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FORTY YEARS OF NIOSH/USBM-DEVELOPED CONTROL TECHNOLOGY TO REDUCE RESPIRABLE DUST EXPOSURE TO MINERS IN INDUSTRIAL MINERALS PROCESSING OPERATIONS

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ABSTRACT

Worker exposure to dust—especially respirable crystalline silica—has long been a paramount concern for the health of our nation's miners and other workers. The inhalation of respirable crystalline silica can lead to silicosis, a disabling and potentially fatal lung disease, as well as also having other major health consequences. One main area of focus for the Pittsburgh Mining Research Division of the National Institute for Occupational Safety and Health, and the former U.S. Bureau of Mines, has been to conduct research to lower exposure to respirable crystalline silica dust and other respirable dusts and contaminants in mining operations. This proceeding provides an overview of a number of engineering control technologies and interventions that have been developed and tested over the past 40 years and which have been demonstrated to be successful in lowering mine workers' respirable dust exposure at metal/nonmetal mines and mills, and specifically at industrial mineral processing operations.

INTRODUCTION

In May 1994, the National Institute for Occupational Safety and Health (NIOSH) considered crystalline silica to be a potential occupational carcinogen as defined by the Occupational Safety and Health Administration's (OSHA) carcinogen policy [29 CFR 1990], and this information was used in establishing the NIOSH Recommended Exposure Limit (REL) at 50 µg/m^3 [NIOSH 2014]. NIOSH has long realized that occupational overexposure to respirable crystalline silica (RCS) dust can lead to the development of silicosis, an incurable and often fatal lung disease, but can also result in health problems that include chronic obstructive pulmonary disease, tuberculosis, chronic bronchitis, emphysema, and chronic renal disease. Probably the most significant occupational travesty which brought focus to the effects of silicosis was the Hawk's Nest Tunnel Disaster in southern West Virginia where a 4.83 km (3-mile) tunnel was driven through the Gauley Mountain. The material being removed during the mining of this tunnel for the development of a hydroelectric power plant was a sandstone and limestone ore containing very high levels of crystalline silica. Within months of the completion of this work, 476 of the workers died from acute silicosis [Cherniack 1986; Stalnaker 2006]. This acute silicosis was caused by extremely high respirable dust concentrations while driving this tunnel and was attributed to inconsistent dust control methods including poor ventilation and minimal use of water, not allowing the dust to settle after blasting occurred before workers returned back inside the tunnel, and no use of respiratory protection.

Over forty years ago, the Mine Safety and Health Administration (MSHA) implemented the Federal Mine Safety and Health Act of 1977, which states "the first priority and concern of all in the coal or other mining industry must be the health and safety of its most precious resource—the miner" [MSHA 2009]. This Act has since impacted the health and safety research program of the U.S. Bureau of Mines (USBM), and subsequently NIOSH. One of the consistent research goals for both USBM and NIOSH was to lower the respirable dust exposure to all mine workers, and as it specifically relates to this paper, RCS dust exposure to metal/nonmetal miners working in industrial minerals processing operations.

Between 1968 and 2016, there have been 17,155 American worker deaths due to silicosis, with 637 of those deaths occurring since 2010 [NIOSH NORMS 2018]. The latest work-related lung disease surveillance report shows that from 1990 to 1999, 20.2 percent of the total deaths (178 of 881) have occurred in the metal/nonmetal (M/NM) mining industry [DHHS 2008]. Throughout the metal/nonmetal mining cycle, ore is mined underground or in open pits and quarries. This ore is then processed in industrial mineral processing operations where it goes through a series of crushing, grinding, cleaning, drying, and product-sizing sequences as it is processed into a marketable commodity. Because these operations are highly mechanized, they are able to process high tonnages of mined ore. This in turn generates large quantities of dust, often creating elevated levels of RCS dust and other contaminants, which is liberated into the work environment and exposes miners working in these operations.

The serious health effects from overexposure to respirable dust from these mining operations has been known for many years. When one considers that the ore being processed within the M/NM mining industry often contains RCS dust, the health effects to miners are even greater [NIOSH 2002; Hessel et al. 1988]. This is the reason MSHA mandates a reduced respirable dust standard when silica is present [MSHA CFR 2008], which results in a maximum exposure equivalent to 100 µg/m^3 of RCS dust. In 2016, OSHA passed a new regulation that established a 50 µg/m^3 RCS standard for non-mining industries. MSHA has a request for information, including an appropriately reduced permissible exposure limit for RCS, on its 2019 spring regulatory agenda [MSHA 2019].

CONTROL TECHNOLOGY TO REDUCE RESPIRABLE CRYSTALLINE SILICA DUST EXPOSURE

The purpose of this document is to highlight a number of effective dust control techniques that have been developed and tested over the past 40 years by NIOSH and the USBM since the implementation of the 1977 Mine Safety and Health Act.

The following, although not exhaustive, are some of the major efforts that impact the health of our nation's miners by lowering their respirable dust exposures. The discussion of engineering controls and other advances in technology come from NIOSH's second edition of the Dust Control Handbook for Industrial Minerals Mining and Processing (Figure 1) [NIOSH 2019]. Specifically, effective controls discussed within this proceeding include filtration and pressurization for environmental enclosures, Helmet-CAM assessment technology and EVADE Software, clothes cleaning booth systems, total structure ventilation system, dual-nozzle bagging system, overhead air supply island system, bag and belt cleaner systems, and semi-automated bag palletizing systems.[1] For additional detail of these and additional controls, a downloadable copy of the handbook is available here: https://www.cdc.gov/niosh/mining/works/coversheet2094.html.

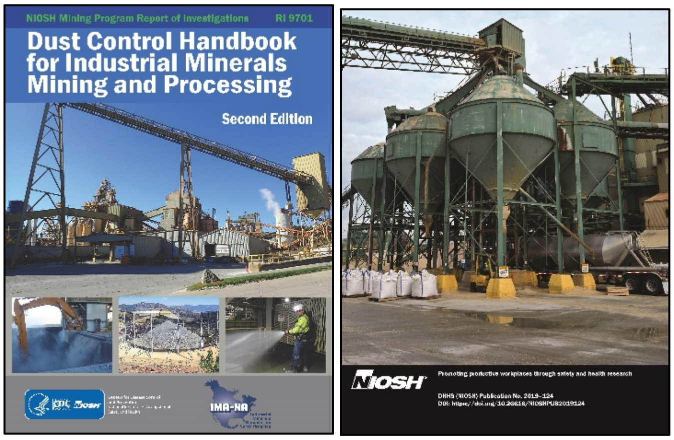


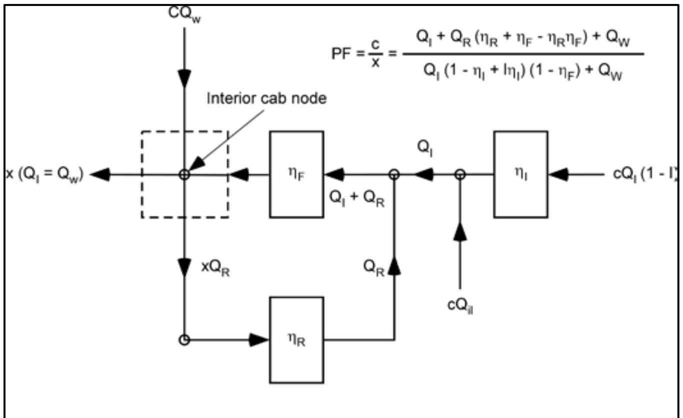
Figure 1. Front and rear covers of the Dust Control Handbook for Industrial Minerals Mining and Processing—Second Edition, published in March 2019.

Filtration and Pressurization for Environmental Enclosures

Environmental enclosures, such as enclosed cabs, operator booths, and control rooms, have been used for many years to isolate workers from dust sources in mining and mineral processing operations. When properly designed, installed, and maintained, they can provide a safe work environment by supplying clean and acceptable air quality to mine workers. Enclosed cabs on mobile equipment are unique in that the equipment is constantly moving and working in different mining areas and are therefore subjected to vastly different dust conditions. Operator booths and control rooms do not experience this constant stress from movement but can be affected by significant vibration from various work processes such as the dumping of a large volume of product into the primary crusher hopper, as well as from primary or secondary crushers. In addition, operator booths and control rooms are normally larger in volume when compared to enclosed cabs, and typically there is significantly more ingress and egress in the booth or room by multiple workers. In short, mine workers in environmental enclosures are surrounded by dynamic working conditions that have highly variable dust sources. These enclosures create a microenvironment where workers can be either more protected or more vulnerable to respirable dust and other contaminants.

The most effective technique for reducing mine workers' exposure to airborne dust in environmental enclosures is with filtration and pressurization systems. The most effective systems have heating, ventilation, and air-conditioning (HVAC) components tied in as an integral part of the system. NIOSH conducted a controlled laboratory study to evaluate key factors necessary for achieving an effective enclosure filtration and pressurization system [NIOSH 2008a; Organiscak and Cecala 2009b]. In the course of the laboratory study, the significance of the filtration system parameters were evaluated and the following mathematical model was developed for a three-filter system (intake, recirculation, and final filter). Figure 2 shows the optimal design with a three-filter cab system in a node layout, along with the NIOSH-developed dimensionless mathematical model to provide performance measurements in terms of corresponding protection factors (PF).

This model was formulated from a basic time-dependent mass balance model of airborne substances within a controlled volume with steady state conditions. It determines the protection factor in terms of intake air filter efficiency, intake air quantity, intake air leakage, recirculation filter efficiency, recirculation filter quantity, and outside wind quantity infiltration into the cab. The equation allows for a comparison of how changes in the various parameters and components in the system impact the protection factor. The wind quantity infiltration (QW) can be assumed to be zero if the cab pressure exceeds the wind velocity pressure. By using this equation, operations have the ability to determine the desired parameters necessary to systematically achieve a desired protection factor in an operator's booth, control room, or enclosed cab to improve the air quality to safe levels, and to ultimately protect their workers [Organiscak and Cecala 2009a].



$$PF = \frac{c}{x} = \frac{Q_I + Q_R(\eta_R + \eta_F - \eta_R\eta_F) + Q_W}{Q_I(1 - \eta_I + I\eta_I)(1 - \eta_F) + Q_W}$$

Where: c = outside contaminant concentration penetrating the filtration system
x = inside cab contaminant concentration (interior cab node)
η = filter reduction efficiency, fractional
I - η = filter penetration, fractional
Q = airflow quantity
I = intake air leakage, fractional
With the following filter efficiency and air quality subscripts:
I = intake
F = final
R = recirculation
W = wind

Figure 2. Three-filter cab system node analysis layout with the final filter downstream of the intake and recirculation (left) and dimensionless equation model (right). Air quantities used must be in equivalent units, filter efficiencies and intake air leakage must be fractional values (not percentage values).

The advancement of engineering and scientific knowledge gained from this research led to an understanding and the development of key critical components and optimal design features for effective filtration and pressurization systems. The following are the major key components for an effective system, as well as a few secondary considerations.

Key Considerations

Effective pressurized intake air. An effective intake air component provides numerous important functions for a filtration and pressurization system. It provides the required amount of outside air to ensure mine workers in environmental enclosures do not become asphyxiated from being in the closed space. A minimum of 0.71 m^3/min (25 cfm) of intake/outside air per worker should be the minimal amount per person to dilute CO_2 quantities exhaled per individual. Considering an enclosed cab on mobile equipment involves almost always a single operator, it is recommended that the lower limit for pressurized intake air would be somewhere around 1.13 m^3/min (40 cfm) in order to achieve minimal cab pressurization. A good rule of thumb for pressurized intake air on an enclosed cab would be a range between 1.13 and 3.96 m^3/min (40 and 140 cfm). For larger environmental enclosures, it is recommended to have a minimum of 1.13 m^3/min for the first person and then an additional 0.71 m^3/min for each additional

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[1] All of the content in this proceeding has been reviewed and is excerpted and adapted from the second edition of the Dust Control Handbook for Industrial Minerals Mining and Processing or other NIOSH and USBM publications. The purpose of this proceeding is to provide a summary of key previously published content in one document to better highlight effective engineering controls and technologies to reduce worker exposure to RCS.

person as a minimum. Another important aspect for intake air is to create enough positive pressurization to prevent the wind from blowing dust and contaminants into the enclosure.

High-efficiency intake filters are also a necessity for an effective design. For the majority of systems in mining applications, a MERV-16 filter, which is greater than or equal to 95 percent filtering efficiency on particles in all respirable-sized ranges (i.e., 0.3–10-microns particles), would be optimal. This filter should also be fabricated mainly from mechanical filter media, which becomes more efficient as it loads with contaminants and develops a filter cake, thus becoming even more efficient at removing particles from the intake airflow over time and use. The last critical aspect is to be a powered intake unit, versus a static (non-powered) design, so that the intake air is delivered into the enclosure regardless of the fan setting or other system factors.

Effective recirculation filter. The use of a recirculation system is the next critical component for an optimal filtration and pressurization system. The volume of air recirculated should typically be in the range of three to four times greater than the intake air quantity, thus normally being in the range of 5.66 to 8.50 m^3/min (200 to 300 cfm) for a typical enclosure. In this range, this recirculation component can quickly remove dust from enclosure contaminants or from workers entering or exiting the area. Even a 1:1 ratio of intake to recirculation air could be used, but this is not as effective because it requires more conditioning of the intake air for heating or air-conditioning needs.

The second aspect to consider is the filtration efficiency of the recirculation filter, which should be in the range of a MERV-14 and a MERV-16 filter. A MERV-14 filter media has a 75 percent to 84.9 percent capture efficiency on 0.3- to 1.0-µm particles and >90 percent capture efficiency on respirable particles > 1.0 µm. The actual operating conditions where the environmental enclosure is located should dictate the filter efficiency rating chosen, and this rating should be based upon such factors as the dust type, the silica content, the dust levels and dust sources inside the enclosure, the frequency with which workers enter or exit the enclosure, or even how often a worker opens the door to perform a task or communicate with coworkers. An additional benefit of using a recirculation filter is that it allows cleaner air to be recirculated through the HVAC system, thus providing better thermal efficiency and resulting in less maintenance.

Enclosure integrity. The third key component is structural or enclosure integrity, which is necessary in order to achieve pressurization and is critical for system effectiveness. To prevent dust-laden air from infiltrating the enclosure, the inside static pressure must be higher than the wind's velocity pressure [Heitbrink et al. 2000]. Gaskets and seals within the filtration and pressurization system also need to be monitored and changed when they show signs of cracking or wear or when they are damaged. Such aging can allow dust-laden air to be blown into the unit, bypass the filtration component, and flow directly into the enclosure. In addition, it is also beneficial during inspection of the system to determine the cleanliness of the unit's ductwork, because dust seen on the inside of ductwork on the clean air side of the unit's filters is a good indication of a system failure. Effective protection factors were realized in various field studies when pressures between 2.49 and 99.64 Pa (0.01 and 0.40 inches of water gauge) were achieved because of good enclosure integrity [Cecala et al. 2009].

Use of a three-filter system (final filter). A three-filter system arrangement (intake filter, recirculation filter, and final filter) should be used whenever possible because it greatly improves the system's performance for all types of environmental enclosures, and this approach has been verified through both theoretical and field tests. A one-filter system that only filters the intake air can be effective and is superior to not providing any filtering. Then, adding a recirculation component only further enhances the air cleaning capabilities of the system to achieve lower airborne contaminant levels inside of environmental enclosures. Further substantial and cost-effective improvements in contaminant reductions can be achieved by adding a high-efficiency final air filter to the system. It is typically recommended to use the same filter efficiency as the intake filter, which would normally be a MERV-16 efficiency filter. It is important that the ultimate filtration system needs to be designed up front so the HVAC fans can be selected to accommodate the additional restriction and pressure drop of a high-efficiency final filter.

A FEW SECONDARY CONSIDERATIONS

Minimize interior dust sources and upkeep, maintenance and cleanliness. Good housekeeping practices are needed to keep enclosure interiors clean and to eliminate inside dust sources. One field study showed a significant increase in dust levels (0.03 mg/m^3 to 0.26 mg/m^3) when a floor heater was used. The fan from the floor heater stirred up dust lying on the cab floor [Cecala et al. 2005]. 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 clothing, specifically their pant legs. Because of the significant increase in dust levels with floor heaters, it is recommended that they not be used.

Keep doors and windows closed. In order to achieve and maintain enclosed cab pressurization, doors and windows must be closed at all times except for when 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; NIOSH 2008b]. 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 was 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. 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.

There are numerous other secondary design considerations to be evaluated before designing or purchasing a filtration and pressurization system for any type of mining environmental enclosure [NIOSH 2019; NIOSH 2018].

HELMET-CAM ASSESSMENT TECHNOLOGY AND EVADE SOFTWARE

Helmet-CAM is a lightweight video recording system used in conjunction with a respirable dust monitor which allows for an assessment of a mine worker's personal dust exposure while performing work activities throughout the work day. Although video exposure monitoring (VEM) to evaluate worker exposure to different types of contaminants is not a new concept, the NIOSH-developed Helmet-CAM assessment tool was designed specifically for the mining industry. The Helmet-CAM assessment system provides insight into how, when, and, where mine workers are being exposed to respirable dust. Part of this assessment system is a NIOSH- developed software (called EVADE) which provides an easy-to-use interface for synchronizing playback of recorded video and dust exposure data. This assessment technology allows for an accurate and efficient identification and assessment of key work areas and/or processes that significantly impact a mine worker's respirable dust exposure.

The Helmet-CAM system has proven to be a very simple and relatively inexpensive technology to use. The setup requires some type of wearable means for miners to carry the video camera and dust monitor so they can perform their duties with minimal interference. Numerous testing has shown that the most viable wear option is a lightweight backpack with various pockets to hold the instantaneous dust monitor and camera recorder. This backpack affords the ability to adjust the two shoulder harnesses, as well as a chest and waist strap to securely tighten the backpack to the wearer, regardless of the miner's height or shape. This is especially beneficial for mobile workers whose duties require them to travel throughout the processing operation. The shoulder straps allows the respirable dust cyclone to be placed near the worker's breathing zone.

The video camera was originally attached to the miner's hardhat and the reason for the term "Helmet-CAM.". Over time, this progressed to the camera being attached to the shoulder strap of the backpack because it was determined to be advantageous in many ways, included the comfortability of wearing the backpack and the ease of housing the instrumentation. When attaching the video camera, it is important that it be properly aligned to document the miner's activities. Using some type of mounting bracket or even duct taping the lens in place on a shoulder strap ensures the lens does not lose its alignment as the miner moves around and performs his or her work duties. Typically, both the video and dust monitor are started simultaneously but this is not necessary for the EVADE 2.0 software because adjustments can be made to synchronize the time. Once the backpack has been adjusted to the wearer's satisfaction, the miner is then requested to wear the system for approximately two hours and is instructed to perform normal routine work duties and tasks. For all of NIOSH's testing, the miners were also informed that the video's microphone function was deactivated so as to not include any sound playback of recorded voice interactions.

Once the miner returned the Helmet-CAM system, the dust monitor and video camera data were downloaded and stored on the hard drive of a computer. At this point, the NIOSH-developed EVADE software is utilized and then merges the video and dust data to visually show the areas, tasks, and functions that impact the individual's respirable dust exposure while performing his or her work. The EVADE software provides a very easy-to-use interface for synchronizing playback of recorded video and dust exposure data on an easy-to-view computer video screen.

NIOSH completed numerous studies to test and evaluate the use of the Helmet-CAM assessment system. All of these intervention studies were extremely successful and resulted in significant knowledge-building activities among NIOSH personnel, the mine site's health and safety specialist and management, and, most importantly, the actual miner. A few examples of elevated respirable dust exposures, including some trends identified in worker practices, are as follows:

- Dusty work clothing/rubbing and clapping hands together and on work clothing;
- Not using ventilation systems already in place (i.e. fans) to blow, exhaust, or circulate air;
- Work processes for obtaining a product sample for lab analysis;
- Cloth seats in mobile equipment, light utility fleet vehicles, and chairs in work locations including offices, lunch and break areas;
- Spraying/hosing down areas around the plant site by using a too forceful water spray jet while performing necessary housekeeping work activities;
- Dust-laden objects workers use to maneuver while performing tasks—i.e., opening handles, bolts, installing new items stored on location in cardboard boxes, stacking bags, tying bulk bags (flexible intermediate bulk containers), as well as using open cell foam padding to work or kneel on while performing various job tasks and functions.

Beyond respirable dust exposure, this Helmet-CAM setup can also be used to assess exposure to other contaminants such as diesel particulate matter (DPM), noise, and chemicals, when a real-time person-wearable sampler is available to monitor the contaminant. Additionally, EVADE 2.0 allows for multiple contaminant assessments and cameras to be used and viewed simultaneously, as well as the ability to sync all video and exposure assessments. As one example, Figure 3 shows an assessment of a worker's respirable dust and noise exposure simultaneously and the dual contaminant output in EVADE 2.0.

From April 2011 through July 2012, NIOSH researchers performed 12 different studies at mining operations with the purpose of evaluating the effectiveness of the VEM technology at assessing miners' elevated respirable dust exposures [Cecala and O'Brien 2014; Cecala et al. 2013; Joy 2013]. The system was tested on more than 100 different miners, including some for noise [Cecala et al. 2015].

Additionally, from April 2015 through September 2016, NIOSH researchers performed five intervention studies with 48 miners with the purpose of identifying effective controls for elevated respirable dust exposures [Haas and Cecala 2015; Cecala et al. 2017; Haas and Cecala; 2017]. Currently, NIOSH is working with cooperative partners within the National Stone, Sand and Gravel Association to tie Helmet-CAM respirable dust exposure assessment along with the NIOSH developed field-based crystalline silica sample analysis method to provide the rapid analysis of the 37-mm dust filter used on the instantaneous respirable dust monitor used with the Helmet-CAM assessment system.

Figure 3. Simultaneous assessment of a miner's respirable dust and noise exposure using the Helmet-CAM system.

The Helmet-CAM technology is being successfully used in the U.S. and internationally to identify and control respirable dust exposures and other contaminants and has already been shown to be an effective technology to lower the respirable dust exposure of miners and other workers. Since tracking was enabled on NIOSH's mining website in June 2015, EVADE has been downloaded approximately 1,027times. In addition, for those users who opt-in to report their usage to NIOSH, 158 users have completed 1,694 sessions—668 in the United States; 522 in Australia; 98 in South Korea; 44 in the United Kingdom; 42 in France; 34 in Belgium; 32 in Japan; 32 in Singapore; 26 in Ireland; 15 in Taiwan; 7 in Canada; 7 in India; 7 in Indonesia; 6 in Denmark; a hospital in Norway, and 65 unknown locations.

Additionally, Helmet-CAM has been used and adopted for training and assessment purposes by some companies with the U.S. M/NM and industrial minerals mining associations, by some universities, and by a number of major industrial instrumentation manufacturers and laboratories. It is believed that in the future, the Helmet-CAM technology/EVADE software will be further expanded to include the assessment of any type of physical, chemical, or biological agent where an instantaneous monitoring device is used.

CLOTHES CLEANING BOOTH SYSTEMS

One known source of high respirable dust exposure is contaminated work clothing [Cohen and Positano 1986; Fogh et al. 1999]. A USBM study documented a number of cases of high worker exposure from background dust sources in the minerals processing industry. A report from this study highlighted two cases of a 10-fold increase in respirable dust from contaminated work clothing [USBM 1986]. It must be noted also that once a miner's clothing becomes contaminated, it is a continual source of dust exposure until the clothes are changed or cleaned.

To address this worker dust contamination issue, a clothes cleaning booth technology was developed, with Unimin (now Covia Corporation) approaching NIOSH with a concept and NIOSH researchers designing the technology. This technology was not intended to eliminate the need to launder work clothing, but to provide an interim solution to allow miners to safely remove dust from their work clothing periodically throughout the day until laundering could be performed after the work shift.

The clothes cleaning system is made up of four major components: (1) a cleaning booth, (2) an air reservoir, (3) an air spray manifold, and (4) an exhaust ventilation system. The schematic on the left in Figure 4 represents the design of the clothes cleaning system. To perform the clothes cleaning process with this system, a worker rotates in front of the air spray manifold while dust is blown from the clothing via compressed air while wearing required personal protective equipment (i.e., safety glasses, respirator, hearing protection). In less than 20 seconds, the cleaning is completed and the worker can exit the booth with significantly cleaner work clothing (Figure 4, bottom right).

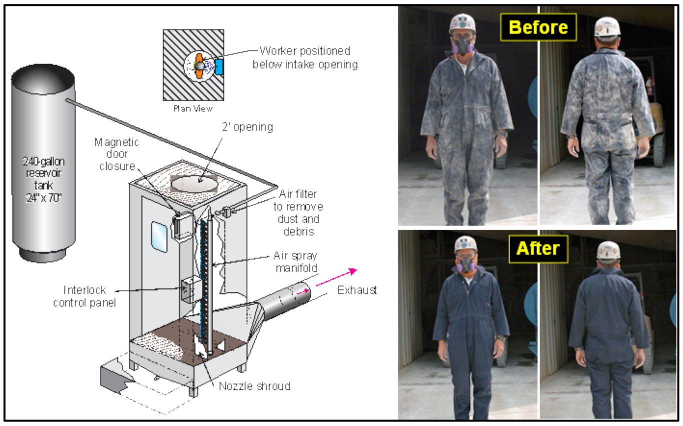

Figure 4. Design of clothes cleaning system (left) and before and after cleaning effectiveness on test subject (right).

The clothes cleaning booth is 121.9 cm (48 inches) wide by 106.7 cm (42 inches) deep, which provides the mine worker with sufficient space to rotate in front of the air spray manifold to perform the cleaning process. An air reservoir is necessary to supply the required air volume to the air nozzles used in the spray manifold. The size requirement can be either 120- or 240-gallon for the reservoir, depending on the number of miners needing to clean their clothes in sequence. If multiple mine workers will be using the booth one after another, then the 240-gallon reservoir must be used. This reservoir should be pressurized to at least 1.03 MPa (150 psi), be located close to the cleaning booth, and be hard-piped to the air spray manifold located in the booth. A pressure regulator must be installed immediately before the air spray manifold to regulate the nozzle pressure to a maximum of 0.21 MPa (30 psi.)

Intake air enters the booth through a 0.61 m (2-foot) opening in the roof and then flows down through the enclosure before exiting through an air plenum on the bottom back wall of the booth. As this intake air flows through the booth, it entrains dust removed from the miner's clothing during the cleaning process and forces it down towards the air plenum and away from the worker's breathing zone. The exhausted dust-laden air then travels from this air plenum at the base of the booth to the exhaust ventilation system.

In order to perform the clothes cleaning process, a miner dons personal protective equipment, enters the cleaning booth, activates a start button, and rotates in front of the air spray manifold while dust is blown from the clothing via forced air. After a short time (18 seconds), the air spray manifold is electronically de-activated, and the miner can exit the booth with significantly cleaner work clothing.

For effective dust removal, it is critical that the cleaning booth be ventilated under negative pressure at all times so as to not allow any dust liberated from the clothing to escape from the booth and into the work environment. In the design stage of this technology, testing validated that an exhaust volume of 56.63 m^3/min (2,000 cfm) was sufficient to maintain a negative pressure throughout the entire clothes cleaning cycle [Cecala et al. 2008].

During development, in several NIOSH studies, the clothes cleaning technology was compared to both the MSHA-approved vacuuming approach and a single handheld compressed air hose. Results showed that the cleaning booth was 40 percent more effective in removing dust than vacuuming and 50 percent more effective than a compressed air hose, while only requiring a fraction of the cleaning time [Pollock et al. 2006; Pollock et al. 2005].

Because MSHA prohibits the use of compressed air directed at workers and the Occupational Safety and Health Administration (OSHA) restricts compressed air for cleaning to 0.21 MPa (30 psi), a petition for modification must be obtained from MSHA prior to using the clothes cleaning booth, and the air pressure within the cleaning booth must be regulated to 0.21 MPa. After meeting with representatives from NIOSH and the Industrial Minerals Association–North America (IMA-NA) and learning of the NIOSH study results, MSHA agreed to streamline the petition for modification process for cleaning booths using the NIOSH-developed system.

There are currently two known companies that are offering units that appear to be very similar to the cleaning technology developed by NIOSH and Covia. Clothes Cleaning Systems commercialized the NIOSH-developed clothes cleaning booth technology and sells the Tempest WindDraft models I and II, as well as a mobile versions of each system [NIOSH 2019]. Mideco, an Australian-based manufacturer and distributor of environmental technology, began manufacturing a clothes cleaning booth technology in 2014 called the "Bat Booth." At one installation of the Bat Booth, which is equipped with an internal counter, there were over 10,000 clothes cleaning cycles in one year [NIOSH 2019].

TOTAL STRUCTURE VENTILATION SYSTEM

The first strategy to lower dust exposures in any structure is to have an effective primary dust control plan that captures major dust sources at their point of origin, before the dust is liberated into the work environment and contaminates mine workers. Most minerals processing operations control respirable dust by using various standard engineering controls, including such techniques as local exhaust ventilation systems, water spray application, conveying and bagging controls, as well as other similar type systems. These engineering controls are effective at reducing and capturing dust generated and liberated from primary sources; however, they do not address the continual buildup of dust from background dust sources, such as the following:

- Product residue on walls, beams, and other equipment which becomes airborne from plant vibration;
- Product that accumulates on walkways, steps, and access areas, and which may be released as workers move through the plant and by plant vibration;
- Leakage or falling material from chutes, beltways, and dust collectors;
- Lids and covers of screens that are damaged or when they are removed for inspection and cleaning; and
- Product released because of imperfect housekeeping practices.

Since most mineral processing structures can be considered closed systems, the background dust sources listed above, along with numerous other unnamed sources, can cause dust concentrations to continually increase as the day or shift progresses inside these closed buildings. One method that can be used to control these background dust sources is a total structure ventilation system.

The basic principle behind the total structure ventilation design is to use clean outside air to sweep up through a building to clear and remove the dust-laden air. This upward airflow is achieved by placing exhaust fans at or near the top of the structure and away from miners working both inside and outside the structure. The size and number of exhaust fans is determined based upon the initial respirable dust concentration and the total volume of the structure. All the processing equipment within a mill generates heat and this produces a thermodynamic "chimney effect" that works in conjunction within the structure ventilation design [Cecala and Mucha 1991; USBM 1994; Cecala 1998; Cecala et al. 1995]. Figure 5 shows the concept of the total structure ventilation design, and there are three design criteria that must be met for this system to be effective: (1) provide a clean makeup air supply, (2) an effective upward airflow pattern, and (3) a competent shell structure.

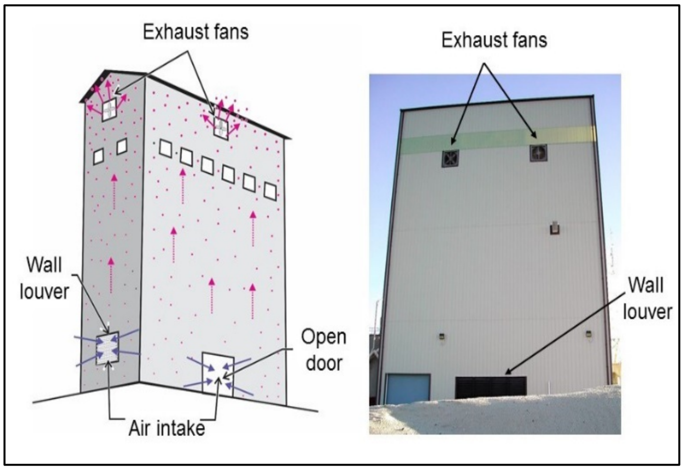

Figure 5. Illustration and photo showing the basic design of a total structure ventilation system.

Intake air needs to be brought in at the base of the structure by strategically located wall louvers or open plant doors. It is critical that this air be free from outside dust sources such as bulk loading, high traffic areas, etc., which could cause dust-laden air to be drawn into the structure and could ultimately increase respirable dust levels. By using wall louvers or closing doors, the intake air locations could be changed based upon the outside dust conditions.

The system should provide an effective upward airflow pattern that ventilates the entire structure by sweeping the major dust sources and work areas. Strategic positioning of both exhaust fans (high in the walls or roof) and makeup air intakes (at the base) creates the most effective airflow pattern for purging the entire building. It needs to be noted that this system is not applicable to buildings with multi-story solid floors since this will not allow air to flow up through the structure.

A competent outer shell of the structure is necessary because the ventilation system draws the makeup air through the points of least resistance. Therefore, the structure's outer shell must be free of open or broken windows, holes, cracks, and openings, especially in the vicinity of the exhaust fans. The exhaust fans create negative pressure and if the building is not structurally competent, air will be brought in from unwanted areas with potential dust sources and will not allow for an effective airflow pattern for purging the building.

A normal range of airflow for a total structure ventilation design is between 10 and 35 air changes per hour (acph) and is dependent on baseline respirable dust levels. During the development of the total structure ventilation design concept, two different field studies were performed in an effort to document its effectiveness. In the first study, with a 10 acph ventilation system, a 40 percent reduction in respirable dust concentrations was achieved throughout the entire structure. In the second study, the total structure ventilation system was capable of providing both 17 and 34 acph. Average respirable dust reductions throughout the entire structure ranged from 47 to 74 percent for the two exhaust volumes, respectively [Cecala et al. 1995].

The direction of the prevailing wind is a variable that needs to be considered when initially designing a total structure ventilation design because of its impact on exhausting and possible re-entrainment of contaminants from the building. It is ideal to have the fans exhaust with the prevailing wind direction to minimize any possible recirculation. It is recommended that every mineral processing structure should have some type of total structure ventilation design. Just as an office building requires some type of ventilation system that provides HVAC-controlled airflow to offices, this is also the case for industrial minerals processing operations—every structure should have a designed total structure ventilation system.

DUAL-NOZZLE BAGGING SYSTEM

The dual-nozzle bagging system was designed to reduce major dust sources of the bag filling process, and thus, lower the dust exposure of bag operators. A number of dust sources must be controlled to achieve this goal. The primary dust sources from the fill nozzle and bag valve area are product blowback and product spewing from the fill nozzle area. Product blowback occurs as excess pressure builds inside the bag during bag filling and is then relieved by air and product exiting the bag around the fill nozzle, creating a considerable amount of dust. As the bag is ejected from the filling machine, a "rooster tail" of product is thrown from the bag valve and fill nozzle. The rooster tail occurs because the bag is pressurized as it leaves the machine, releasing dust into the air and contaminating the outside of the bag. These contaminated bags then become a major dust source for bag stackers and any other individuals handling the bags.

The dual-nozzle bagging device uses a two-nozzle arrangement with an improved bag clamp to control the dust sources. The two-nozzle arrangement uses an inner nozzle to fill the bag and an outer nozzle to relieve excess pressure from the bag after it has been filled. Depressurizing of the bag is accomplished once filling is completed with the aid of an eductor, which uses the venturi principle to exhaust excess air from the bag at approximately 1.42 m^3/min (50 cfm). A pinch valve is then used to open and close the bag exhaust. The bag is slightly overfilled and held in place until the exhaust system depressurizes the bag. After a few seconds, the bag clamp opens and the bag falls from the fill station. The exhaust system continues to operate as the bag falls away, cleaning the bag valve area. The exhausted material is then recycled back into the system.

The other key component of the system is an improved bag clamp. This bag clamp makes direct contact with approximately 60 percent of the nozzle, thus reducing the amount of product blowback during bag filling. A controlled amount of blowback is necessary, so the bag does not rupture, but this occurs at the bottom of the nozzle, minimizing dust contamination to the outside of the bag. Figure 6 shows the design of a dual-nozzle bagging system and the improved bag clamp design.

Figure 6. Photos of dual-nozzle system (left) and improved bag clamp design (right).

Several field evaluations were performed to determine the effectiveness of the dual-nozzle bagging system [USBM 1984]. During one study, there was an 83 percent reduction in the bag operator's dust exposure with the dual-nozzle system. Further, a 90 percent reduction was measured in the hopper below the fill station, indicating a substantial reduction in product blowback during bag filling.

The use of the improved bag clamp allows for a significant decrease in the amount of dust and product on the outside of the bag. This resulted in a 90 percent reduction in the bag stacker's dust exposure while bags were being loaded into an enclosed vehicle during the testing of this system [USBM 1984].

The dual-nozzle system is mainly recommended for operations with three- and four-fill nozzle bag machines because there is a slight decrease in production due to the time needed to depressurize the bags after filling is completed. The system can be used on a one- or two-nozzle machine, but this decreases the production rate even further because the bag operator must wait on each individual bag instead of a cycle of bags.

OVERHEAD AIR SUPPLY ISLAND SYSTEM

The overhead air supply island system (OASIS) was developed to provide an envelope of clean, filtered air to a miner working at a stationary location. One of the main advantages of the OASIS is that it is suspended over a miner and operates independently of any processing equipment.

The OASIS is a relatively simple concept design and system. Plant air is drawn into the unit and passes through a primary filtering chamber which is typically a HEPA-rated cartridge filter. After the air exits the primary chamber, it passes through an optional heating or cooling chamber, which can be incorporated in the unit if temperature control is desired. The air then flows through a filter distribution manifold, which also serves as a secondary filter when exiting the unit. This provides an even distribution of clean filtered airflow down over the miner while providing backup filtering in case there is a problem with the primary filtering chamber. This filtered air flows down over the miner at an average velocity of roughly 114 m/min (375 ft/min), which normally keeps any plant air from entering this clean air zone. The system should incorporate some type of differential pressure monitor to evaluate filter loading and serves as input for an automated self-cleaning filtering technique. In addition, the pressure monitor should also indicate when the filter needs to be replaced.

During an evaluation of the OASIS at two different sites, the miner's respirable dust exposure was reduced by 82 and 98 percent, as compared to when the unit was not being operated [Robertson 1986]. At both of these operations, the dust concentration within the clean filtered air of the OASIS remained under 40 μg/m^3.

The OASIS can be used when miners are either sitting (some bag operators) or when standing. In some cases, it may also be advantageous to place clear plastic stripping down along the side of the OASIS, which allows miners to recognize the boundary of the clean air zone and a physical reminder of their inability to be protected once exiting outside of this physical barrier of plastic stripping (Figure 7) [Cecala et al. 2000].

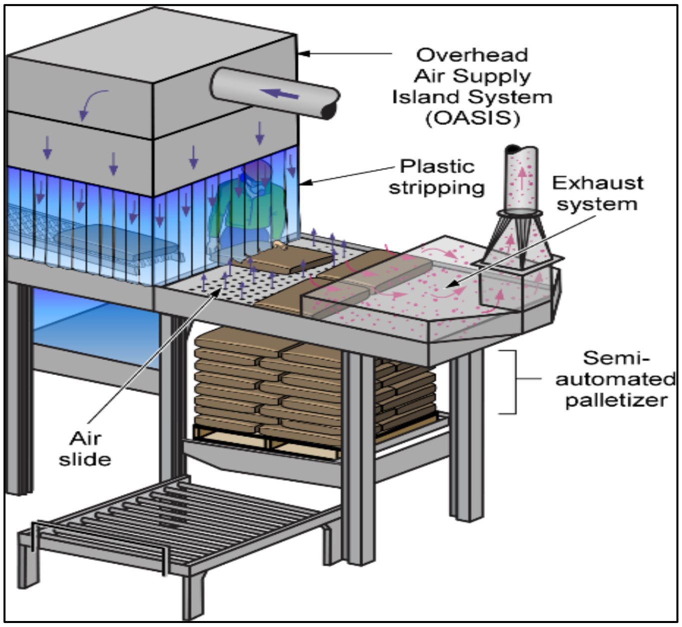

Figure 7. Design drawing of OASIS with clear plastic stripping to indicate clean air zone to miners.

An additional benefit provided by the OASIS is that the filtering system provides some general cleaning and improves the overall air quality at the entire mineral processing structure. This occurs because the OASIS is drawing air from the operation, filtering it, and then blowing this clean air down over a miner. After flowing over the worker, it then becomes part of the general plant air again. During one evaluation, there was a 12 percent reduction in respirable dust levels in the entire building where the OASIS was used [Volkwein et al. 1986]. The volume of clean air delivered by the OASIS is variable based upon the size of the unit, but it is normally in the range of 170 to 283 m^3/min (6,000 to 10,000 cfm). Other studies have also shown the benefit of recirculating air back into the building after it has been cleaned [Godbey 2005]. The OASIS is generic in design and can be fabricated and installed in-house or through any local engineering company that handles ventilation and dust control systems. In addition, NIOSH has performed and is currently performing tests on the "canopy air curtain" system—this is almost an identical concept to the OASIS which is being used on underground mining machinery at lower airflow rates [Reed et al. 2017, Reed et al. 2018, Reed et al. 2019].

BAG AND BELT CLEANER SYSTEM

The bag and belt cleaner device (B&BCD) is designed to reduce the amount of dust escaping from bags as they travel from the bag loading station to the stacking/palletizing process. This device reduces the dust exposure of all workers in and around the conveying process, as well as anyone handling the bags once they are filled at the loading station. This system should be applicable to any mineral processing operation that loads product into 50- to 100-lb paper bags and should be located in-line on the conveyor at the closest available position to the filling station to control this dust source as quickly as possible. Also, it is important to have the B&BCD unit under sufficient negative pressure to ensure that any dust removed from the bags of product or from the conveyor belt does not leak from the unit and contaminate the general plant air, and ultimately mine workers in these facilities.

The USBM designed and fabricated the prototype B&BCD, which was 3.05 m (10 ft) long and used a combination of brushes and air jets to clean all sides of the bags. As the bag travelled through the B&BCD, it entered through a curtain made of clear, heavy-duty flexible plastic stripping to seal it from the plant air. Once inside the unit, a stationary brush on a swing arm started the cleaning process on the front and top of each bag. The bag went through a second set of plastic stripping and into the main chamber section, where it travelled under a rotating circular brush that further cleaned the top of the bag. The sides were cleaned by a stationary brush located on each side of the bag. An air jet was located at the end of these brushes to provide for additional cleaning.

The side with the bag valve used a higher-volume (velocity) air jet to provide for the maximum amount of cleaning. After passing through the air jets, the bag travelled over a rotating circular brush located beneath the bag which cleaned the bottom of the bag. The bag exited the device by traveling through another air lock chamber with flexible plastic stripping.

A chain conveyor was used for the entire length of the device in the prototype design to allow product removed from the bags during cleaning to fall into a hopper. Product collected in this hopper was then recycled back into the process, normally using a screw conveyor. Once exiting the B&BCD, both the bags of product and the conveyor belt should be essentially dust-free.

Although this section describes one particular B&BCD system, there are numerous types that can be purchased from manufacturers, fabricated in-house by mineral processing plants, or fabricated by a local engineering firm. These devices normally require electricity and compressed air to power the cleaning unit and the blow-off nozzles, respectively.

During the evaluation of this specific B&BCD at two mineral processing plants, the device showed very favorable results in lowering respirable dust levels. The most relevant data from this testing was the amount of dust removed from the surface of the bags, with a 78 to 90 percent range of reduction (Figure 8) [Cecala et al. 1997; USBM 1995].

Figure 8. Pallet of bags without being cleaned by the B&BCD system (left) and with being cleaned by the system (right).

SEMI-AUTOMATED BAG PALLETIZING SYSTEMS

Semi-automated systems use workers in conjunction with an automated system to perform the bag stacking process. These can include a vast array of different setups and types of systems. In one case, a worker performs the bag stacking task manually, but is assisted by a hydraulic lift table. This lift table allows the height for stacking the bags to remain constant throughout the entire pallet loading cycle. The lift table is set to approximately knuckle-height for the worker, which is the most ergonomic loading height. A push-pull ventilation system is used on either side of this pallet to capture the dust liberated during the bag stacking (palletizing) process [Cecala and Covelli 1991]. This system is composed of a low-volume, high-velocity blower operating at approximately 3.40 m^3/min (120 cfm) to direct a stream of air over the top layer of bags on the pallet. The blower system is composed of two 7.6 cm (3 inch) air jets (approximately 1,200 fpm velocity) directed toward an exhaust system on the opposite side of the pallet. As these air jets travel approximately 25.4 to 30.5 cm (10 to 12 inches) above the top of the pallet, they entrain the dust generated during bag stacking. The exhaust ventilation system pulls approximately 70.8 m^3/min (2,500 cfm) of air and dust through the exhaust hood. This exhaust air can then be dumped into an LEV system (Figure 9).

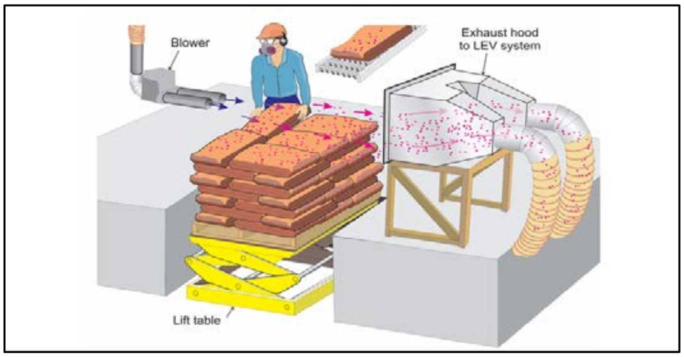

Figure 9. Illustration of a semi-automated bag palletizing system showing a push-pull ventilation system and hydraulic lift table, which also provides ergonomic improvements to the bag stacking process.

In other cases involving palletizing systems, the miner slides the bags of product on an air table one layer at a time and the actual stacking is performed automatically. Since back injuries represent such a major potential lost-time for bag stackers, this design significantly reduces back stress by eliminating the need to manually lift any bags of product. In some cases, the air slide can cause dust to be blown from the bags and contaminate the miner. Using the OASIS system in conjunction with an air slide device can work effectively to minimize this dust source. An exhaust hood used next to the air slide area to capture the dust blown from the bags can also be a very effective addition to the other techniques [Cecala et al. 2000].

CONCLUSION

The former USBM and now NIOSH continues to perform research to reduce the dust exposure to miners in the U.S. metal/nonmetal mining industry. This manuscript has highlighted some of the key engineering control technologies that have been developed through this research effort by the USBM/NIOSH over the past 40 years. All of the engineering controls described have all been tested and proven to be effective in lowering miners' respirable dust exposures and can be implemented at existing mining operations. NIOSH is very grateful to numerous mining companies and trade associations for their collaboration and support in many of these research efforts. It is NIOSH's hope that through these and other similar controls and interventions, mine workers' respirable dust exposures will be reduced and that, ultimately, the likelihood of miners developing silicosis and/or other respiratory diseases will be eliminated.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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