Key components for an effective filtration and pressurization system for mobile mining equipment

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Abstract ■ Enclosed cabs have been used for many years to isolate workers on mobile equipment in the mining industry for health and safety reasons. These enclosed cabs create a microenvironment for workers where they can be either more protected or more vulnerable to contaminants. Over the past decade, the U.S. National Institute for Occupational Safety and Health (NIOSH) has performed substantial research efforts to improve the air quality inside enclosed cabs of underground and surface mobile mining equipment. In these efforts, NIOSH has partnered with mining companies, original equipment manufacturers (OEMs) and manufacturers of filtration and pressurization systems in a synergistic effort to reduce respirable dust and improve the air quality inside these enclosed cabs. Various field studies over this time have shown an array of results ranging from very minor to very significant reductions (protection factor: 3-89) in respirable dust levels inside these enclosed cabs. In addition to and concurrent with the field work, NIOSH also performed a comprehensive laboratory study to evaluate all the factors involved in cab filtration and pressurization systems and identified those factors that were most significant for an effective system. From this comprehensive research effort, the key components for an effective filtration and pressurization system have been identified in an effort to provide the best air quality to equipment operators inside of enclosed cabs of mobile mining equipment, thus minimizing respirable dust exposure.

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Introduction

Enclosed cabs have been used on mobile mining equipment for many years to protect operators from health and safety hazards. Enclosed cabs provide fall protection to the equipment operator and protect the mobile equipment operator from noise, dust and diesel contaminants. Protection of the operator from respirable dust inhalation was the primary focus of this research. The primary evaluation method used to determine the effectiveness of the pressurization and filtration system is to compare the respirable dust concentration inside the enclosed cab to those levels outside the cab. One would assume that without any protection in place, dust levels inside and outside the cab would be somewhat comparable. Even with an enclosure in place, this would also be the case when equipment operators leave the door and/or the windows open.

Throughout the past decade, the U.S. National Institute for Occupational Safety and Health (NIOSH) has partnered in a number of cooperative studies to determine the effectiveness of new filtration and pressurization systems installed on mobile mining equipment in an attempt to improve the air quality inside these enclosed cabs (Organiscak et al., 2004; Chekan and Colinet, 2003; Cecala et al., 2004; Cecala et al., 2005; Cecala et al., 2012). In all of these studies, pre- and post-evaluations of respirable dust concentrations using instantaneous and gravimetric sampling instrumentation, as well as airflow and pressurization measurements, were performed on filtration and pressurization systems installed on the enclosed cabs. These studies highlighted some very important factors, such as cab filtration, cab integrity and work practices and their impact on improving the air quality and ultimately protecting the workers with protection factors ranging from 3 to 89.

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Laboratory study

From the various cooperative research efforts performed to lower silica and other respirable dust contaminants inside enclosed cabs, a number of different factors appear to be most significant in an effective system. In order to evaluate these factors, a controlled laboratory experiment was performed at NIOSH's Pittsburgh laboratory (Organiscak and Cecala, 2008; NIOSH, 2008). Figure 1 shows the cab filtration system setup used for this laboratory study and indicates the various parameters evaluated.

In Fig. 1, the parameter definitions are as follows: 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; η_R = recirculation filter efficiency, fractional; Q_R = recirculation air quantity; Q_W = wind quantity infiltration; V_o = air velocity through an orifice; A_o = area of orifice; and V_C = cab volume. Airborne particle counting measurements were conducted inside and outside the laboratory cab test stand while using different levels of experimental test parameters.

The results of this laboratory study indicate that intake filter efficiency and the use of a recirculation filter had the greatest impact on improving the air quality inside 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 intake airflow and cab pressure significantly. The cab air quality was also affected by intake filter loading and air leakage.

Mathematical model to determine enclosure protection factor. 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) 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 (*PF*) 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. This model's applicability to determining cab filtration system performance was verified with the protection factor measurements and cab test parameters studied during the laboratory experiments.

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

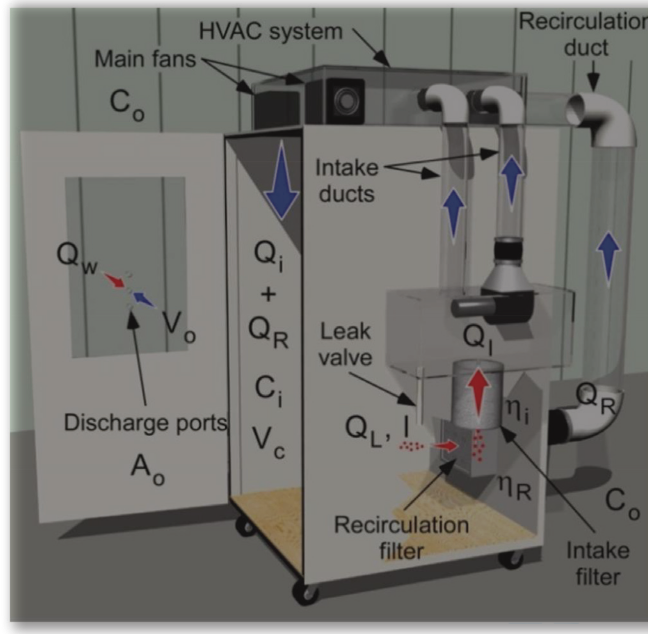
Equation (1) allows for a comparison of how changes in the various parameters and components in the system impact the *PF*. The wind quantity infiltration (Q_W) can be assumed to be zero if the cab pressure exceeds the wind velocity (Fig. 1). By using Eq. (1), operations have the ability to determine the desired parameters necessary to systematically achieve a desired *PF* in an enclosed cab to improve the air quality for the equipment operator.

Key components for an effective enclosed cab system

Based on the knowledge gained from NIOSH's laboratory and numerous cooperative field studies, the two most significant components necessary for an effective system for enclosed cabs in the mining industry are: 1) a competent

Figure 1

Design drawing showing various components of test setup to evaluate various operational parameters on a filtration and pressurization system for an enclosed cab.



filtration system comprised of a pressurized intake and a recirculation component and 2) an enclosed cab with structural integrity to achieve pressurization. These two keys components will be addressed, along with numerous secondary design considerations that should be considered for an effective system.

1. Effective filtration system

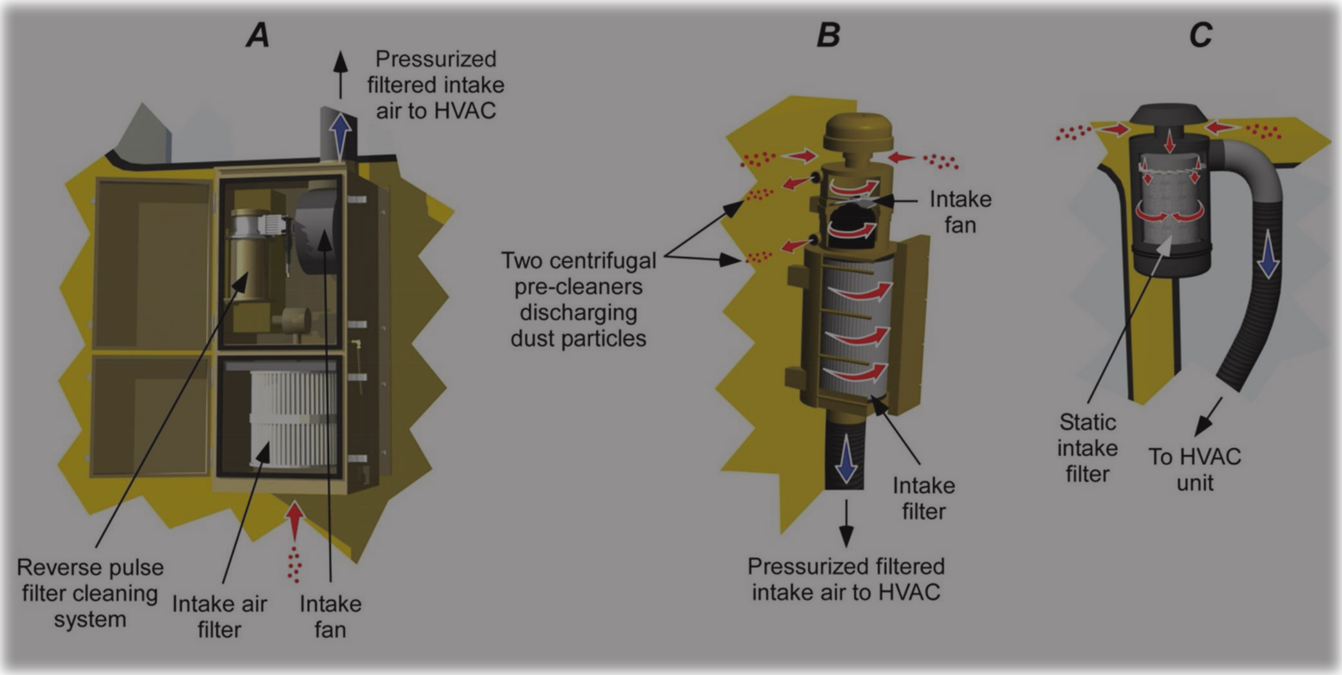
An effective filtration system is composed of a pressurized intake component as well as a recirculation component.

Effective pressurized intake air. An effective pressurized intake air component provides numerous important functions in an optimized system. First, it provides the required amount of outside air to ensure the equipment operator does not become asphyxiated from being in an enclosed area. A minimum quantity of at least 0.71 m^3/min (25 cfm) of intake/outside air per person is necessary to dilute CO_2 quantities exhaled by each worker (ASABE, 2003). Since almost all enclosed cabs for mobile equipment in the mining industry are designed for a single operator, a recommended lower limit for pressurized intake air would be somewhere around the 1.13 m^3/min (40 cfm) level range in order to achieve a minimal cab pressurization, while also ensuring a level of safety in regards to the CO_2 issue. A good rule of thumb for an acceptable pressurized intake air range derived from the various field testing would be between 1.13 and 3.96 m^3/min (40 and 140 cfm).

The second important aspect in relation to an intake air component is to create enough positive pressurization to eliminate the wind from blowing dust and contaminants into the enclosed cab (discussed in the "Cab integrity" section). The amount of intake air delivered to create this pressurization must be carefully controlled and optimized. Optimal intake air quantity is relative to the size of the cab, number of occupants, capacity of the cab to hold pressure and the efficiency of the intake and recirculation filtration. Maintain-

Figure 2

Design drawing showing two types of powered intake systems (A & B) as compared to static design (C).



ing the correct balance between these factors over extended periods is the goal of an optimized system. Increasing the air volume beyond this point degrades the system by increasing particle penetration and decreasing filter efficiency by allowing more contaminants to flow through the filter media. As the intake air volume increases, it creates higher demands on the HVAC system to either heat or cool the air for operator comfort, which is another reason to optimize the intake air volume.

High-efficiency intake filters are a necessity for an effective design. For the majority of enclosed cabs for mining applications, a MERV-16 intake filter using mechanical filter media would be the optimal design. When using a mechanical filter media, the filter becomes more efficient as it loads with dust and develops a filter cake. A nonloaded MERV-16 media would have a greater than 95% filtering efficiency on particles in the respirable size range, being from 0.3 to 10 µm. The MERV-16 filter is the highest rated type below the HEPA rating. As this filter media loads with dust, it then becomes even more efficient at removing particles from the intake airflow. It is a common trend today to immediately want to use a HEPA quality filter, which has an efficiency rating of 99.97% for particles greater than 0.3 µm in size. However, this filter is obviously more costly and restrictive than the MERV-16, which places additional demands on the entire system including the intake fan. In a recent NIOSH laboratory study to evaluate a number of different MERV rated filters, including a HEPA filter, on diesel particulate, it was believed that the MERV-16 rated filter would be the optimal design (Noll et al., 2011). In mining applications, a HEPA filter would load much more quickly with dust and diesel contaminants and this is thought to be more of a detriment than a benefit for filtration and pressurization systems for enclosed cabs in mining. NIOSH is currently performing a field study to compare MERV-16 to HEPA quality filters on the systems of two pieces of mobile equipment at an underground stone mine which will provide additional information on this comparison.

The last critical aspect is our recommendation that the intake be a powered unit versus a static (non-powered) system. On a powered unit, the intake air has its own fan, so the air is delivered at positive pressure through ductwork to the main HVAC unit. In this case, a known quantity of intake air is always being blown into the enclosed cab. Obviously, as the intake filter loads with dust, the intake air quantity will decrease, but there is a known air quantity range from a clean to a fully loaded filter. In addition, there are two proven techniques that can be used to minimize dust loading on the intake filter: 1) the use of a self-cleaning filter technique or 2) the use of a centrifugal design that spins out the over-sized dust particles (>5.0 µm) before the intake filter. A common self-cleaning method is to use a reverse-pulse or back-flushing technique that uses a compressed air system to blow the dust cake off the filter. This reverse-pulse can be set up on a regular time interval or based upon a differential pressure across the filter. With the centrifugal design, the system spins the oversized particles out of the system back into the atmosphere to minimize the number of particles being deposited on the intake filter. This system has an approximately 90% efficiency with particles greater than 5 µm. Both of these techniques have been tested by NIOSH during cooperative research studies and were shown to be very effective at providing a known quantity of intake air to the enclosed cab while minimizing dust loading on the intake filter (Cecala et al., 2004; Cecala et al., 2012). In a static design, the actual intake air quantity is dependent on the loading rate of all of the filters used in the system, and it is difficult to determine or control the intake to recirculation air ratio. It also becomes much more difficult to ensure that the minimal air quantity of 1.13 m^3/min (40 cfm) is being maintained. Figure 2 shows the two types of recommended powered intake systems as compared to the static design.

Effective recirculation filtration. The use of the recirculation system is a very important component for any filtration and pressurization system design and there is a range of operating parameters that can be used in an effective system. The first parameter to consider is the filtration efficiency of the recirculation filter and the recommended range should be between a MERV-14 (greater than 90% filtering efficiency on particles in the respirable size range, being from 0.3 to 10 µm) and a MERV-16 filter. The actual mining conditions in which the mobile equipment operates should dictate the actual filter efficiency rating chosen and should be based upon such things as the dust type, the silica content, the in-cab dust sources and dust levels, and the frequency that the mobile equipment operator enters or exits the enclosed cab, or even opens the door to perform a task or communicate with coworkers. It must be remembered that the ultimate effectiveness of the recirculation system is measured by the reductions that can be achieved through multiple cycles through the recirculation filter of the interior cab air (Organiscak and Cecala, 2009). The other consideration with the recirculation component is the volume of air recirculated and its proportion to the amount of intake air. The optimal amount of recirculation air derived from the laboratory and field research would be in the range of 3 to 4 times greater than the quantity of intake air, thus normally being in the range of 6-8 m^3/min (200 to 300 cfm) for a typical enclosed cab. When the recirculated air is in this range, it can quickly remove in-cab dust sources, such as dust brought in from the operator's work boots or clothing or dust allowed in when entering or exiting the enclosed cab. Obviously, even a 1 to 1 ratio of intake to recirculation air could be used, but this is not as effective because it requires more tempering of the air for heating or air-conditioning needs. Laboratory experiments showed a 10-times increase in protection factors when using a MERV-15 filter, which is 85 to 94.9% efficient on 0.3-to-1-µm particles, as compared to no recirculation filter. Laboratory testing also showed that the time for the interior to stabilize after the door was closed (decay time) was reduced by more than 50% when using the recirculation filter. The average decay times were between 16 and 29 minutes without the recirculation filter and between 6 and 11 minutes with the recirculation filter. Thus, the use of a recirculation filter greatly improved the air quality and reduced the exposure time after the cab door was closed (Organiscak and Cecala, 2008; NIOSH, 2008). An additional benefit of using a recirculation filter is that it allows cleaner air to be circulated through the HVAC system, thus providing better thermal efficiency and less maintenance, as stated above.

2. Cab integrity

Cab integrity is the second key component for an enclosed cab system and is necessary in order to achieve pressurization, which is critical for an effective system. To prevent dust-laden air from infiltrating into the enclosure, the enclosure's static pressure must be higher than the wind's velocity pressure (Heitbrink et al., 2000). Equation (2) is used to determine the wind velocity equivalent for an enclosure (the wind velocity at which the cab is protected from outside infiltration as determined by the static pressure):

$$\text{Wind velocity equivalent} = \left(\sqrt{\Delta p_{cab}}\right)\text{Pa} \times 4.48 \text{ @ standard air temperature and pressure} \quad (2)$$

Table 1

Average respirable dust concentrations (mg/m^3) inside enclosed cab for three days of testing with cab door closed and open.

	Door closed	Door open
Day 1	0.08	0.84
Day 2	0.17	0.39
Day 3	0.03	1.21

where Δp = cab static pressure in Pa.

In addition to maintaining an effective static pressure inside enclosed cabs as stated above, structural integrity is also important in regard to the filtration and pressurization system. Testing has shown that the installation of new door gaskets and seals, as well as plugging and sealing cracks and holes in the shell of the enclosure, has a major impact on increasing the enclosure pressurization. Gaskets and seals also need to be monitored and changed when signs of age (cracking or wear) or damage occur, because this could cause dust-laden air to be drawn into the unit, bypass the filtration component and be blown directly into the cab. In addition, it is also beneficial during inspection of the system to determine the cleanliness of the unit's ductwork. Dust seen inside the ductwork on the clean air side of the system is a good indication of a system failure.

Secondary design considerations

The following are other secondary design considerations for an effective filtration and pressurization system on mobile mining equipment.

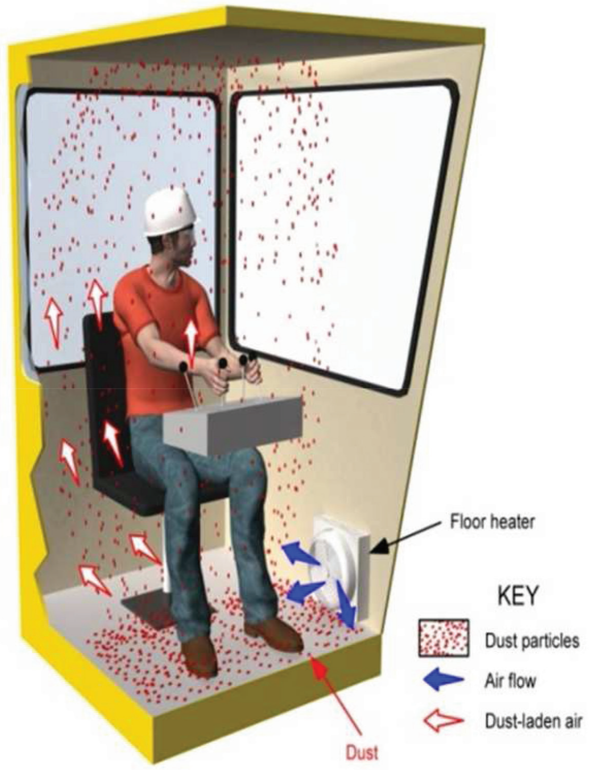
Intake air inlet location. The intake air inlet pickup location needs to be considered in the system design. Locating the cab air inlet near major dust sources causes unnecessary high dust loading on the air filtration system. This high dust loading burdens the filtration system and reduces its effectiveness by increasing the pressure drop across the loaded filter and decreasing the quantity of air and cab pressurization. In addition, the increased pressure drop across the loaded filter also increases the potential for dust leakage around the filter cartridge. This requires that the filter cartridge be cleaned or changed more frequently, which also increases the filter cost. Finally, air filtration is based on relative dust capture efficiency, so filtering higher outside dust levels creates higher inside cab dust concentrations.

In an effort to minimize these effects, it is recommended to place the enclosure's air inlet strategically away from dust sources to reduce dust loading of the filter cartridge (NIOSH, 2001). This can usually be accomplished by locating the outside air intake inlet at higher levels, away from the ground, and on the opposite side of the enclosed cab and away from dust sources. This location also enables the cab to shield some of the dust from the inlet.

Keeping doors and windows closed. In order to achieve and maintain enclosed cab pressurization, doors and windows must be closed at all times except while the operator is enter-

Figure 3

Problem created by heater stirring up dust from the floor and blowing dust off of the worker's clothing.



ing or exiting the cab. This problem was noted during a field study on a surface drill, when the operator repeatedly opened the cab door to manually guide the drill steel into place each time an additional section was needed (Cecala et al., 2007; Organiscak and Cecala, 2008). The cab door was usually open somewhere between 20 and 45 seconds each time this process took place before being closed again. Because no drilling was occurring and no dust cloud was visible as the cab door was opened, the impact to the drill operator's respirable dust exposure was initially thought to be insignificant. However, when dust data from inside the enclosed cab were analyzed, a substantial increase in respirable dust concentrations was noted during the periods when the door was open. This significant increase was unexpected when one considers that drilling had ceased approximately two minutes before the door was opened. Table 1 shows average concentrations for each of the three days of testing for the time period when the cab door was closed and open. The average concentration for all three days was 0.09 mg/m^3 with the cab door closed and 0.81 mg/m^3 with the door open. Despite no visible dust cloud during the time when the cab door was open, respirable dust concentrations inside the cab were nine times higher than when the door was closed and drilling was being performed.

The results of this testing clearly stress the importance of keeping doors and windows closed at all times in an effort to keep the compartment pressurized and working properly. Again, the only exception to keeping the door closed should be when the equipment operator enters or exits the cab. It also needs to be stressed that even when dust clouds are not visible outside, respirable dust levels can be significantly higher than filtered levels inside cabs.

Floor heaters. Any type of floor heater or fan located low in the enclosed cab that can stir up dust should be eliminated for an effective design. During a field study, it was found that a floor heater fan used during the winter months to provide heat to an operator of a surface drill greatly increased the respirable dust concentrations inside the enclosed cab (Fig. 3) (Cecala et al., 2001). The floor heater can be a serious problem because the floor is the dirtiest part of the cab due to the operator bringing dirt in on his or her work boots. Then, as the operator moves his or her feet around, dust is created and is then blown throughout the cab by the fan on the floor heater. This fan also tends to stir up dust that may be on the drill operator's clothes.

Because of the significant increase in dust levels with floor heaters, it is recommended that they not be used. If removal is not an option, they should be repositioned to a higher area in the enclosure where they are less prone to pick up dust from the floor and operator's clothing. Also, no type of fan should be used low in the cab because of the potential to stir up in-cab dust sources. Ideally, the heater unit should be tied into the filtration and pressurization unit to deliver the heated air at the roof of the cab.

Good housekeeping (cab cleanliness). To maintain pressurization and filtration systems, good housekeeping practices are essential in that systems need to be cleaned periodically and filters need to be changed when necessary. In addition, the enclosed cab must also be inspected for integrity to ensure that pressurization is maintained by replacing gaskets and seals when wear appears, and by plugging and sealing holes and cracks in the wall, ceiling, and cab floor. It must be understood that a system that is not properly maintained will deteriorate over time to a point where it is no longer providing an acceptable level of protection, thus causing workers to be exposed to respirable dusts.

During the field studies, a number of filtration units were found in all forms of disarray and had deteriorated to a condition where they were no longer providing acceptable levels of protection to the worker. In some cases, it appeared that the air quality or the protection provided to the worker was not a priority as long as the operator remained comfortable in regard to temperature controls. Although many cabs used standard heaters and air conditioners to control temperatures, in some instances workers resorted to just opening windows in an effort to be comfortable, thus bypassing the protection provided by the enclosed cab. With a little time, effort and finances, effective maintenance can be performed on filtration and pressurization systems to transition them from poor systems to ones that will again provide clean and acceptable air quality to workers.

Enclosure floors are commonly soiled from workers tracking dirt and product inside the enclosure upon entering from the mine site. In almost all cases, a substantial amount of dust and product gets tracked into the cab and housekeeping should be performed on a daily or shift basis. It is critical that the inside of an enclosed cab be maintained in a manner that minimizes the worker's respirable dust exposure.

Ease of filter change. When designing filtration and pressurization systems, one key component is the ease with which filters can be replaced when necessary. It defeats the purpose of a good system if a filter to be changed is so difficult to access that the operator or maintenance workers do not want to take the time to perform the task. Another consideration is dust contamination during the filter change. It also should be noted that, in many cases, this dust-laden filter will have some percentage of silica mixed in with the other types of dust; therefore, extreme care should be taken to minimize the exposure to the worker changing the filter. The easier a filter is to change, the less contamination should occur to the worker performing the task and to the work area. When changing a canister filter, a common and effective technique is to remove the new filter from the cardboard box and then insert the old dust-laden filter into the box, tape it closed, and dispose of it.

Mechanical filter media. It is highly recommended that the outside air and recirculation filters be a mechanical type filter media, as compared to an electrostatic media. Mechanical filters become more effective as they load with product. This occurs because, as the filter loads with dust, a dust cake forms on the filter media and captures additional dust particles, which further improves the filter efficiency. Increased filter efficiency occurs with enhanced loading until the point where the air flow through the filter drops to an unacceptable level and the system effectiveness is compromised. At this point, the filter needs to be cleaned or replaced. Filtration and pressurization systems can use a reverse pulse air jet to clean the dust cake from the filter media based on a preset time sequence or when a predetermined pressure loss occurs across the filter to effectively deal with this situation.

Monitoring cab system performance. An effective method to monitor a cab filtration and pressurization system's performance is a pressure differential indicator that notifies the operator of pressure changes. With any new filtration and pressurization system, the starting pressure should be determined and the change in pressure should be monitored over time as the filters load with contaminants. The pressure monitor provides a real-time indication of the system's performance. A magnehelic pressure gauge is one method to effectively monitor the cab filtration and pressurization system. In addition, a newly developed cab pressure monitor is currently available that uses an LED display to inform the equipment operator of the cab pressure. It also has an audible alarm that can be engaged to sound at a predetermined cab pressure to inform the operator of the need for service.

Since filter loading rates are different in all cases based on contaminant levels, using a filter cleaning or changing schedule based on time is not the preferred method because, as previously mentioned, a mechanical filter becomes more efficient as it loads with contaminants. The cab pressure indicator would inform the equipment operator or maintenance worker of the ideal filter changing time when the loss in cab pressure is such that it is detrimental to the overall system performance (maintaining positive pressure). On the other hand, based upon field experience, it is believed that the filter should be changed at 1,000 hours of use, and/or at least once a year for integrity issues, even if maintaining positive cab pressure does not become an issue. Conversely, a rapid increase in positive cab pressure also indicates a system failure. This could include such things as a hole or tear in the filter media, a clog in the recirculation system such as a plastic bag or a rag covering the recirculation inlet, or even a maintenance worker removing a used filter and then forgetting to replace it with a new one.

Unidirectional design. The use of a unidirectional airflow pattern should be considered whenever possible to maximize the air quality at the breathing zone of the operator inside the enclosure. In most systems, the intake and discharge for the recirculation air are located in the roof. Unfortunately, this location causes the dust-laden air within the enclosure to be pulled directly over the worker as it is drawn into the ventilation system. Further, in many designs, the contaminated return air and clean filtered air are ducted within inches of each other at the ceiling. This poor design allows for recirculated air to be short-circuited and allows dust-laden return air to be pulled directly back into the ventilation system and over the operator's breathing zone. A more effective design is to draw the recirculated air from the bottom of the enclosure, away from the worker's breathing zone (Cecala et al., 2009).

Conclusions

NIOSH has conducted a substantial effort during the past decade in an attempt to improve the air quality inside of enclosed cabs of mobile equipment in the mining industry. From many different cooperative field studies, along with an in-depth laboratory study, the key components for an effective filtration and pressurization system have been identified in an effort to minimize the respirable dust exposure and provide the best air quality to the equipment operator. The two most significant components necessary for an effective system are a competent filtration system comprised of a pressurized intake and a recirculation component, and an enclosed cab with structural integrity to achieve pressurization. Some other secondary considerations include: locating the intake air inlet at a point to minimize as much dust loading on the filter as possible; having the operator keep doors and windows closed; the elimination of any fans or heaters located on the floor of the cab, which stirs up dust from the operator's clothing and the floor; performing good housekeeping techniques, including periodic filter changes on the filtration system and daily cleanings of the enclosed cab; using a system that allows for easy access for the filter changes; using mechanical filter media which becomes more efficient as it loads with dust; using some type of visual pressure indicator to inform the equipment operator of the cab pressure and when a filter is damaged or clogged; and considering a uni-directional design to minimize respirable dust flowing over the equipment operator's breathing zone as it is drawn into the recirculation inlet duct. These components are necessary to provide an operator cab that minimizes respirable dust exposure and delivers the best air quality to the equipment operator. ■

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Disclosure

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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