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A Second Case Study of Field Test Results for Comparison of Roof Bolter Dry Collection System with Wet Collection System

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Abstract
Silicosis is an occupational respiratory disease that roof bolter operators are susceptible. It is caused by overexposure to respirable quartz dust (RCS) and has no cure and may ultimately be fatal. The only method of prevention of silicosis is by preventing exposure to RCS. The wet box collection system is a newly developed dust collection system for roof bolting machines, a modification of the existing dry box collection system utilizing water to saturate the material that is collected by the dust collection system. Testing was conducted for 3 days on a dual boom roof bolter with the wet box installed on the left side and the dry box installed on the right side. Sampling, using the coal mine dust personal sampling unit (CMDPSU), during cleaning of the collector boxes demonstrated that using the wet box dust collection system instead of the dry box dust collection system can reduce RCS exposures during cleaning of the collector boxes by 71% (day 1), 82% (day 2), and 88% (day 3). In addition, the quartz content of samples collected during cleaning of the wet box was 0.0%, while the quartz content of the samples collected when cleaning the dry box was 4.6%, 10.3%, and 7.4%.

Keywords Respirable dust · Roof bolter · Coal · Silica dust

1 Introduction

Respirable dust is defined as dust with a D_{50} of 4.0 µm [1]. The D_{50} is defined as the median diameter of a particle size distribution. Since respirable dust's D_{50} = 4.0 µm; therefore, 50% of particles are less than 4.0 µm and 50% are greater than 4.0 µm. Exposure to respirable coal mine dust can result in the occurrence of coal workers' pneumoconiosis or black lung, which is an occupational respiratory disease that has no cure and is ultimately fatal [2]. It can only be prevented by eliminating exposure to respirable coal mine dust. In addition, respirable silica or quartz dust is a health hazard to which roof bolter operators can also be exposed. Overexposure to respirable quartz dust can result in the incidence of silicosis. This is also an occupational respiratory disease that has no cure and may ultimately be fatal. Like black lung, silicosis can only be prevented by eliminating exposure to respirable quartz dust [3].

From the NIOSH Hazard Review: Health Effects of Occupational Exposure to Respirable Crystalline Silica, "Silica refers to the chemical compound silicon dioxide (SiO_2), which occurs in a crystalline or noncrystalline (amorphous) form." [4]. This crystalline silica can be found in different forms: alpha quartz and beta quartz, where beta quartz is formed when alpha quartz is heated above 573 °C [5]; tridymite and cristobalite which are rare [6]; and other forms (stishovite, coesite, and keatite) that are extremely rare in nature [5]. The alpha form of quartz is the most common and is generally the form that miners are exposed. This form is so abundant that the term quartz is often used instead of the general term crystalline silica [5, 7].

The Federal Coal Mine Health and Safety Act of 1969 enacted a RCMD standard limiting respirable coal dust to 3.0 mg/m^3. Three years after the enactment of the 1969 Act, the RCMD standard was reduced to 2.0 mg/m^3 which remained the standard in use for over 40 years [8]. It also created a respirable silica dust standard if the mine atmosphere of the workplace contained more than 5% quartz. The silica standard was calculated as 10 divided by the percent quartz present. Beginning in August 2016, the Mine Safety

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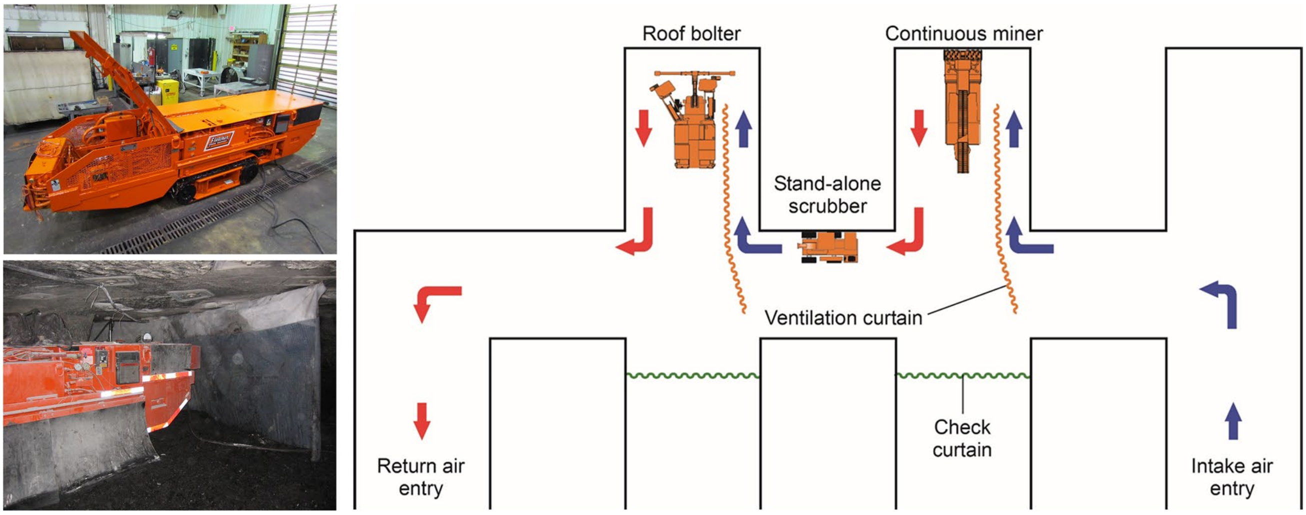

Fig. 1 The dry scrubber depicted in the lab (upper left) and in the mine entry (lower left). Also shown is a schematic of the typical layout for using the dry scrubber (right) [14]

and Health Administration (MSHA) set the respirable coal mine dust standard at 1.5 mg/m^3; this is the maximum allowable respirable coal mine dust for a full working shift in the active workings [9]. If respirable quartz greater than 100 µg per cubic meter equivalent concentration is encountered in the atmosphere, then the coal mine respirable dust standard is reduced to 10 divided by the percentage of silica from sampling [10]. This standard can be significantly lower than the 1.5 mg/m^3 respirable coal mine dust standard.

Sources of exposure to respirable coal mine dust and silica dust for roof bolting occupations include operating downwind of the continuous miner and frequent maintenance and cleaning of the vacuum dust collection system [11]. It has been documented that respirable coal mine dust concentrations up to be 12 mg/m^3 in the immediate return of the continuous miner can occur when the continuous miner scrubber is not operating. Even with the scrubber operating, respirable coal mine dust concentrations up to 7 mg/m^3 have been documented in the immediate continuous miner return [12, 13]. These are potential exposures to roof bolter operators when the roof bolter machine is operated downwind of the continuous miner. The MSHA attempts to mitigate this exposure by limiting roof bolter operation downwind of the continuous miner to one working place or entry per shift, if downwind operation is allowed at all. Additional methods to mitigate these potential exposures to roof bolter operators are the dry scrubber and canopy air curtain.

The dry scrubber is a machine that provides clean air downstream of its operation. It is mobile and can be remotely operated. Tramming occurs using hydraulic-powered crawlers. The machine consists of a 22.4-kW (30 hp) vane axial fan (480 V) with variable frequency drive speed controller. It filters the air by incorporating dual 71-cm (28-in.) O.D. cylindrical air filters rated at 99% efficiency for 2-µm particles. It is powered using 480 V via a trailing cable. To provide protection for the roof bolter operators, the machine is set up between the entries containing the continuous miner and roof bolter. Field testing demonstrated that it had collection efficiencies for respirable dust of 46.3% to 59.9%, thus reducing the respirable dust concentrations to an entry directly downstream of the dry scrubber [14]. Figure 1 shows the dry scrubber and the typical layout for its use.

The canopy air curtain (CAC) is a dust control device which has been recently evaluated. This device is a system integrated into the roof bolter machine with the hydraulically driven fans and intake filters mounted on the roof bolter body and the discharge area or plenum is incorporated into the roof bolter canopy, the location where the roof bolter operator works during bolting operations. The system works as the fans pull air through a filter mounted on their intake side. The fan exhausts are connected to the canopy via a 10.2-cm-diameter hose. The filtered air is distributed evenly across the plenum and provides clean filtered air over the operator [15]. The left and right sides of the roof bolter each have a CAC system in-place, which operates during roof bolter operation. Figure 2 depicts the CAC system on the roof bolter. Field testing has shown that the CAC can provide respirable dust reductions ranging from 3% to 60% in one study [16] and 11% to 40% in another [17]. The reductions were variable due to the amount of time the operator is under the plenum, the movement of the operator while working underneath the plenum, variations in height of the CAC plenum above the operator, and the variations in face ventilation [17, 18].

Other means to protect the roof bolter operator from respirable quartz dust exposure are to optimize the roof

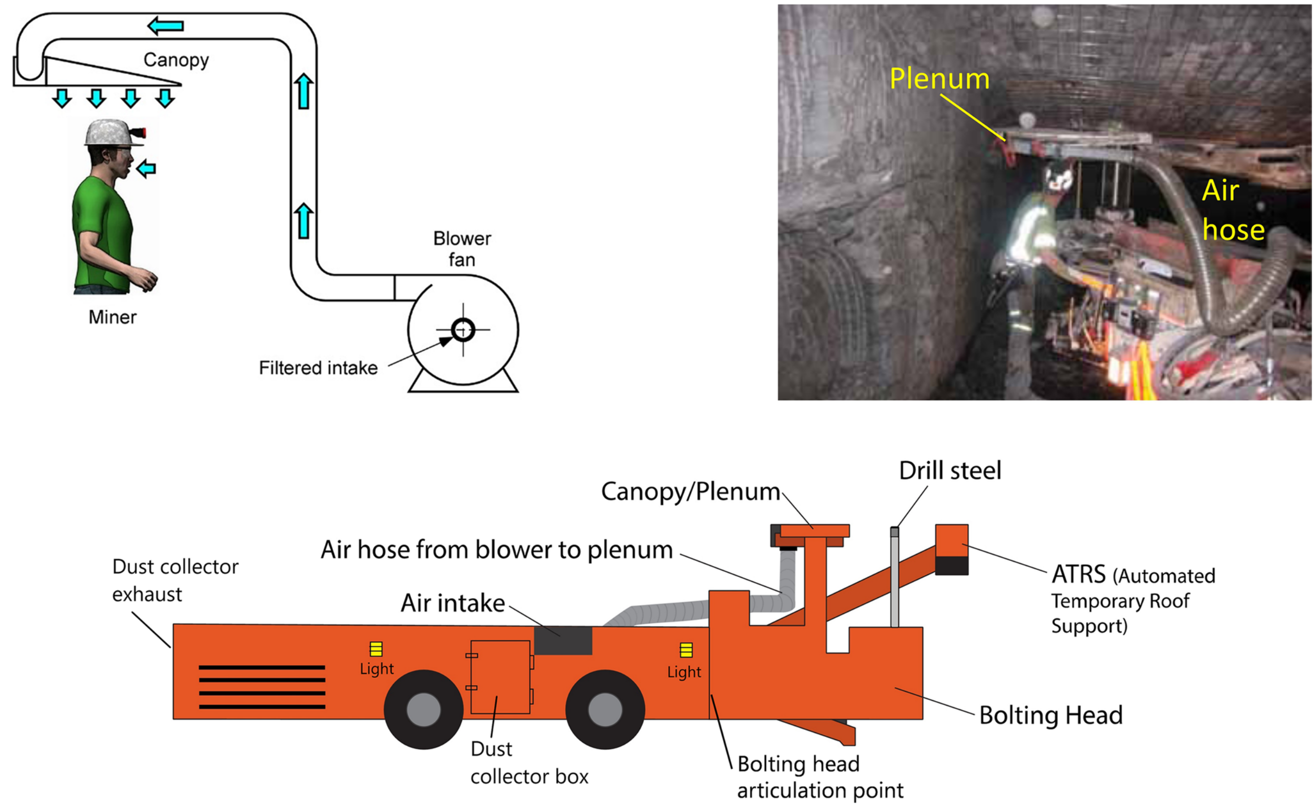

Fig. 2 An overview of the canopy air curtain system and its components is shown (upper left) and the canopy air curtain in use in an underground coal mine (upper right). The canopy air curtain components and their approximate location are depicted in relation to the roof bolter machine schematic—not to scale (bottom)

bolter machine operation and maintain the dust collection system in proper operating condition. Optimizing the drilling parameters was investigated in a study that conducted lab experiments testing a range of drill bit rotation rates and penetration rates. The results examined the bite depths of the drill bit from the various drill bit parameters which ranged from 0.053 to 0.373 cm/revolution. It was found that larger bit bite depths produced less dust in the dust collector box, thereby reducing the amount of respirable dust in the collector box. Overall, it was determined that the amounts of respirable and inhalable dust were inversely proportional to drill bit bite depth [19]. Additional work was conducted to create a bolt-hole drilling mechanical model which ascertains the important drilling parameters on energy consumption and dust generation during drilling. Importantly, it considers the drill bit condition (new or worn) in its analysis, looking at drill bit bite depth in relation to bit wear to determine specific energy used in drilling and dust generation effects. Modeling results were verified with lab testing and determined that bite depth is significant to reduce respirable dust generation. Larger bite depths produced less respirable dust. In addition, bit wear was shown to decrease energy efficiency and increase respirable dust generation during drilling with worn bits [20].

In maintaining the dust collection system, operators are generally diligent to keep the dust collection system in good operating condition. It is normally a requirement in the ventilation plan to check the vacuum pressure at the drill chuck before the shift to check proper operation. The vacuum pressure is measured using a special pressure gauge that measures the vacuum in units of inches Hg. The vacuum pressure must be at least the pressure listed on the nameplate of the roof bolting machine. Any deviation below the rated pressure indicates a problem with the collection system which must be addressed.

Much of the prior work produced results to protect roof bolter operators from respirable dust exposure during bolting operations. Cleanout of the dust box is necessary as the box fills with material as bolting operations occur. Jiang's work considers the particle size distribution of the material entering the box and how to reduce fine material by optimizing drilling parameters [19, 20]. However, there is still a large amount of fine material in the dust collector box. Methods of cleaning out the collector boxes investigated using a metal rake to pull material from the box dumping onto the mine floor, using a rigid box with open top to collect the material, and using a lightweight bag inserted into the box to collect the material. Lab testing showed that using the rigid box to collect the drill cutting material produced the least amount of dust exposure compared to the other two methods. Though, there was still a high amount of dust produced during cleaning with any of these methods [21]. Another study evaluated collector bags that were installed in the dust collector box. These bags were connected to the dust collector chamber inlet, similar to a vacuum cleaner, and received the drill cutting material. Testing was conducted in the lab on cleaning the dust collector with and without using the bags. This testing showed that dust levels are higher from the roof bolter dust collector system exhaust when testing was conducted without the bags installed. Dust levels were lower when the bags were installed. Field testing was conducted and demonstrated that the dust levels from the collector exhaust when not using the bags in the collector were higher than those when the bags were used. When cleaning the boxes, there was no difference in the dust levels encountered with the bagless and bagged collectors. However, the cleaning time was 4 min for the bagless collector and 30 s for the bagged collector [22].

The wet box dust collection system is a recent development that has been tested in a prior study. This system is a modification to the dry collector system to convert it to a wet collector system. This system was originally developed at the Deserado Mine located in Rangely, CO [23, 24]. The system at the Deserado Mine was tested by researchers from the National Institute for Occupational Safety and Health (NIOSH). However, even though some of the data was compromised, researchers were able to conclude that using a wet box collection system could provide dust reductions of up to 60% during cleaning over the dry box collection system [23, 24].

1.1 Description of the Dry and Wet Collection Systems

Roof bolter machines typically use a dry vacuum dust collection system that collects the cutting material when drilling the roof bolt holes in the mine roof in underground coal mining. The drill cutting material is generally roof rock which consists of shales, clay, sandstone, etc. which can have very high silica content. A previous study showed percent quartz ranging from 29% to 53% [24]. This system uses a blower to create a vacuum system to pull all the material from the vertical roof bolt hole through the drill bit and drill steel and send it via a vacuum hose into the dry collection box. This material generally passes through a precleaner, which is a cyclone that removes large particles or over-sized material (> 100 μm) from the drillhole cutting material. This over-sized material is dumped on the

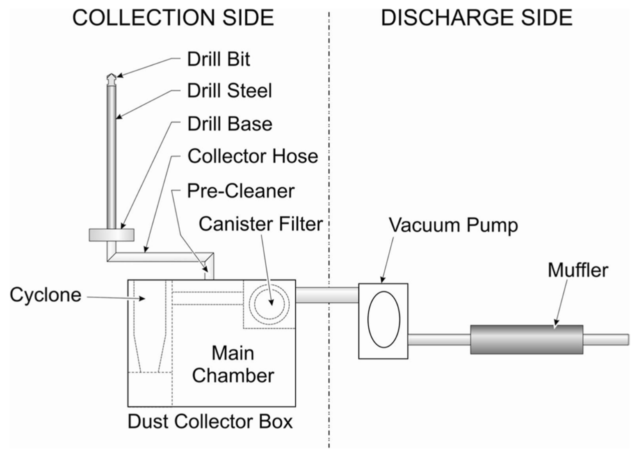

Fig. 3 A schematic of the dry dust collection system showing the components. The material and air enter through the drill bit passing through the drill steel and hose. The material enters the main chamber with most dropping out; then, the air passes through a set of cyclones removing additional fine material before passing through the final filter and exhausting out through the vacuum pump or blower exiting the rear of the roof bolting machine [22]

ground. The under-sized material which has been shown to consist of 36% particles < 10 μm enters the dry collection box [22]. The material entering the dust box is either deposited on the floor of the dust box or into a dust collector bag. A previous study has shown that the amount of material < 4.0 μm can range from 6% to 16% of the material [24]. In this case, dust collector bags were not used on this roof bolter dry collection system. The vacuum airflow leaves the dust box and is routed through a set of cyclones before exhausting through a final filter, generally specified as the Model 123990, Donaldson, Inc., Minneapolis, MN, with 99.90% efficiency [24]. Figure 3 shows a schematic diagram of the dry collection system for the roof bolter.

During roof bolter operation, the material builds up in the dry collection box which then requires frequent cleaning. This cleanout can occur as frequently as once per shift or up to after completing each bolting entry. It has been shown that the amount of material in the dry collection box can potentially contain 22.8 kg or more material [24]. The method used to clean out the dry collection box is to open the dust collection box door and physically remove the material from the box by pulling it out with a metal scraper and dumping the material on the mine entry floor (a procedure that directly exposes the operator cleaning out the box). A few operations use a wet drilling system where water is used to flush the cutting material from the bolt holes. In this case, no dust collection system is used. However, the dry vacuum dust collection system is more common. These systems are used to aid in the prevention of exposures of roof bolter operators to respirable quartz dust.

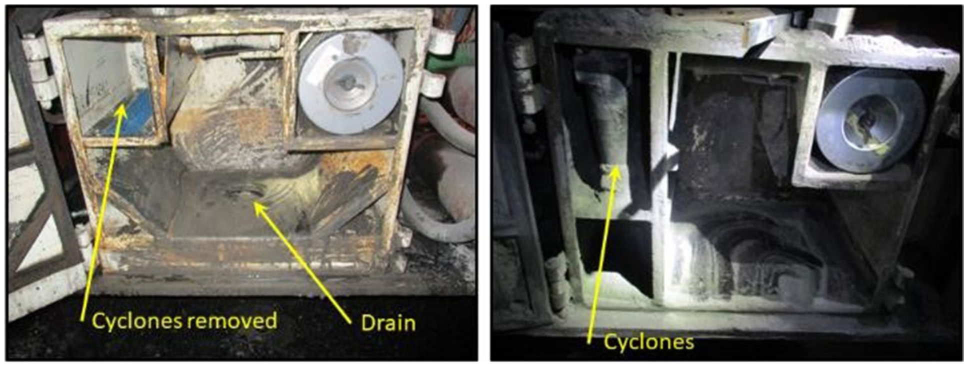

Fig. 4 Inside view of the wet box (left) and the dry box (right)

The wet collector system utilizes the same components as the dry collector system. It uses a vacuum system to pull material from the vertical roof bolt hole but incorporates a #2 continuous miner spray (for example, BD-2 Whirljet® Nozzle Spraying Systems, Inc., SH-2 Spraylet™ Hollow Cone Nozzle Steinen Mfg. Co.) located inside the dust box at the bottom with its orientation directed towards the inlet. The flow through the nozzle is rated at 2.4 L (0.63 gpm) at 0.7 MPa (100 psi). Random checks of the water flow meter throughout the study indicated the waterflow was consistently 3.8 L/min (1.0 gpm) when the water was turned on. The air and material follow the similar pathway as for the dry collection system. However, the conversion to the wet collector system removes the precleaner and the cyclones inside the dust box. The material is thoroughly wetted, collecting in the main chamber. The resulting material or sludge that builds up during bolting operation is then emptied through a drain in the bottom of the box onto the mine floor, while the air passes through the final filter to the exhaust.

Emptying the collector box is controlled by a rotary valve at the drain location, and the draining action is performed when drilling and roof bolting are completed. The rotary valve is opened and closed using a control lever located at the roof bolter operator's working position. The final filter is a specially designed filter that is water resistant and is still used to prevent any possible respirable dust from leaving the dust box through the exhaust. During operation, the wet collector dust box is opened and hosed clean after roof bolting 12.2 m (40 ft) of entry or at least after every shift. Figure 4 shows the inside of the wet box and the dry box, both in a clean condition (i.e., no dust inside the boxes).

2 Test Location

Field testing occurred on a roof bolting machine in a longwall three-entry development section at the West Elk Mine in Colorado. The mine's management requested the NIOSH to test the wet system in conjunction with the dry collection system and to compare the dust concentrations encountered when operating and when cleaning out each system to determine their performance for dust control.

The mine used a three-entry system for longwall development. Face ventilation was provided using a ventilation tubing setup with an exhausting face ventilation arrangement. The entries were numbered 1 through 3, with entry #1 as the intake and entry #3 as the return. Each entry had ventilation tubing exhausting air from the entry using three separate ventilation fans (one for each entry) that were located in the return entry #3 (Fig. 5).

The roof bolting machine was a J.H. Fletcher dual boom crawler high seam bolter with inside controls with the rib bolting option (model #: CHDDR, serial #: 91–102). The roof bolter machine had J.H. Fletcher's dry collection system installed on the intake (right) side of the roof bolter. The dust material was collected inside the physical dimensions of the dry box instead of using bags to collect it. The return (left) side of the machine had J.H. Fletcher's new wet box collection system installed. Testing of these systems occurred simultaneously over three working shifts.

3 Sampling Method

Both gravimetric and instantaneous samplers were used for testing to determine the wet box collector system's ability for respirable dust control. The gravimetric sampler, also known as the coal mine dust personal sampling unit, consisted of an ELF Escort pump operating at 2.0 L/min, a 10-mm Dorr-Oliver cyclone, and a 37-mm 5-µm PVC filter in a coal cassette. The instantaneous sampler was the pDR-1000. The pDR-1000 is a dust sampler that uses optical methods. Therefore, the use of the pDR-1000 requires calibration with a gravimetric sampler in order to use the instantaneous data across all locations [25]. Both of these samplers were used for area sampling. Additionally, each bolter operator was outfitted with a continuous personal dust monitor (CPDM) which allowed determination of respirable dust levels at the roof bolter operator position during operation. Figure 6 shows the sampler types used in this study.

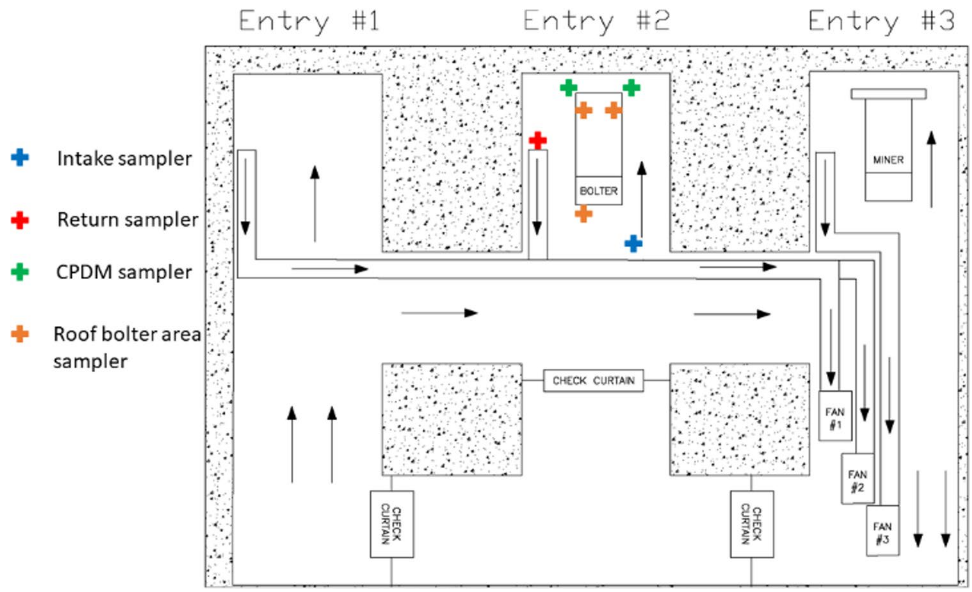

Fig. 5 The layout of the three-entry system showing the locations of sampling packages for testing the dry dust collector and the wet dust collector. Entry #1 is intake and Entry #3 is return

Fig. 6 The samplers used during the study; gravimetric (left), instantaneous (middle), and CPDM (right)

The gravimetric and instantaneous samplers were combined into sampling packages that comprised two gravimetric samplers and one instantaneous sampler. These packages sampled respirable dust at different locations in the roof bolter entry. Figure 5 shows the locations of the sampling packages. Referring to Fig. 5, the intake sampler (blue) was located in the intake of the roof bolting entry. The return sampler (red) was located in front of the exhaust tubing. This sampler was moved as the exhaust tubing was advanced. Additional sampling packages (orange) were placed near or as close to the roof bolter operators on the left/return and right/intake side of the bolter. Another was located behind the roof bolter machine in the dust collector exhaust flow.

For sampling collector box cleanout/inspection activities, two sampling vests each consisting of four gravimetric samplers and a pDr-1000 were used by operators, one vest worn for each dust box (wet and dry). One set of two filters was changed out for each cleanout, and the other set of two filters was used the entire day sampling all cleanouts. The operator conducting the cleanout/inspection of the dust collector boxes wore a vest during this operation, with the samplers turned on just prior to donning the vest. Once completed, the vests were removed from the operators, the samplers were turned off, and the vests were stored in a clean location, either inside a pelican case or in intake air, until their next use. Figure 7 shows the sampling package used for area sampling and the sampling vest used during clean out activities of the dust collector box. This depiction of the sampling vest only shows two gravimetric samplers. Four were used on the sampling vest in the study and the two not shown would have their sampling heads located adjacent to the two in the picture.

Fig. 7 The sampling packages used during the study. The area sampling package consisting of two gravimetrics samplers and one instantaneous sampler (left) and the sampling vest (right)

Table 1 Entry locations during testing with corresponding face ventilation information

Date	Entry	Width (cm)	Height (cm)	Airflow quantity (m^3/s)	Mean entry air velocity (m/s)
8-Oct	Entry 2 right	643	284	6.9	0.4
8-Oct	Entry 1	625	305	6.9	0.4
8-Oct	Entry 2 right	549	307	6.9	0.4
9-Oct	Entry 1	625	279	8.3	0.5
9-Oct	Entry 2	559	302	8.1	0.5
9-Oct	Entry 2	615	274	8.1	1.5
10-Oct	Entry 1	706	292	7.9	0.4
10-Oct	Entry 3	551	320	8.5	0.5
10-Oct	Entry 1	704	292	7.9	0.4
10-Oct	Entry 1	627	328	7.9	0.4

4 Testing

Prior to bolting each entry, a vacuum pressure measurement was taken at each bolter head using a J.H. Fletcher pressure gauge to ensure the dust collection system was operating properly. Throughout testing, the dust collector vacuum pressure was stable at 17.0–19.0 in. Hg for both sides of the roof bolter, which was above the rated minimum vacuum pressure on the roof bolter plate.

The roof bolter dust collector wet box also had pressure gauges installed for the inlet and outlet of the wet box. Typical operating pressure differentials ranged from 1.0 to 7.0 in. Hg during the study. Higher pressure differentials (> 10.0 in. Hg) were encountered at the end of the study, but this was due to the operator neglecting to shut off the water to the wet box during a roof bolter machine idle time. During this instance, the box had filled with water resulting in the inlet being plugged, which required material removal from the box. J.H. Fletcher representatives stated that the wet box final filter has been redesigned so that water should not negatively impact its filtration ability. These pressure gauge measurements are not included as they did not impact the respirable dust concentrations encountered during the study.

Ventilation measurements to determine airflow quantity and velocity into the bolting machine entry were recorded for each entry. The operators were expected to follow their normal ventilation plan. Additionally, new dust collector filters were in place at the beginning of testing. Table 1 shows the ventilation information gathered during the study.

The CPDMs were programmed at the surface to operate the entire shift and were generally in operation prior to outfitting the bolter operators underground. Once the sampling packages were set up in their respective locations, testing began. The roof bolter operators completed their normal tasks. The sampler for the collector exhaust advanced with the roof bolter machine and all other samplers followed the roof bolter as it moved from entry to entry. Time studies were conducted on the roof bolter machine monitoring bolter operation.

Respirable dust sampling was conducted during dust collector box cleanout/inspection using the sampling vest. Cleanout/inspection of the dust collector box occurred after completion of each bolting location. At this point in time, each operator was outfitted with the personal sampling vest. One operator cleaned out the left collector box (wet box) while the other operator cleaned out the right collector box (dry box). The operator cleaning out the wet box started cleaning actions first. Then after the wet box cleaning was completed the operator cleaning out the dry box commenced cleaning the dry box. This procedure was used to prevent cleanout activities of the wet box from contaminating the cleanout activities of the dry box. The actions of operators when opening the dust box for cleanout and the amount of time required to perform the task were recorded. During cleanout, bulk samples were taken of the material in the dust box. The changeout of final filters of the collector system was dependent upon the mine's normal changeout schedule.

This study was conducted over 3 days for testing of the dry collection system roof bolter machine simultaneously with the wet collection system roof bolter machine. Three bolting locations per day were obtained in order to obtain the necessary information to determine collector system performance.

Table 2 Respirable dust concentrations for the roof bolter entry intake, entry return, and roof bolter exhaust during testing

Date	Filter location	Time (minutes)	Concentration (mg/m^3)	% quartz
8-Oct-19	Intake	375	0.853	0.0
8-Oct-19	Intake	376	0.858	NC
8-Oct-19	Return	379	0.870	NC
8-Oct-19	Return	380	0.882	6.6
8-Oct-19	Roof bolter exhaust	376	0.845	NC
8-Oct-19	Roof bolter exhaust	376	0.855	6.8
9-Oct-19	Intake	304	1.265	NC
9-Oct-19	Intake*	305	1.338	0.0
9-Oct-19	Return	376	1.681	NC
9-Oct-19	Return	377	1.331	5.2
9-Oct-19	Roof bolter exhaust	299	0.985	0.0
9-Oct-19	Roof bolter exhaust	299	0.927	NC
10-Oct-19	Intake	356	0.729	NC
10-Oct-19	Intake	357	0.737	0.0
10-Oct-19	Return	365	0.717	NC
10-Oct-19	Return	366	0.807	0.0
10-Oct-19	Roof bolter exhaust	371	0.631	0.0
10-Oct-19	Roof bolter exhaust	370	0.605	NC

*Filter casing was cracked but no damage to filter.

NC, no silica analysis completed.

5 Silica Analysis

Filters from gravimetric samplers were analyzed to determine the amount of crystalline silica or quartz present. One filter with the most mass of respirable dust collected was selected from the gravimetric sampling packages. The selected filter samples were sent to an external laboratory to be analyzed using the standard NIOSH 7500 method Silica, Crystalline, by X-ray diffraction [26]. The results of the analysis provide information on the respirable quartz content (%) for each sample and are presented in Tables 2, 3, 4, 5, and 6 that present the respirable dust concentrations.

6 Results from Sample Filters

The following presents the results from the gravimetric and CPDM sampling during the study. It should be noted that the results from the filters and CPDM cannot be used for compliance sampling. In order to compare the gravimetric results with the CPDM results, all samples must be converted to MRE (Mine Research Establishment)[1] equivalent results. For the gravimetric samples, the MRE equivalent is 1.38 times the sample concentration result [27]. Therefore, each gravimetric sample result was multiplied by 1.38. For the CPDM samples, the MRE equivalent is 1.05 times the sample concentration result [28]. Each CPDM sample result was multiplied by 1.05. All results from the gravimetric filters and CPDMs are shown as MRE equivalent.

The instantaneous data from pDR-1000 was available to use to evaluate respirable dust concentrations during specific activities. Since the evaluation of the wet box collector and dry box collector at the operator location was conducted over the entire daily survey time frame, the pDR-1000 data was not needed. Additionally, during cleanout, the pDR-1000 data was not needed as the gravimetric samplers were turned off and on when cleanout activities occurred. Therefore, the calibration with gravimetric samplers mentioned previously was not required.

[1] MRE is the UK Mining Research Establishment which used a sampler designed specifically to match the UK British Medical Research Council (BMRC) criterion (Page et al., 2008).

Table 3 Respirable dust concentrations encountered by roof bolter operators, both gravimetric and CPDM concentrations

Date	Bolter	Type of collector	Number of bolts drilled	Time (minutes)	TWA* concentration (mg/m^3)	TWA percent difference (%)	CPDM concentration (mg/m^3)	CPDM percent difference (%)	% quartz
8-Oct	Left/return	Wet	50	388	0.845	8.3	0.840	−26.4	0.0
8-Oct	Right/intake	Dry	56	307	0.780		1.141		0.0
9-Oct	Left/return	Wet	41	NA**	NA	NA	0.768	−31.3	NA
9-Oct	Right/intake	Dry	43	300	1.068		1.118		1.6
10-Oct	Left/return	Wet	52	370	0.812	3.0	0.731	−19.1	0.0
10-Oct	Right/intake	Dry	65	370	0.788		0.904		0.0

**TWA*, time-weighted average.

***NA*, not available, filters damaged during transport.

Table 4 Respirable dust TWA concentrations measured from MSHA-requested sampling

Date	Bolter	Type of collector	Number of bolts drilled	Bolting time (minutes)	TWA concentration (mg/m^3)	% Difference	% quartz
9-Oct	Left/return	Wet	41	192	0.864	18.2	0.0
9-Oct	Right/intake	Dry	43	192	0.731		0.0

Table 5 Respirable dust TWA concentrations from cleaning out dust collector boxes

Date	Bolter	Type of collector	Cleaning time (minutes)	TWA concentration (mg/m^3)	% Reduction	% quartz
8-Oct	Left/return	Wet	8	1.257	87.9	0.0
8-Oct	Right/intake	Dry	19	10.399		4.6
9-Oct	Left/return	Wet	20	0.656	82.3	0.0
9-Oct	Right/intake	Dry	24	3.696		10.3
10-Oct	Left/return	Wet	17	1.458	71.0	0.0
10-Oct	Right/intake	Dry	17	5.024		7.4

Table 6 Respirable dust concentration from the single filter used all 3 days of the study

Date	Bolter	Type of collector	Cleaning time (minutes)	TWA concentration (mg/m^3)	% Reduction	% quartz
8-Oct thru 10-Oct	Left/return	Wet	45	1.010	82.1	0.0
8-Oct thru 10-Oct	Right/intake	Dry	60	5.638		12.0

7 Intake, Return, and Roof Bolter Machine Exhaust Samples

Table 2 shows the time-weighted average (TWA) concentrations and percent quartz from the roof bolter entry intake, entry return, and roof bolter exhaust samples. These samplers operated daily from the time roof bolting started until the end of the survey when roof bolting ended. These samplers were turned on and turned off while underground.

The entry intake and return sample TWA concentrations are nearly similar for each day of testing. The roof bolter exhaust sampler was placed at the dust collection system exhaust location. At this location, the exhausts from both the wet and dry box were located adjacent to each other. The TWA concentrations determined from this sample location include any respirable dust in the airflow from both exhausts. There is no way to differentiate the concentrations for each type of exhaust—wet or dry. The results show that the environmental concentrations were relatively stable throughout testing.

The percent quartz in each sample was generally 0.0%, except for the bolter return and bolter exhaust on October 8th and the bolter return on October 9th. The bolter return samplers were located directly in front of the exhaust tubing inlet. Therefore, this dust was being removed from the entry. The bolter exhaust samplers, being located at the roof bolting machine dust collector exhaust ports, could represent material from those ports or ambient air. The TWA concentrations of the bolter exhaust samples are relatively consistent for each day and are not higher than the TWA concentrations from the intake and return samplers. Any dust from the bolter exhaust most likely flows to the exhaust tubing intake and does not reach the bolter operators. Table 3, which shows the respirable dust concentrations and percent quartz at the bolter operator locations, does not show any high percent quartz.

8 Roof Bolter Operator Samples

Table 3 shows the TWA and CPDM concentrations along with the percent quartz of respirable dust encountered for each day of the study. Again, the gravimetric samplers were turned on and turned off while underground, operating from the time roof bolting started until the end of the daily survey when roof bolting ended. The continuous personal dust monitor (CPDM) records the cumulative mass of respirable dust collected in 1-min intervals [29]. NIOSH was able to download the data and evaluate the mass collected throughout the shift. To calculate the dust concentrations of a specific time interval, the cumulative mass collected by the CPDM at the beginning of the time interval and at the end of the time interval is used. The intervals are the start and stop times of the gravimetric samplers used in conjunction with the CPDM. The following equation is used to calculate the respirable dust concentration:

$$Conc. = \frac{\left(Mass_2 - Mass_1\right) \times 1000}{\left(2.2 \times Time_{Int}\right)} \quad (1)$$

where.

Conc. the concentration (mg/m^3);
$Mass_2$ the cumulative mass recorded at end time of time interval (mg);
$Mass_1$ the cumulative mass recorded at begin time of time interval (mg);
2.2 flowrate of the CPDM (lpm);
$Time_{Int}$ the total time of the time interval from beginning to ending (minutes).

The left bolter operator's dust collection system was the wet box, while the right bolter's system was the dry box. The left bolter operator was on the return side of the entry, while the right bolter operator was on the intake side of the entry. Once underground to conduct the study, the best placement of the gravimetric samplers was to set up on the boom of the ATRS, (automated temporary roof support) of the roof bolter (Fig. 8). These locations were selected so the sampling packages were in safe locations (i.e., would not be damaged) and would not interfere with the operations. These samplers were located very close to each other, and as such the TWA concentration results are very similar as seen by the percent difference in Table 3. The percent difference of the left-side concentrations compared to the right-side concentrations was calculated using:

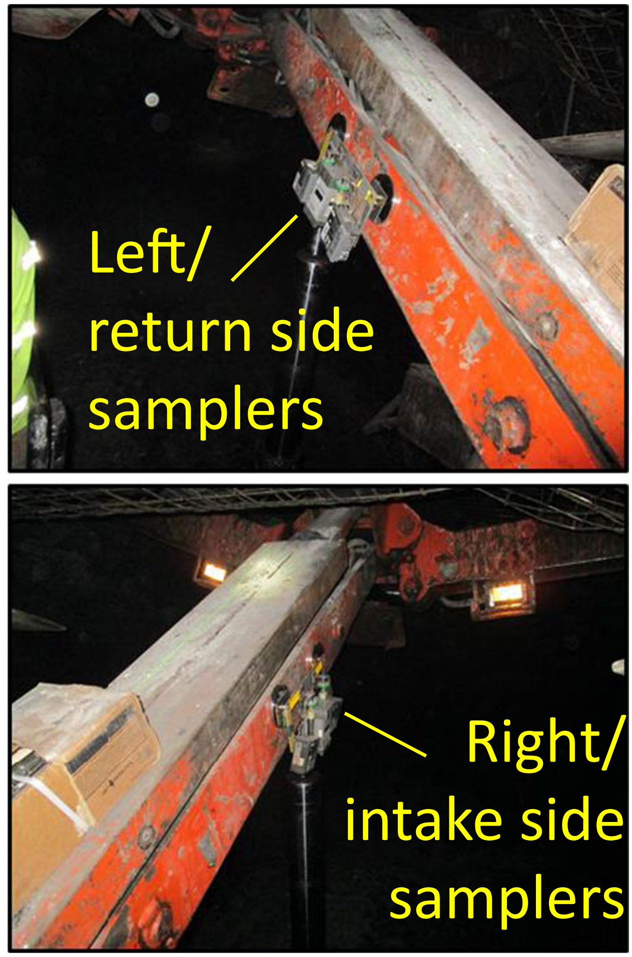

Fig. 8 Location of the gravimetric samplers for the left/return side bolter (top) and the right/intake side bolter (bottom)

$$\%Differ = \frac{\left(Conc_L - Conc_R\right)}{\left(Conc_R\right)} \times 100 \quad (2)$$

where.

% Differ the percent difference (%);
$Conc_L$ the TWA concentration of the left bolter (mg/m^3);
$Conc_R$ the TWA concentration of the right bolter (mg/m^3).

Fig. 9 Locations of MSHA-requested respirable dust sampling. The left/return operator sampler corresponds with the wet box collector (left). The right/intake operator sampler corresponds with the dry box collector (right)

Table 3 shows a percent difference for the gravimetric samplers of 8.3% for the left/return bolter over the right/intake bolter on October 8th and 3.0% for the left/return bolter over the right/intake bolter on October 10th. The percent quartz was 0.0% with the exception of the right/intake bolter operator location on October 9th, which had 1.6% quartz.

The CPDM showed different results—a − 19 to − 31% percent difference. The negative percent difference shows the left/return bolter's CPDM concentration being lower than the right/intake bolter's CPDM concentration. The difference between the gravimetric results and the CPDM results may be the fact that the operators wore the CPDM with the inlet located on their lapel and worked in their separate locations, whereas the bolter gravimetric samplers were located centrally adjacent to each other.

9 MSHA Requested Sampling of Roof Bolter Operators

During the study, the MSHA requested roof bolter sampling with sampling occurring only when the roof bolter operators were installing bolts. These samplers were located underneath the canopy on the post supporting the canopy (Fig. 9), operating only when roof bolting occurred. These locations had to be monitored to prevent damage to the sampler due to raising and lowering of the canopy. The NIOSH instructed the roof bolter operators to turn the samplers on when beginning roof bolting operations. When they left the area for other work, they were instructed to place the samplers on hold. Therefore, only respirable dust concentrations during roof bolting activities were obtained with these samplers.

Only 1 day of results is available and is shown in Table 4. Sampling was not conducted on the first day, October 8th, because the final request from the MSHA was not received in time. The sampling that was conducted on Oct 10th encountered problems with the pump times not being equivalent after sampling that day. It is assumed that one of the operators forgot to restart the sampling pump when returning to bolting operations. Additionally, the filter numbers were not recorded for that day. Therefore, the Oct 10th sampling is unusable. The sampling collected on Oct 9th (Table 4) showed the return bolter's respirable dust TWA concentration is higher than the intake bolter's TWA concentration. This is possibly due to the sampling location on the canopy post being closer to the rib than the roof bolter gravimetric and CPDM samplers. These samplers would be more within the ventilation airflow with the intake air following the rib on the right side and the return air following the rib on the left side. However, the percent difference is only 18%. The percent quartz in these filters was 0.0% for each location.

10 Dust Collector Box Cleaning

An important aspect of this study was to measure the respirable dust exposure to the roof bolter operators during cleaning of the roof bolter dust collector boxes. The roof bolter operators performed their normal procedures for cleanout/inspection of the collector boxes. To sample respirable dust at this time, operators wore the sampling vest which contained four gravimetric samplers. As previously mentioned, two vests were used—one for cleaning of the wet box (left side) and the other for cleaning of the dry box (right side). Of concern was obtaining sufficient mass on the filters for silica analysis. Therefore, two samplers on each vest used filters that were not changed out during the study; the same filter was used on Oct 8th, Oct 9th, and Oct 10th. The other two samplers on the vest had their filters changed out daily. These vests only sampled during the cleanout of the boxes. Again, the wet box was cleaned out first with the dry box being cleaned out second. Table 5 shows the TWA concentrations and the percent quartz encountered during the daily cleanouts. Table 6 shows the TWA concentrations and percent quartz from the filters used on all 3 days of the study.

Results show that the wet box has substantial reductions in respirable dust TWA concentrations when cleaning the

Fig. 10 Inside view of the wet box (left) and the dry box (right) after bolting an entry

boxes, 71% to 88% reductions compared with the cleaning of the dry box. Silica analysis of the gravimetric filters shows that while cleaning the dry box the operator encountered respirable quartz dust with quartz contents ranging from 4.6% to 10.3% quartz. When cleaning the wet box, the operator did not encounter any respirable quartz dust as the quartz contents were 0.0%. This is due to the material being fully saturated and not able to entrain any dust during material movement.

Figure 10 shows the inside views of the wet box and dry box after completion of bolting one entry. It should be noted that although the material is fully saturated, the wet box contains more material than is usually encountered. This is due to the training period required to operate the wet box. Once the vacuum of the dust collector is turned off after bolting, the operator must open the hydraulically actuated valve located at the bottom of the wet box to allow the material to discharge. There were times when the operators had not fully opened the discharge valve. J.H. Fletcher representatives stated that once the wet box is fully utilized, the operators will get a better “feel” for opening and closing the hydraulically actuated valve, which will result in less material in the wet box.

Additionally, once the wet box is fully installed, a hose can be installed in the water circuit that can be used to hose out the wet box to clean it. This action will allow the operator to maintain even more distance from the collector box, thereby further reducing their exposure to respirable dust.

11 Conclusions

The results of the field study show that the wet box dust collector can provide better protection from respirable dust exposure. The roof bolter CPDMs showed that the percent difference ranged from − 19% to − 31%, with a negative percent difference denoting that the operator on the wet box side of the roof bolter had lower CPDM concentrations than the operator on the dry box side. The gravimetric sampler results are essentially similar with percent difference < 10% (3% and 8%). The MSHA-requested sampling percent difference was approximately 18%, denoting that the operator on the wet box side of the roof bolter had higher TWA concentrations than the operator on the dry box side. The reasoning for the wet box side being higher was previously explained due to the wet box side being on the return side of the entry and the placement of the MSHA-requested samplers. The sampler location was thought to be more impacted by the ventilation airflow through the entry since the samplers were possibly more closely aligned with the main ventilation airflow stream. The quartz contents of gravimetric sampling at the roof bolter operators’ location and the MSHA-requested gravimetric sampling were 0.0% with the exception of the right/intake roof bolter location, which was on the dry collector side on October 9th where the quartz content was 1.6%. Due to the variation of respirable dust concentrations at the differing sampling locations by different samplers, no conclusion can be made that the operation of the wet box or dry box collector system had any influence on operator exposure during bolting operations.

However, from the sampling conducted during the dust collector box cleaning, the wet box provided more protection from respirable dust exposures to the operators. The TWA concentrations encountered during wet box cleaning were 71–88% lower than the TWA concentrations encountered for the dry box cleaning. In addition, the quartz content in the filter samples collected during wet box collector cleanout were 0.0%, while the quartz content in the filter samples collected during the dry box collector cleanout ranged from 4.6% to 10.3%. The wet box material was fully saturated, so no dust was re-entrained during cleanout, while re-entrainment of dust occurred during dry box collector cleanout. Other advantages for using the wet box are:

- There is no dry material to handle during cleanout. This includes handling of any collector bags, if used. With no dry material available, any possibility of dry material from the collector box accumulating on the miner’s clothing is eliminated. Silica-bearing material embedded in the clothing can become a source of silica overexposure throughout the rest of the work shift, once the clothing is contaminated [30, 31].

- Material from the precleaner is eliminated, since the precleaner is removed. Eliminating the possibility of re-entrainment of dry material from the precleaner dump into the mine environment.
- The wet box collection system operation should reduce the number of times clean out has to occur, as the material/sludge should self-drain when the drain valve is opened. This would minimize the need to clean out the wet box after every entry.
- The frequency of changing the final filter should be reduced. Since water may reach the final filter, it has been redesigned to be water resistant. Additionally, the elimination of dry material should reduce the frequency of final filter changes.
- Cleaning times of the wet box should be shorter than cleaning times for the dry box. Especially, once personnel are fully trained and experienced on wet box operation and cleanout.
- The addition of a water hose in the water supply system to the roof bolter can be used to wash out the wet box. This water hose would allow the roof bolter operators to wash out the box allowing them to stand further away from the box during cleanout. This is an attribute not available for dry box collector cleaning.

Overall, this field testing indicates that the wet box dust collector can reduce respirable quartz dust exposures to roof bolter operators during cleaning operations, with 71% to 88% reductions in respirable dust exposures when compared to the dry box collector cleanout. Also, the wet box samples during cleanout did not contain any quartz, with percent quartz being zero. Discussions with roof bolter operators from the previous study indicated that once they used the wet box, they did not want to go back to using the dry dust collectors which involve handling of the dry roof bolter drill cutting material [22].

Declarations

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

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