained during field studies and examining the effects of intake filter efficiency, intake filter loading, intake air leakage around the filter, recirculation filter use, and wind on cab filtration performance. An original two-filter mathematical equation was formulated from a basic time-dependent mass balance model of airborne substances within a control volume with steady-state conditions. Over time, this mathematical model was further developed and expanded to the point where it now includes the ability of multiple filters through the HVAC system to improve the air cleaning performance and robustness of the cab filtration system design (10).

The above studies highlighted the important factors identified for improving the air quality in enclosed cabs and ultimately improving the air quality to the workers. The knowledge gained from NIOSH's laboratory and numerous cooperative field studies was used to determined that the two critical factors for an effective system are first, a competent filtration system comprised of a pressurized intake and a recirculation component, and second, an enclosed cab with structural integrity in order to achieve a level of positive pressurization. These two critical factors, along with numerous secondary factors, can be paramount in the design of an effective filtration and pressurization system and the ability to provide acceptable air quality to mobile equipment operators (7).

TESTING

To perform this comparative evaluation of the air quality in the enclosed cabs of a J.H. Fletcher Company roof-bolter and face drill machine using MERV 16 and HEPA quality filters, the same test protocol was attempted to be identically repeated, approximately one year apart from each other. Although the original design of the filtration and pressurization system by J.H. Fletcher Company on both pieces of equipment was a three-filter system composed of an intake, recirculation, and final filter, the recirculation filter component was not used in this comparative study because it was deemed more of a hindrance or detriment to the system's performance from a previous study based on how quickly it overloaded with dust and needed to be changed due to its small filter surface area (13). Figure 2 shows the filtration and pressurization unit on the face drill machine along with the plan view of this system design which was identical on both pieces of equipment. Each filtration and pressurization unit used a RESPA®-CF Vortex HyperFLOW intake air filtration pressurizer unit (Sy-Klone International, Jacksonville, FL) and a final panel filter (J. H. Fletcher & Co.) inside the HVAC component in which all the intake and recirculation air flowed through before entering the cab. The RESPA®-CF intake air filter pressurizer contained a cyclonic pre-cleaner which uses a centrifugal design to expel the dust particles greater than 5.0 μm from depositing on the filter, thus minimizing dust loading and extending filter life. The standard size 6-in. diameter by 8-in. high RESPA®-CF filter cartridges were used throughout this study. The 11.38-in. wide by 17.5-in. high by 3.75-in. thick J.H. Fletcher & Co. final panel filter was mounted at the exhaust discharge of the HVAC system. All cab testing was conducted with the pressurizer unit operating with the HVAC system fan on the high flowrate setting.

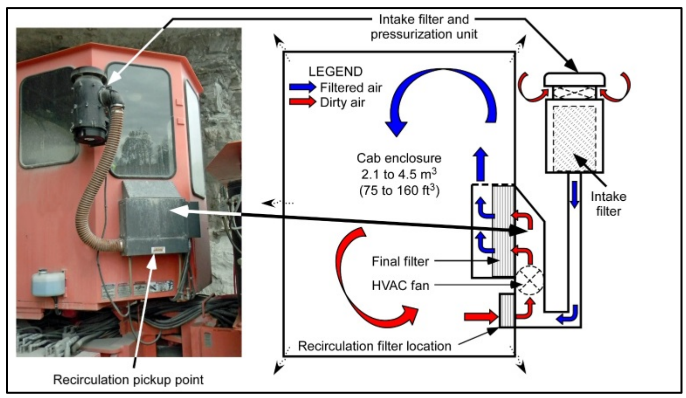

Figure 2. Actual filtration and pressurization unit on enclosed cab (left) and plan view design drawing and airflow pattern of the same unit (right).

To begin this study, a verbal agreement to perform testing at its operation was established with the mine manager of Shelly Materials Company, which had recently opened a new underground limestone mine near Zanesville, Ohio. This underground limestone mine operated one shift (daylight) per day when this testing was performed, which went from approximately 6:00 am until 3:30 or 4:00 pm. At the end of the shift, the equipment operators would bring the equipment outside the mine to service, which involved filling with diesel fuel, with water for dust suppression for wet drilling, greasing the equipment, as well as performing additional periodical maintenance. When the servicing was completed, the equipment operator would park the machine outside of the mine and then turn it over to NIOSH researchers to perform our testing.

NIOSH's test protocol included measuring and recording a number of aspects on the equipment but the two most important issues were to perform both particle count and airflow measurements. The particle count measurements were performed to determine a protection factor value for the filtration and pressurization system's effectiveness on each of the enclosed cabs. Airflow measurements were also taken to determine intake and recirculation air volumes during each test and these values were compared over time as the filters loaded with dust. The engine hours were also recorded during each monthly test to provide a relative measure of equipment use and dust loading on the filters over time. At the beginning of this testing, NIOSH installed a pressure monitoring device and datalogger in the enclosed cab of both the face drill and roof-bolter machines to determine and record the positive cab pressure created by the filtration and pressurization system. Obviously, the thought was to document how this positive pressure decreased over time as the filters loaded with dust and created additional pressure, which would cause the airflow to decrease. The datalogger was attached to each pressure monitor and was capable of recording a 1-minute pressure average for a 28-day period. NIOSH researchers returned within this 28-day period to download the positive pressure data, as well as to perform particle count and airflow measurement tests.

This testing was performed in a static test mode, meaning the equipment was running without anyone in the enclosed cab to stir up or create any in-cab dust sources. This provided the highest possible PF for each of the enclosed cabs. The roughly monthly analysis was started in May and extended until November. After this time frame, the testing was terminated as the equipment could not be left outside the mine overnight without concern for freeze-up problems from low outside air temperatures. From May through November of 2013, testing was performed using MERV 16 rated intake and final filters. Testing was then repeated from May through November of 2014 using HEPA quality intake and final filters.

Particle Counting Measurements

The cabs' PFs were measured by using two model ARTI/Met One HHPC-6 particle counters (Hach Ultra Analytics, Grants Pass, OR) to simultaneously sample and record the inside and outside cab particle size concentrations for one-minute periods over a 30-minute test (22,23,25). These instruments count airborne particles within the six-channel size ranges of 0.3–0.5 microns, 0.5–0.7 microns, 0.7–1.0 microns 1.0–3.0 microns, 3.0–5.0 microns, and > 5.0 microns. The test medium was airborne particles present in the ambient air surrounding the unoccupied stationary cab enclosure with the filtration system operating on the high fan setting (low, medium, and high speed settings were available). The inside and outside cab instruments were then alternated for another 30-minute test to average out any instrument sampling biases for each test. Two test replicates were conducted during the field studies given the time constraints at the mine site. The last 15 minutes of data from each test replicate were used to calculate the average outside and inside cab concentrations during the lowest steady-state particle count conditions inside the cab. The PFs were determined from the cumulative submicron (0.3–1.0 microns) particle concentrations because most of the ambient air particles resided in this size range (25). A PF for each test replicate was determined by dividing the average outside particle concentration by the average inside particle concentration. The PF represents a reduction ratio of all the exterior and interior particles removed by dividing the outside concentration by the inside concentration and is the same calculation used when determining the effectiveness of personal protective equipment such as respirators.

Airflow and Cab Pressure Measurements

Airflow readings were measured for the intake and recirculation circuits of the cab enclosures' filtration system to examine the cab operating effects of different filter combinations. During the field study, VELOCICALC hotwire anemometer models 8346 or 9555 (TSI Incorporated, Shoreview, MN) were used to measure the centerline air velocity inside the middle of a 30-inch-long section of smooth 2.4-inch-dia. PVC pipe which was added to the outlet of the intake filtering unit. For the recirculation component, one-minute moving traverse velocity measurements were made with a vane anemometer (Davis Instruments, Vernon Hills, IL) over the recirculation filter inlet area. A more detailed description of these measurements can be found in References 13 and 22.

The cabs' inside-to-outside differential static pressure was also measured to ensure that cab pressurization was achieved. During the MERV 16 filter testing in 2013, the KT-CABPRES-EL1-ENC – Electronic Pressure Monitor System 0.0–0.8-in. water gauge (Sy-Klone International, Jacksonville, FL) was used. During the HEPA filter testing in 2014, the DM-2003-LCD Differential Pressure Transmitter 0.0–0.500-in. water gauge (Dwyer Instruments, Inc., Michigan City, IN) was used. Both of these static pressure monitors had an electronic output and this pressure data was downloaded to a HOBO Model U12-006 datalogger device (Onset Computer Corp., Pocasset, MA). The pressure data was stored on the datalogger as 1-minute pressure averages for up to a 28-day period.

RESULTS

The intent of this study was to evaluate and compare the effectiveness of MERV 16 and HEPA quality filters in the enclosed cabs of a face drill and roof-bolter machine being used on a daily basis at a working underground limestone mine. Testing was started in May of 2013 using a MERV 16 intake and final filter on both pieces of equipment and repeated on roughly a monthly basis until November 2013. In May of 2014, this test was repeated with all aspects being identical except the use of HEPA quality filters. Since all of these tests were under static conditions, there were no workers entering, exiting, or sitting inside the enclosed cab who could generate and liberate in-cab dust sources. Because of this, the PF values achieved were at their most favorable and represented performance levels.

Figure 3 shows a comparison of the PFs determined from the particle count instrument testing for the enclosed cabs of the face drill and roof-bolter machines, as well as the intake airflow with both the MERV 16 and HEPA quality filters. The PF values shown in this figure are displayed in a log-normal scale and show very significant improvements in air quality achieved with both the MERV 16 and HEPA quality filters for both pieces of equipment. There are three missing data points in these results. The first two are missing points for the face drill and roof-bolter in the October 2013 time frame due to the federal government shutdown which started on October 1 and extended for a number of weeks. The final missing data point was for the August 27, 2014, test in which the face drill was not operational.

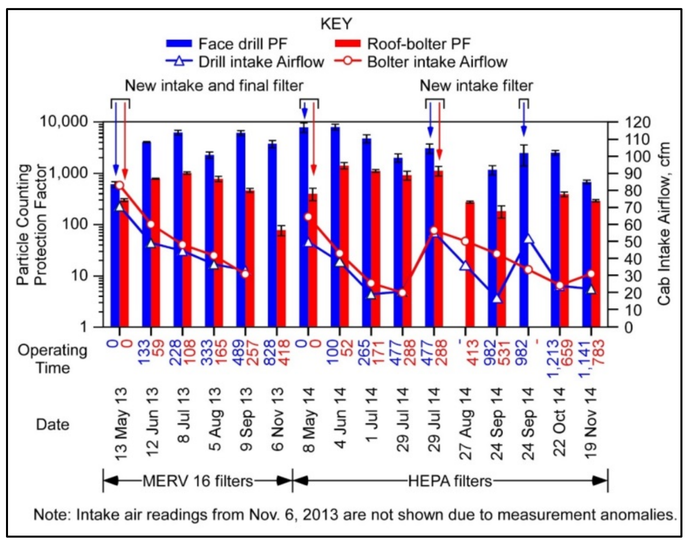

Figure 3. PF from particle count instruments for the enclosed cabs of the face drill and roof-bolter machines, as well as the intake airflow with MERV 16 as compared to HEPA filters.

The PF for the face drill ranged from 612 to 6,337 for the MERV 16 filters and from 685 to 8,133 for the HEPA filters. This compares to the PF for the roof-bolter machine of 77 to 1,021 for the MERV 16 filters and from 182 to 1,425 for the HEPA filters. Based upon these ranges, the assumption would be that the HEPA quality filters provided a higher PF than the MERV 16 filters; however, when all the values are averaged over the entire test period, this is not the case as shown in Figure 4. The average PF value for the face drill was 3,898 with the MERV 16 filters and this is slightly higher than the 3,677 average with the HEPA filters. For the roof-bolter, the average PF with the MERV 16 was slightly lower than the HEPA with a value of 573 to 681, respectively. Statistically at the 95 pct. confidence level, there is no difference between the PF values for either the face drill or the roof-bolter machine between both types of filters. This conclusion is based on insignificant differences found between the filter types when using a two-tailed parametric t-test (assuming unequal variances) and a nonparametric Wilcox test. The 95% confidence levels for the cab PFs are also shown in Figure 4 and illustrate no significant differences between the filters used on each cab. Obviously, there is a significant difference in the PF values when comparing the enclosed cabs on the face drill to the roof-bolter machine and this will be discussed in the following section.

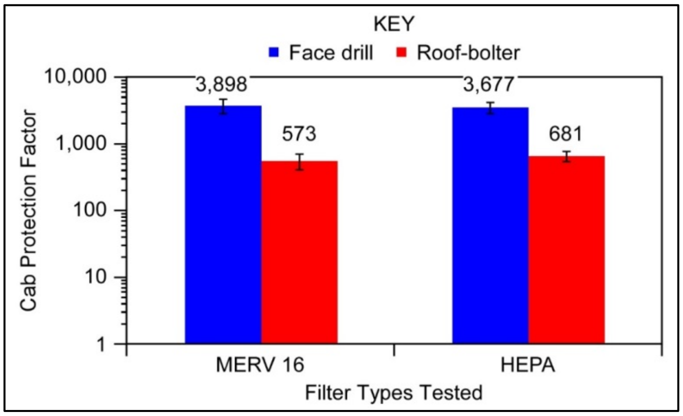

Figure 4. Average PF values for the face drill and roof-bolter machines comparing the MERV 16 and HEPA quality filters.

When considering the results, the first point to note is the extremely high PF values for both pieces of equipment and especially the face drill, indicating the tremendous improvement in the air quality in the enclosed cabs. These PF values are the highest recorded for any of NIOSH's field testing to date and it is believed that the static test conditions and the use of a final filter were the two significant factors contributing to this. In a previous NIOSH publication (10), it was stated that any filtration and pressurization design which directs all the intake and recirculation airflow through a final filter significantly increases the system's effectiveness, which was the case for J.H. Fletcher design in both the roof-bolter and face drill (Figure 2).

Another interesting point to note is the PFs for the MERV 16 filters tested in 2013, when comparing the values for new filter conditions (May) with those for the following two readings (June and July) as the intake and final filters load with dust and become more efficient. When considering the face drill, the PF was 612 with new filters and then increased to values of 4,106 and 6,337, respectively, for the following two readings. The same occurrence was observed for the roof-bolter with PF values of 300 for new conditions and then 790 and 1,021, respectively, for the following two readings. Averaging the PF values for the following two months when the filters were loaded with dust shows the tremendous increase in filtering efficiency for both the face drill and roof-bolter with an improvement factor of 8.5 and 3.0 times the original (clean filter) value, respectively.

This was not the case when considering the results for the HEPA filter testing performed in 2014. Obviously at the start of the test, there were new intake and final filters in both pieces of equipment. As the intake filter loaded with dust as testing progressed, once the intake airflow dropped below the 25-cfm level then a new intake filter was implemented into the system. For HEPA testing, there were five cases where new intake filters tests were used (3 for the drill and 2 for the roof-bolter). In only one of these five instances was there a significant PF increase for the same 2-month post-analysis used for the MERV 16 comparison. This occurred for the first HEPA filter test on the roof-bolter where there was a 3.2-times increase in the PF when the average of the 2-post month values was compared to the PF value with all new filters. For the three instances of new intake filters on the face drill, there was one case of a very slight improvement of 1.1 times the original PF value.

The last area to be highlighted from the results is the intake airflow values shown in Figure 3. In a previous publication (7), NIOSH has stated that in order to provide a sufficient quantity of intake air to ensure the equipment operator does not become asphyxiated from being in an enclosed area, a minimum quantity of at least 25-cfm be delivered to dilute the CO_2 exhaled by each worker (26). Based upon this value, it was determined during this study that whenever the intake airflow on either piece of equipment reached or dropped below the 25-cfm level, a new intake filter would have to be installed. If this was the case, after taking the particle count and airflow measurements with the old filter, a new intake filter would then be added and the same particle count and airflow measurement would be repeated. For testing performed in 2013 on the MERV 16, there were no intake filter changes necessary (although a new filter would have been needed on the face drill if the test had continued past November). For the HEPA testing, new intake filters were necessary on two occasions for the face drill on July 29 and September 24, and on the roof-bolter machine for the July 29 test. By comparing the decline in the intake airflow for the MERV 16 to the HEPA filters on both pieces of equipment, it shows how quickly the HEPA filters loaded with dust and diesel particles and needed to be replaced. This is also shown in Figure 5 where the cab pressure and intake airflow values are plotted for both the MERV 16 and HEPA testing on the face drill machine. This graph shows the starting point for intake airflow and cab pressure for both filters types and then how these values decline as the both the intake and final filter load with dust. This graph highlights how the operating life cycle for the MERV 16 filter was superior to that of the HEPA quality filter with higher cab pressure throughout the life cycle, as well as how an in-cab pressure monitor could be used to indicate the need for filter changes. Recirculation airflows for both cabs were between 144 and 247 cfm for the MERV 16 final filter and between 135 and 207 for the HEPA final filter with the HVAC on the highest fan setting during the study.

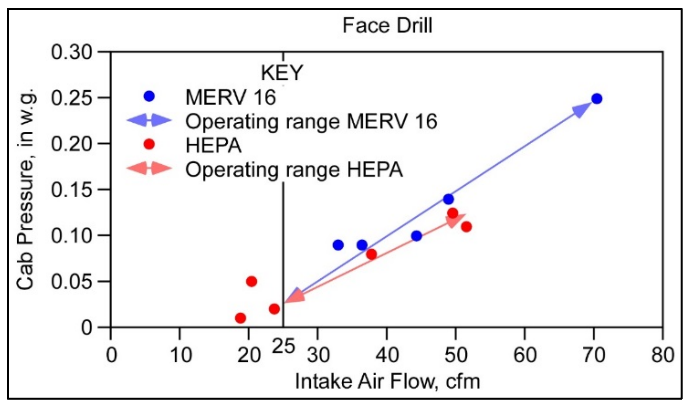

Figure 5. Comparing of intake airflow and positive cab pressure on the face drill with both the MERV 16 and HEPA quality filters.

DISCUSSION

Although this research showed no long-term significant difference in a cab's PF when using the MERV 16 and HEPA filters, it did show a significant difference in the PF between the roof-bolter and face drill when using identical filters. This difference was speculated to be the result of sealing or integrity deviations between the mechanical structures of the two identical HVAC/filtration systems. Additional evidence to this effect was observed early in the MERV 16 filter testing on the bolter when several extra filter combinations were particle count tested (after 257 hours of operation) to examine the mathematical modeling of these system changes (10). The filter combinations tested included adding a used recirculation filter to the system and removing the final filter from the system. Figure 6 shows the results of these tests as well as the test when the intake and final MERV 16 filters were new. This figure also shows the modeled PFs (developed in Reference 10) under these test configurations using their specified filter efficiencies (intake, final, recirculation, new, used, etc.), measured airflows (intake and recirculation), and an assumed intake air leakage of 2% or 0.02 with zero wind infiltration (assumed for positive cab pressurization). The recirculation filters used during this testing had their 0.3–1.0 micron particle collection efficiencies previously measured in the laboratory and significantly reduced the recirculation airflows of the HVAC system (10). These smaller 3-in. high by 16-in. wide by 2-in. thick recirculation filters were placed in the recirculation filter location near the floor of the cabs for the additional testing (see Figure 2).

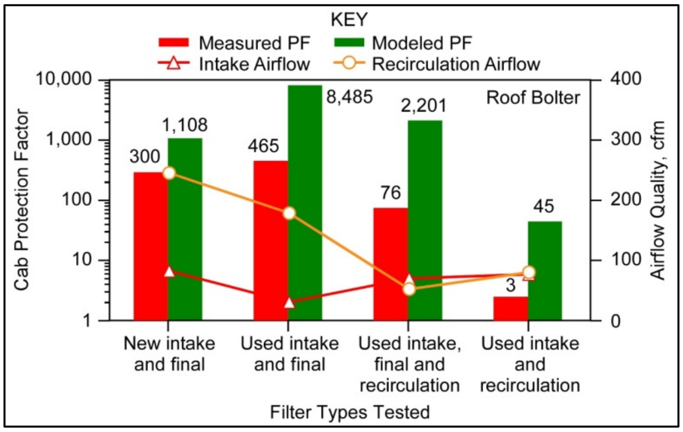

Figure 6. Roof-bolter cab performance changes with respect to different filters used in the system.

As illustrated in Figure 6, the measured PF was notably lower than the modeled PF. In order to achieve agreement between these two values, the intake air leakage into the system would have to be greater than 65% or 0.65. This would appear to be an extreme amount of air leaking around the MERV 16 intake air filter through small cracks or gaps in the HVAC system, and it is more logical that there were probably additional air leakages around the other filters in the system. Visual inspection of the HVAC system with the filters removed on the roof-bolter showed dust deposits downstream of the intake and final filters, indicating multiple leaks in the HVAC system around the filters. A more refined cab filtration system model was formulated with these additional leaks and is shown in the Appendix. A more sensible proportioning of the leakage around the cab filters as shown in Table 2 will better model the PFs measured during field testing. Additional two- and three-filter system combinations (intake with final and/or recirculation filter; MERV 16 and HEPA; new and used) were also tested on these cabs throughout the long-term study and modeled using the cab modeling parameters shown in Table 2 at their measured airflow quantities. Roof-bolter filtration system leakages were doubled in the model as compared to the face drill, given the significant PF differences observed between the cabs during the long-term MERV 16 and HEPA filter field study. Air leakages were also doubled in the model from using a new to used filter because of the anticipated increase in pressure differential and air leakage across used filters.

Table 2. Cab Modeling Parameters Used.

Cab Parameters	Face Drill	Roof Bolter
New MERV 16 Filter Efficiency	0.95	0.95
New HEPA Filter Efficiency	0.9997	0.9997
New Unrated Recirculation Filter Efficiency	0.12	0.12
New Filter – Intake Air Leakage	0.04	0.08
New Filter – Recirculation Air Leakage	0.02	0.04
New Filter – Final Air Leakage	0.02	0.04
Used MERV 16 Filter Efficiency	0.98	0.98
Used HEPA Filter Efficiency	0.9997	0.9997
Used Unrated Recirculation Filter Efficiency	0.76	0.76
Used Filter – Intake Air Leakage	0.08	0.16
Used Filter – Recirculation Air Leakage	0.04	0.08
Used Filter – Final Air Leakage	0.04	0.08

Wind Infiltration Quantity = 0

Figure 6 shows the graph of the measured cab PFs as compared to the modeled cab PFs, showing reasonable agreement along a unity line. The spread in the data is presumed to be primarily a result of the actual unknown field leakage deviations from the assumed modeled leakages in Table 2. It is also shown in this graph that the lowest PFs were measured and modeled when no final filter was used. Additionally, there was no observable cab PF benefit to adding the recirculation filter into this system when using the final filter as shown by the opening points in Figure 7. Adding the recirculation filter into the system significantly reduced the recirculation airflow and cab PF as illustrated in Figure 6. A negative aspect of not having the recirculation filter in the system is that dirt and dust from inside the cab gets drawn into and deposits in the HVAC system, thereby increasing maintenance issues. An alternative solution to improving this cab filtration system would be to increase the size of the recirculation filter to increase its airflow capabilities. Finally, leakages in the HVAC/filtration system have a significant impact on cab PFs, as shown when comparing the differences of the measured and modeled PFs of the two vehicle cabs. Therefore, the cab HVAC/filtration system needs to be well-sealed to extract the benefits of using high-efficiency dust filters.

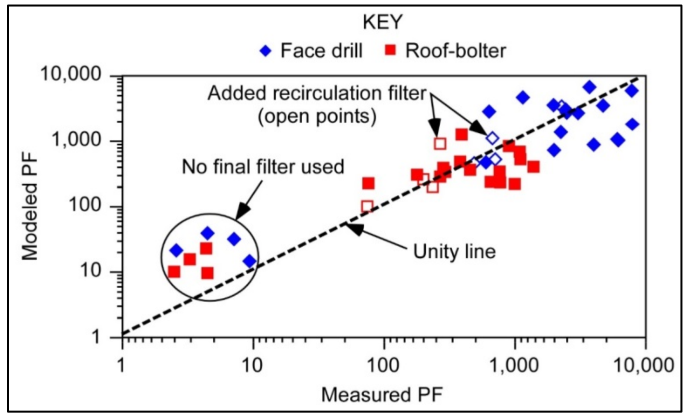

Figure 7. Measured and modeled protection factors of the face drill and roof-bolter during the filter field study.

CONCLUSION

NIOSH performed a comparative study to evaluate the filtering efficiency and the air quality inside the enclosed cab of a roof-bolter and face drill being used at an underground limestone mine when using MERV 16 and HEPA quality filters. The filtration system on both pieces of equipment for this testing was composed of an intake and final filter. The final filter provided a second filtering of the intake air, along with filtering all the air recirculated from within the enclosed cab. This testing showed there was no statistical difference between these two filter types at the 95 pct. confidence level on both pieces of equipment. In almost all cases when testing the HEPA filters, the PFs were at their highest levels when the filters were first installed. As testing progressed and these filters became loaded with dust, the PF, as well as the intake airflow, continually decreased until the system was not able to provide a sufficient intake airflow and the filters needed to be changed. Because HEPA filters are so restrictive in order to achieve the 99.97 pct. efficiency rating on 0.3-micron particles, it takes less dust loading to create significant restrictions and increased pressure differentials across the filter. Higher pressure differentials create lower airflows and encourage greater system leakage, as the air follows the path of least resistance from by-passing the filter. Because of the loss of intake airflow, this also creates a lower system positive pressure differential and subsequently increases the likelihood that outside cab dust and contaminants can be blown into the enclosure through cab imperfections.

By contrast to the HEPA filters, the MERV 16 filters showed an improved filtering efficiency over time and use as the filters loaded with dust. Since the MERV 16 rated filters were less restrictive and provided greater cab pressure, they did not have to be replaced as often as the HEPA quality filters. This testing also showed the benefits of using a mechanical filtering media, which becomes more efficient with dust loading and the creation of a filter cake. For both pieces of equipment used in this comparative study, the MERV 16 mechanical filter design was the optimal choice not only for performance but also for cost. Since MERV 16 filters are less expensive than HEPA quality filters, and they do not need to be changed as often which significantly lowers maintenance labor costs, this equates to significant cost savings.

Another key component of this testing was the validation of the substantial improvement in the effectiveness of filtration and pressurization systems when using a final filter design. The final filter adds another level of filtration to removed particulates that leak around the other filters in the HVAC system. However, filters used in the HVAC system should be adequately sized so as not to restrict airflow, thus lowering the system's effectiveness. This was shown not only through the modification expansion of NIOSH's model to include multiple filter applications but also from the actual test matrix performed on the filtration and pressurization systems of the roof-bolter and face drill machines.

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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.

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Appendix – Mathematical Formulation of Air leakages in Cab Filtration Systems

Figure A1 illustrates the node diagram of the three-filter system with potential leaks around the filters. As shown in this particular filtration system, the final filter is downstream of the intake and recirculation filters. Outside contaminants enter into the filtration system circuit through the intake filter, leakage around the intake filter, and direct penetration into the cab enclosure openings when wind velocity pressure exceeds cab pressure. Other air leaks in the system can occur around the recirculation and final filters. Some of the filtered interior cab air is pushed outside by the intake airflow and any outside wind penetration, while the remaining portion of the cabin air is recirculated through the recirculation and final filters.

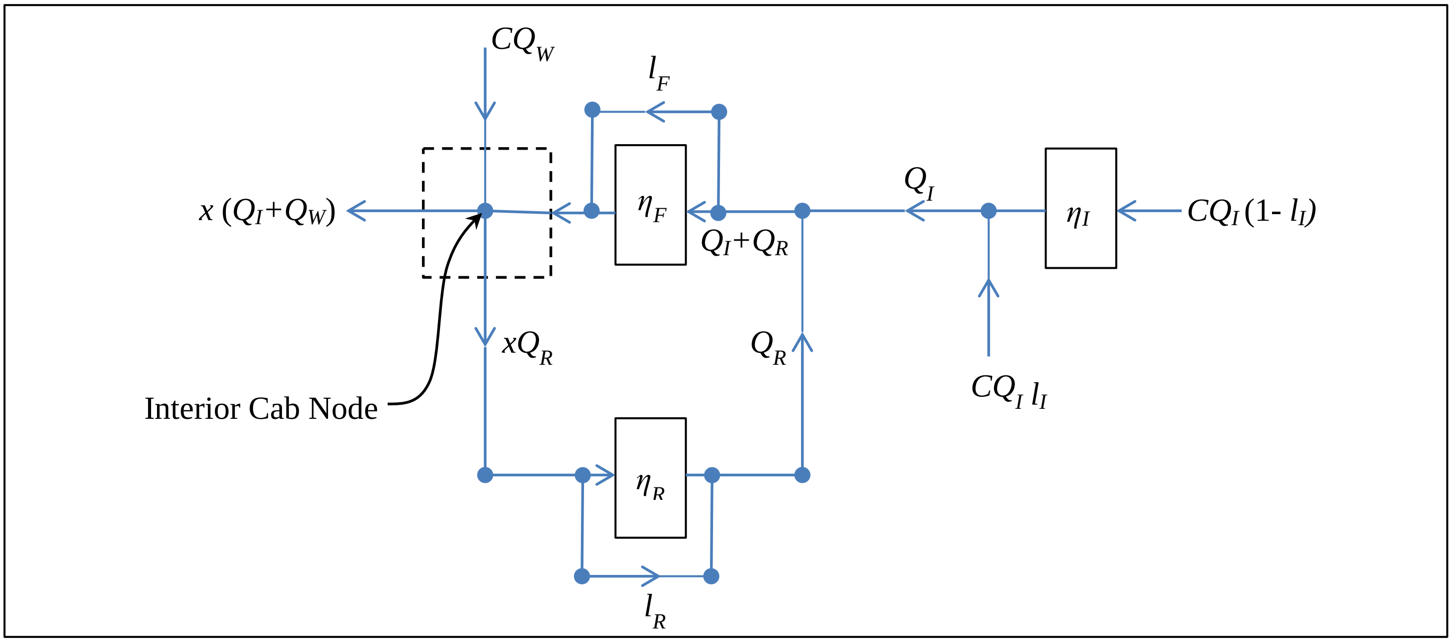

Figure A1. Three-filter cab system with potential leaks around the filters (*Q*'s denote air quantities, *x*'s & *C*'s denote contaminant concentrations, and *η*'s denote filter efficiencies).

The filtration system model is formulated as an equality of the incoming contamination mass to the exiting contamination mass at the interior cab node as defined in equation 1 while assuming steady-state conditions:

$$Mass_{in} = Mass_{out} \qquad (1)$$

The incoming mass is what penetrates the cab filtration system and the outgoing mass is what leaves the cab interior and is recirculated through the filtration system as shown in equation 2:

$$[CQ_I(1 - l_I)(1 - \eta_I) + CQ_I l_I + xQ_R(1 - \eta_R)(1 - l_R) + xQ_R l_R] \times [(1 - \eta_F)(1 - l_F) + l_F] + CQ_W = x(Q_I + Q_W) + xQ_R \qquad (2)$$

where:

C	=	outside contaminant concentration penetrating the filtration system,
x	=	inside cab contaminant concentration (interior cab node),
η	=	filter reduction efficiency, fractional,
1-*η*	=	filter penetration, fractional,
Q	=	airflow quantity,
l	=	air leakage, fractional

with filter efficiency and air quantity subscripts:

F	-	final,
I	-	intake,
R	-	recirculation,
W	-	wind

The bracketed intake, recirculation and final filter terms are multiplied and re-arranged:

$$[CQ_I(1 - \eta_I + l_I\eta_I)(1 - \eta_F + l_F\eta_F)] + [xQ_R(1 - \eta_R + l_R\eta_R)(1 - \eta_F + \eta_F l_F)] + CQ_W = x(Q_I + Q_R + Q_W) \qquad (3)$$

The outside and inside concentration terms are re-arranged to opposing sides of the equation:

$$[CQ_I(1 - \eta_I + l_I\eta_I)(1 - \eta_F + l_F\eta_F)] + CQ_W = x(Q_I + Q_R + Q_W) - [xQ_R(1 - \eta_R + l_R\eta_R)(1 - \eta_F + l_F\eta_F)] \qquad (4)$$

Next, we solve for protection factor (*PF*) ratio or penetration (*Pen* = 1/*PF*). The equation below was solved for protection factor and can be easily inverted to determine penetration:

$$PF = \frac{C}{x} = \frac{Q_I + Q_R - [Q_R(1 - \eta_R + l_R\eta_R)(1 - \eta_F + l_F\eta_F)] + Q_W}{[Q_I(1 - \eta_I + l_I\eta_I)(1 - \eta_F + l_F\eta_F)] + Q_W} = \frac{1}{Pen} \qquad (5)$$

This expression can also be used for two- and one-filter systems by using zero efficiency for the filters removed from the system.