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KEY COMPONENTS FOR AN EFFECTIVE FILTRATION AND PRESSURIZATION SYSTEM TO REDUCE RESPIRABLE DUST IN ENCLOSED CABS FOR THE MINING INDUSTRY

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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 National Institute for Occupational Safety and Health (NIOSH) has performed substantial research efforts to improve the air quality inside enclosed cabs of both underground and surface mobile mining equipment. In these efforts, NIOSH has partnered with mining companies, original equipment manufacturers (OEMs), and manufacturers of filtrations and pressurizations 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 to 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, thus minimizing the respirable dust exposure, to equipment operators inside of enclosed cabs of mobile mining equipment.

INTRODUCTION

A health screening study performed during the mid-1990s in central Pennsylvania identified a significant number of silicosis cases attributed to operators of mobile mining equipment in enclosed cabs that were not providing an acceptable level of protection [CDC 2000]. In this study, 1,236 miners at eight different surface coal mines were screened for lung disease, and chest x-rays showed that 6.7 percent of these workers were diagnosed with silicosis. In one particular county, 16 percent of the 213 participants were classified with the disease. In this study, surface drill operators had the greatest number of cases of silicosis, although workers on other types of mobile equipment, including dozers, loaders, and haul trucks, were also being overexposed to crystalline silica and respirable dust. One alarming aspect was that in a number of cases, workers that were relatively young in age with relatively little mining experience were being diagnosed with the disease. It was also felt that some of the equipment being used at the mines participating in this study was very old, in particular some of the surface drills. In most cases when mining equipment is new and everything is working properly, respirable dust over-exposures to equipment operators are minimal. The problem occurs as the equipment ages and components deteriorate to the point where the air quality inside the enclosed cab is no longer providing acceptable levels of protection for the equipment operators. Figure 1 graphs overexposure rates to silica dust for both surface coal and metal/nonmetal operations from 1997 through 2011 based on compliance sampling results from the Mine Safety and Health Administration (MSHA) inspection data, showing a fairly consistent trend over this time period. These samples included operators of

backhoe, bulldozer, haul truck, front-end loader, and various types of drills at surface coal and metal/nonmetal operations.

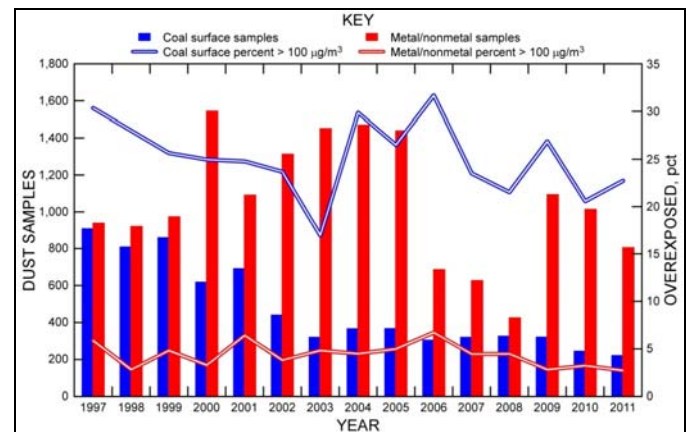


Figure 1. Silica overexposure rates for metal/nonmetal and surface coal mining operations.

Because of these overexposures and silicosis cases, a number of organizations began investigating enclosed cabs to better understand the problem and to determine methods and solutions to improve the air quality and protect workers. NIOSH entered into a number of cooperative research efforts with mining companies, original equipment manufacturers (OEMs), and manufacturers of filtration and pressurization systems in a synergistic effort to address this problem and ultimately reduce worker's dust exposures. In the majority of these cooperative studies, NIOSH partnered with an equipment manufacturer and a mining operation on retrofit cab filtration and pressurization systems. In most cases, the mining operation was asked to choose the piece of mobile equipment with the highest in-cab respirable dust levels based on MSHA compliance and in-house sampling. NIOSH would then perform testing on the mobile equipment to determine baseline dust levels. After this was completed, a filtration and pressurization manufacturer, the mining company, and NIOSH would cooperate to install a retrofitted filtration and pressurization system on the enclosed cab. A series of follow-up evaluations were then completed to determine the performance with the new system in operation. The goal was to evaluate inside and outside cab respirable dust concentrations before and after the installation of the retrofit filtration and pressurization system to determine the protection factor afforded the equipment operator with the new system.

More recently, a cooperative effort was undertaken with J.H. Fletcher & Company, a major manufacturer of underground mining equipment. J.H. Fletcher designed a new filtration and pressurization system for the cabs on its underground metal/nonmetal mining equipment. Once the design was completed, the company approached NIOSH and asked for comments and feedback on the system. It was through this interaction that a cooperative study was initiated to perform a long-term evaluation of this newly designed system in an

underground mine. It was believed that this long-term study would benefit the entire mining industry with the information and knowledge gained. From this, as well as from all of the cooperative studies, modifications have been identified and implemented to improve the air quality in enclosed cabs of mobile mining equipment, thus contributing to improving the health of these workers and moving towards the ultimate goal of eliminating silicosis and other debilitating lung diseases from the mining industry.

BACKGROUND

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 is the primary focus of this report. The primary evaluation method used to determine the effectiveness of a 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 of the cab would be somewhat comparable. Even with protection in place, this would also be the case when equipment operators leave the door and/or the windows open.

There are a number of different descriptors that can be used to provide numerical values to rank the filtration and pressurization system's effectiveness at lowering inside versus outside cab dust levels. The following three descriptors are commonly used for this purpose:

$$\text{Protection Factor (PF)} = \frac{C_o}{C_i}; (\text{ratio})$$

$$\text{Efficiency } (\eta) = \frac{C_o - C_i}{C_o};$$

(fraction, or multiplied by 100 for percent value)

$$\text{Penetration (Pen)} = 1 - \eta; (\text{fraction})$$

where, C_o = outside respirable dust concentration, and C_i = inside respirable dust concentration. A comparison of these descriptors can be provided by the following:

$$PF = \frac{C_o}{C_i} = \frac{1}{1 - \eta} = \frac{1}{Pen}$$

Obviously, the higher the value for both *protection factor* and *efficiency*, and the lower the value for *penetration*, that can be achieved, the better the air quality is inside the enclosed cab. As a comparison, a *protection factor* of 100 would be comparable to an *efficiency* of 99 percent or a *penetration* of 0.01 percent. NIOSH has typically used the *protection factor*(PF) term and it will be the evaluation descriptor used for the various studies presented in this manuscript.

As previously mentioned, 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. The results of a number of these studies can be seen in Table 1, listed in ascending order of effectiveness [Organiscak et al. 2004; Chekan and Colinet 2003; Cecala et al. 2004; Cecala et al. 2005; Cecala et al. 2012].

These studies highlight some very important factors relevant to improving the air quality in enclosed cabs and ultimately protecting the workers. Cab integrity, and the related ability to achieve positive pressurization, was found to be a critical component. As seen in Table 1, when there was very little to no cab pressure detected, this resulted in minimal improvement in the cab's air quality in comparison to

outside cab dust levels. In fact, identical filtration and pressurization systems were installed on the rotary drill and front-end loader, listed as rows 1 and 4 in the table, with the PF varying from 2.8 to 10, respectively. The most notable difference between these two systems was that a small amount of pressurization was achieved in the front-end loader (row 4), whereas it was not possible to achieve any pressurization in the rotary drill (row 1).

Table 1. Summary of field studies evaluating enclosed cabs

Cab evaluation	Mining type	New versus retrofit system	Cab pressure, Pa /inch (wg)	Average inside cab dust level, mg/m ³	Average outside cab dust level, mg/m ³	Protection factor, out/in
1. Rotary drill	Surface	Retrofit	None detected	0.08	0.22	2.8
2. Haul truck	Underground	Retrofit	2.50 (0.01)	0.32	1.01	3.2
3. Roof-bolter	Underground	New	12.5 – 25.0 (0.05 – 0.10)	0.12	0.92	8
4. Front-end loader	Surface	Retrofit	3.75 (0.015)	0.03	0.30	10
5. Face drill	Underground	New	12.5 – 50.0 (0.05 – 0.20)	0.19	2.43	28
6. Rotary drill	Surface	Retrofit	50.0 – 100.0 (0.20 – 0.40)	0.05	2.80	56
7. Rotary drill	Surface	Retrofit	17.5 – 30.0 (0.07 – 0.12)	0.7	6.25	89.3

Although evaluating cab performance using protection factor, or the other two cab performance measures, is very useful, it must always be remembered that the most critical factor is the respirable dust concentration inside the enclosed cab when considering a worker's health. A case in point is the testing on the two pieces of new mobile mining equipment in the same underground metal/nonmetal mine, being rows 3 and 5 in Table 1. In this case, the protection factor was 8 and 28 for the roof-bolter and face drill machines, respectively, and it would appear that the face drill was much more effective at protecting the equipment operator. But when one considers the inside cab dust level, the roof-bolter operator was exposed to a lower respirable dust concentration than the face drill operator, being 0.12 and 0.19 mg/m³, respectively. When considering the actual value of the protection factor descriptor, it must be noted that the outside dust concentration greatly impacts the numerical value. It should be noted that both the protection factor value and the inside dust concentration need to be considered when evaluating the actual health of the equipment operator.

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. Figure 2 shows the cab filtration system setup used for this laboratory study and indicates the various parameters evaluated [Organiscak and Cecala 2008; NIOSH 2008].

In Figure 2, the parameter values are as follows:

PF = protection factor, C_o/C_i ;
 C_o = outside cab concentration;
 C_i = inside cab concentration;
 η_i = intake filter efficiency, fractional;
 Q_i = intake air quantity;
 Q_L = leakage air quantity;
 I = intake air leakage, Q_L/Q_i ;
 η_r = recirculation filter efficiency, fractional;
 Q_r = recirculation air quantity;
 Q_w = wind quantity infiltration; and
 V_c = cab volume.

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 both intake airflow and cab pressure significantly. The cab air quality was also affected by intake filter loading and air leakage.

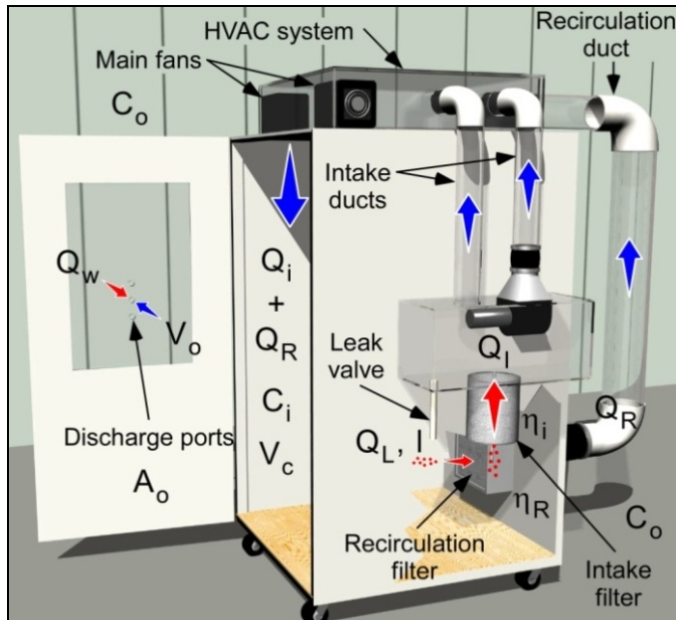


Figure 1. Design drawing showing various components of test setup to evaluate various operational parameters on a filtration and pressurization system for an enclosed cab.

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 1¹ 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 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.

$$PF = \frac{C_o}{C_i} = \frac{Q_i + Q_R}{Q_i(1 - \eta_i + \eta_R) + Q_w} \quad \text{Equation (1)}$$

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 (Figure 2). By using Equation 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 both 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 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.

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 m³/min (25 cfm) of intake/outside air per person is necessary to dilute CO₂ 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 m³/min (40 cfm) level range in order to achieve a minimal cab pressurization, while also ensuring a level of safety in regards to the CO₂ issue. A good rule of thumb for an acceptable pressurized intake air range would be between 1.13 and 3.96 m³/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. Maintaining 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 non-loaded MERV-16 media would have a greater than 95 percent filtering efficiency on particles in the respirable size range, being from 0.3 to 10 microns. This 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. Laboratory experiments showed a 10-times increase in protection factors when using a 99percent efficient filter versus a 38percent efficient filter on respirable sized particles. It is a common trend today to immediately want to use a HEPA quality filter, which has an efficiency rating of 99.97 percent for particles greater than 0.3 microns 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, being: 1) the use of a self-cleaning filter technique, or 2) the use of a centrifugal design which spins out the over-sized dust particles (>5.0 microns) before the intake filter. A common self-cleaning method

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

is to use a reverse-pulse or back-flushing technique which uses a compressed air system to blow the dust cake off the filter. This reverse-pulse can be setup 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 percent efficiency with particles greater than 5 microns. 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 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 m³/min (40 cfm) is being maintained. Figure 3 shows the two types of recommended powered intake systems as compared to the static design.

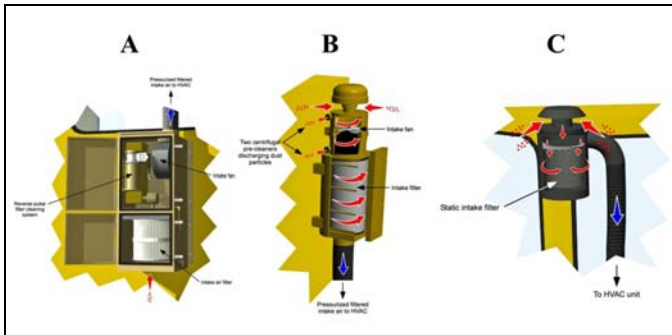


Figure 3. Design drawing showing two types of powered intake systems (A & B) as compared to static design (C).

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 wide range of operating parameters that can be used in an effective system. The first area to consider is the filtration efficiency of the recirculation filter and the recommended range should be between a MERV-14 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 co-workers. It must be remembered the ultimate effectiveness of the recirculation system is 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 would be in the range of 3 to 4 times greater than the quantity of intake air, thus normally being in the range of 200 to 300 cfm for a typical enclosed cab. When the recirculated air is in this range, it can quickly remove dust from in-cab contaminants or from the operator entering or exiting the cab. Obviously even a 1to 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 percent efficient on 0.3 to 1.0 micron 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 percent 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.

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. 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. 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):

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

where Δp = cab static pressure in Pascal's.

Figure 4 provides a graphical display of this wind velocity equivalent. The figure shows that an enclosure pressure of 50, 100, 150, and 200 pascals would be able to withstand wind velocities of 32, 45, 55, and 63 km/hr, respectively, from penetrating dust into the enclosure. Although minimum pressurization has been shown to have positive results from field studies, a good rule of thumb is to have at least 12.5 to 19.9 pascals (0.05 – 0.08 inches wg) of positive pressure in enclosed cabs. A reasonable range of enclosure pressure is between 19.9 and 62.3 pascals (0.08 and 0.25 inches wg).

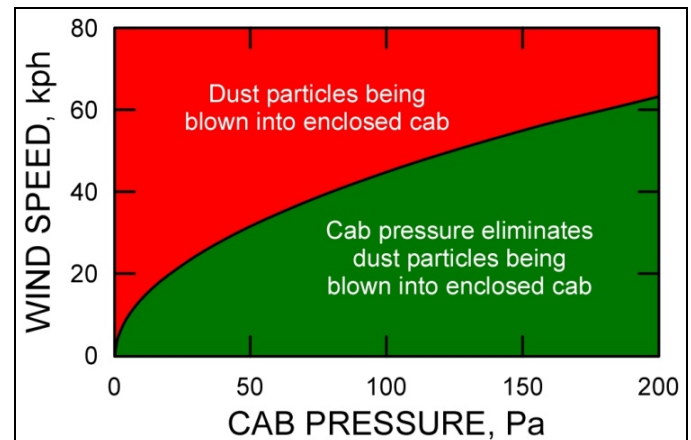


Figure 4. Positive cab pressure necessary to prevent dust-laden air from infiltrating the enclosed cab at various wind velocities.

Table 2 summarizes the criticality of both the filtration and cab integrity components. This table presents the calculated PF using the mathematical model derived from the laboratory study (Equation 1). In this table, the following component parameters have been chosen: intake air quantity (Q_i) of 1.42 m³/min (50 cfm), recirculation system (Q_r) of 8.50 m³/min (300 cfm), a recirculation filter efficiency (η_r) of 0.7 (70 percent), an intake filter efficiency (η_i) of 0.95 (95 percent), and leakage (l) of 0, 5 percent, 10 percent, and 15 percent ($l = 0, 0.05, 0.10, 0.15$).

This table highlights a number of critical factors. First, it shows how the effectiveness of each system deteriorates as the leakage into the enclosed cab increases. Leakage occurs from either a lack of cab integrity or an insufficient intake air volume. The second critical factor is the need for a recirculation system. When one evaluates an enclosed cab with no leakage, the PF is increased from 20 to 104 by the addition of an 8.50 m³/min (300 cfm) recirculation system with a 70 percent efficient filter. This highlights the criticality of the recirculation component. A high efficiency recirculation filter is not necessary as long as a filter within reasonable filter efficiency range is used and maintained (i.e., MERV-14 to -16). This is demonstrated by viewing the first column in Table 2 where $l = 0$ (leakage equals zero) and the PF

only increases by 24 when going from a 70 to a 90 percent efficient recirculation filter. Since the air is constantly being recirculated, any respirable dust inside the cab will be removed within a few passes through the recirculation system.

Table 2. Calculated PF derived from mathematical model.

	$L=0$	$L=0.05$	$L=0.10$	$L=0.15$
$(Q_r) = 1.42 \text{ m}^3/\text{min}$ (50 cfm) $(Q_a) = 8.50 \text{ m}^3/\text{min}$ (300 cfm) $(\eta_i) = 0.95$ $(\eta_R) = 0$	20.0	10.3	6.9	5.2
$(Q_r) = 1.42 \text{ m}^3/\text{min}$ $(Q_a) = 8.50 \text{ m}^3/\text{min}$ $(\eta_i) = 0.95$ $(\eta_R) = 0.70$	104.0	53.3	35.9	27.0
$(Q_r) = 1.42 \text{ m}^3/\text{min}$ $(Q_a) = 8.50 \text{ m}^3/\text{min}$ $(\eta_i) = 0.95$ $(\eta_R) = 0.90$	128.0	65.6	44.1	33.2

In addition to maintaining the competence of the structure on enclosed cabs as stated above, integrity is also important in regards to the filtration and pressurization system. Gaskets and seals within the filtration and pressurization system 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 pick-up 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 intake cab dust concentrations.

In an effort to minimize these effects, it is recommended to place the enclosure's air inlet location 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 entering 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 2 minutes before the door was opened. Table 3 shows average concentrations for each of the 3 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.

Table 3. Respirable dust concentrations inside enclosed cab for three days of testing with cab door closed and open

Average Respirable Dust Concentration, mg/m^3		
	Door Closed	Door Open
Day 1	0.08	0.84
Day 2	0.17	0.39
Day 3	0.03	1.21

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 (Figure 5) [Cecala et al. 2001]. The floor heater can be a serious problem because the floor is the dirtiest part of the cab from the operator bringing dirt in on his or her work boots. Then as the operator moves his or her feet around, dust is created, which 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.

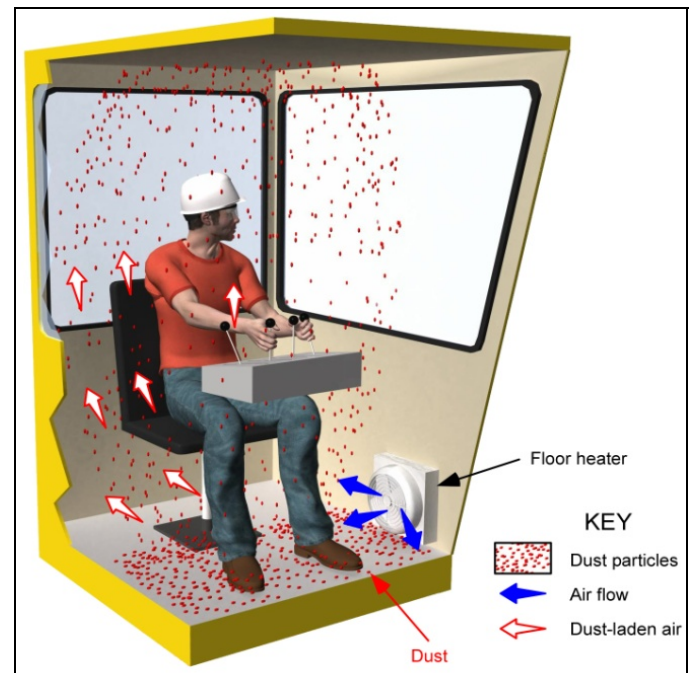


Figure 5. Problem created by heater stirring up dust from the floor and blowing dust off of the worker's clothing.

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 both 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. As the size of this filter cake continues to increase, the efficiency continues to increase. This causes the pressure differential across the filter to increase, which in turn causes the airflow to decrease. As the pressure increases further, it will become so restrictive that the filter will need to be cleaned or replaced.

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 the most real-time indication of the cab'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 which uses an LED display to inform the equipment operator of the cab pressure and also has an audible alarm which 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, the filter should be changed at 1,000 hours of use, and/or at least once a year, 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.

Uni-directional design

The use of a uni-directional 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, both 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 over 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 area 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 which includes periodic filter changes on the filtration system and daily cleanings of the enclosed cab; using a system which 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.

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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