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Design and experimental evaluation of a flooded-bed dust scrubber integrated into a longwall shearer

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ABSTRACT

Continuous mining machines operating in U.S. underground coal mines have, for decades, utilized flooded-bed dust scrubbers for capturing and removing respirable dust generated at the production face. However, the application of dust scrubbers to longwall mining systems has not yet been successful. Considering that nearly 60% of U. S. underground coal production is from longwall mines, the successful application of dust scrubbers to longwall mining systems could have a significant impact on miner health. A full-scale mock-up of a longwall shearer was constructed and equipped with a flooded-bed dust scrubber designed to capture dust produced by the headgate cutting drum. The mockup was installed at the National Institute for Occupational Safety and Health (NIOSH) Longwall Dust Gallery and a series of 40 experiments was conducted to evaluate the scrubber's performance. Results show that the scrubber achieved a 56% reduction of respirable dust in the return airway and a 74% reduction of respirable dust in the walkway area near the shearer. Although these tests were conducted under a controlled environment, the results suggest that a similar scrubber design could be very effective at achieving a significant reduction in respirable dust in longwall mining systems.

1. Introduction

Dust is a detrimental, but inherent, consequence of many mining processes. It is particularly problematic in underground coal mining because of its effects on both health and safety of mineworkers. Coal workers' pneumoconiosis (CWP), commonly referred to as *black lung*, is a debilitating and irreversible lung disease, which results from the long-term inhalation and deposition of coal dust in the lungs. Excessive concentrations of respirable dust particles (<10 μm) cause the formation of scar tissue in the alveolar (gas-exchange) regions of the lungs, resulting in massive fibrosis in the advanced stages of the disease. In addition to this health hazard, float coal dust (<75 μm) is a safety hazard because it can settle on the surfaces of mine entries and propagate a mine explosion if the amount of rock dust applied to mine surfaces is not sufficient to render the coal dust/rock dust mixture inert.

Although the prevalence of CWP has steadily declined over the three decades following the Federal Coal Mine Health and Safety Act of 1969 [1], a study by the National Institute for Occupational Safety and Health (NIOSH) indicates that significant health hazards associated with respirable dust still exist within the coal mining industry [2]. According to the NIOSH study, the declining trend in CWP ended around 1999, and its prevalence has since begun to rise, as shown in Fig. 1 [2]. NIOSH claims that, for miners with 25 or more years of experience, the occurrence rate of CWP has nearly doubled since its low point and that the disease is occurring in younger miners. Furthermore, NIOSH states that the disease's progression rate from beginning stages to more advanced stages has accelerated. It is noted that these results are based on mineworkers who voluntarily participated in the NIOSH Coal Workers' Health Surveillance Program (CWHSP), which may not constitute a representative sample of all mineworkers. Nonetheless, the results indicate that CWP still exists and continues to plague the U.S. coal mining industry. In addition, a recent study involving chest x-rays of Australian underground coal miners found 18 out of 248 positives for opacities suggestive of pneumoconiosis [3].

Current dust-control methods include dilution with ventilation airflow, confinement and isolation by water sprays, wetting and capture by water sprays, and wetting and capture by flooded-bed dust scrubbers. Of these methods, dust scrubbing is the most desirable because it removes the dust from the airstream rather than diluting or confining dust as is done with most other dust control methods.

Because of their effectiveness at removing respirable dust, dust scrubbers have been used successfully on continuous miners for decades. However, there has not been much success in the application of dust scrubbing methods to longwall systems. The approaches previously attempted include ventilated drums, ventilated cowls, water-powered scrubbers, and flooded-bed scrubbers. Although each of these methods showed the potential benefits of dust scrubbing, the

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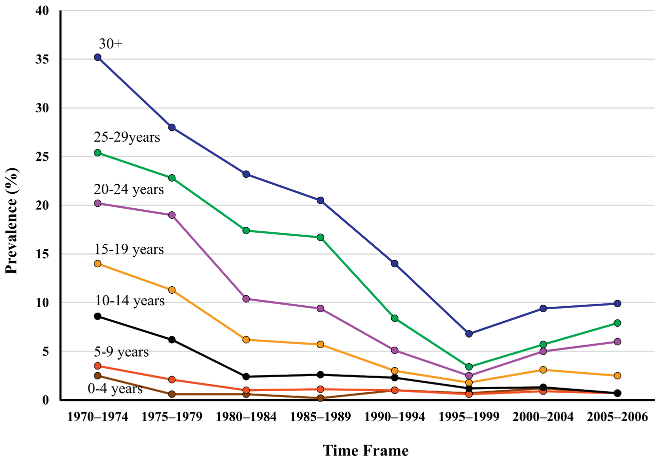

Fig. 1. Prevalence of CWP among examinees employed at underground coalmines [2].

approaches generally had issues with reliability, maintenance, and dust-capture capacity [4–8].

On August 1, 2014, the Mine Safety and Health Administration's (MSHA) new respirable dust rule for U.S. underground coalmines went into effect. Although this rule includes many changes, the most significant ones for longwalls are summarized below.

- The dust concentration limits for respirable coal mine dust has been lowered from 2.0 mg/m^3 at the working face to 1.5 mg/m^3 and from 1.0 mg/m^3 in the intake air to 0.5 mg/m^3, after August 1, 2016 [9].
- The final rule mandates the use of continuous personal dust monitors (CPDMs) to monitor the dust exposure of underground mineworkers in occupations exposed to the highest respirable dust concentration, starting on February 1, 2016. A CPDM is a real-time dust sampler that measures the respirable dust concentration continuously, in real time, and provides a cumulative dust concentration up to the present point in time, a 30-min running average, and the percentage of the permissible exposure limit of the current working shift.
- The term "normal production shift" has been redefined as the production shift that has at least 80% of average production calculated from the 30 most-recent production shifts, as compared with the earlier value of 50% of the average production from the last sampling period. To be considered a valid sample, production for the sampling shift must meet or exceed this 80% average.
- Beginning February 1, 2016, during each calendar quarter, the designated occupation (DO) in each mechanized mining unit (MMU) must be sampled on consecutive normal production shifts until 15 valid representative samples are taken, as compared with the earlier value of five samples collected bimonthly [10].
- The new Rule eliminates using the average of five operator samples for determining compliance, and now requires the use of a single, full-shift operator sample. If the sample exceeds the dust standard, corrective action is required.
- Beginning February 1, 2016, during each calendar quarter, each other designated occupation (ODO) in each mechanized mining unit (MMU) must be sampled on consecutive normal production shifts until 15 valid representative samples are taken [10]. ODO sampling cannot be conducted concurrently with the DO sampling, which extends the total sampling period to a minimum of 30 shifts per quarter.

2. Methods

The objective of this longwall dust scrubber project includes the design, fabrication, and testing of a full-size mockup of a modern longwall shearer with an integrated flooded-bed dust scrubber. Because of the difficulty in developing a scrubber for both cutting drums, the scope of work is limited to a scrubber for capturing dust generated near the headgate drum of the machine. Should this scrubber be shown to be successful, then this technology could be applied to the development of a scrubber for capturing dust generated by the tailgate cutting drum.

2.1. Information gathering and analysis

The research focused on a specific longwall operation to develop the concept and improve the probability of success. Investigators solicited and obtained the cooperation of Alliance Coal, LLC and Joy Global, Inc. (now Komatsu American Corp.) for this initial application. Alliance Coal owns and operates three longwall mines, and the longwall system at its Tunnel Ridge Mine, which includes a Joy 7LS shearer, was used as the test and information-gathering site. The Tunnel Ridge Mine operates in the Pittsburgh coal seam, which has an average seam height of 2.1 m (7 ft).

The research project began with obtaining detailed drawings and specifications of the longwall equipment used at the Tunnel Ridge Mine. Mine visits were made to gather additional information and data. The information included documentation of visual observations of the mining process and dust patterns, with attention being paid to possible scrubber locations on the shearer. Air-quantity and dust measurements were obtained for various locations along the longwall face, and Alliance Coal shared its Mine Ventilation Plan with the research team. Visits were also made to the Joy Global office in Franklin, Pennsylvania and with the NIOSH Dust, Ventilation, and Toxic Substance Branch in Pittsburgh, Pennsylvania. Joy Global provided the research team with detailed dimensional drawings of the 7 LS shearer in electronic format. The obtained data and information from Alliance and Joy were invaluable for constructing computer and physical models of the longwall system.

2.2. Shearer design and construction

2.2.1. Shearer modifications

The research team obtained 2-D and 3-D (.stl files) drawings of the shearer. To create the 3-D model, the shearer was divided into seven parts: main body, headgate drive, tailgate drive, headgate ranging arm, tailgate ranging arm, headgate drum, and tailgate drum. Each part of the shearer model was developed separately, after removing minor details, using the dimensions from the original drawings. The seven parts were then assembled to create a complete shearer model.

Several iterations for the scrubber design were considered before a design was adopted. The final design consisted of the addition of two relatively short modules: a scrubber module located between the headgate module and main body and a fan module located between the main body and tailgate module. An external inlet and duct connecting the scrubber and fan modules and outlet were also included in the design. This integrated design was selected primarily because of height and visibility constraints preventing a scrubber from being added on top of the shearer. Fig. 2 shows the computer model of the modified shearer with the scrubber components shown in blue.

Fig. 2 also shows the shearer-clearer system. The shearer-clearer system consists of a splitter arm that runs from the top corner (walkway side) of the headgate module to approximately 0.46 m (18 in.) beyond the headgate drum. Attached to the splitter arm is a piece of brattice cloth that hangs to the floor. The splitter arm also has a series of spray nozzles attached to it that are directed toward the face. The purpose of this system is to confine the dust generated near the headgate by directing it toward the face, and away from the walkway, where personnel are located. Note that in an operating mine, the passive barrier is composed of heavy mine conveyor belt material rather than brattice cloth. A photo of the shearer-clearer system on the mockup shearer is shown in Fig. 3.

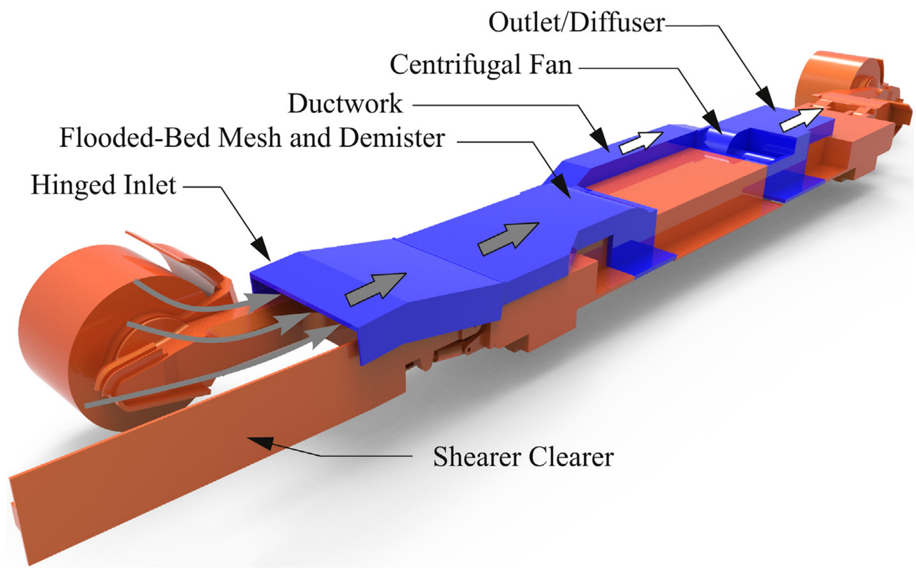

Fig. 2. Final shearer computer model.

Fig. 3. Shearer-clearer system on the experimental shearer.

2.2.2. Flooded-bed dust scrubber

Current dust suppression systems used on longwall faces, e.g., cutting drum sprays and shearer clearer systems, are able to remove some of the dust that is generated by coal extraction activities. However, much of the reduction in dust exposure to miners is achieved by water sprays on the shearer body and splitter arm redirecting the dust-laden air away from the walkway and toward the face. Flooded-bed scrubbers differ in that they are designed to capture and remove respirable dust, as described below.

The general arrangement of a flooded-bed scrubber, consisting of a woven mesh, demister, and fan, is illustrated in Fig. 4. The captured dust-laden air is drawn into the scrubber inlet by the negative pressure created by the fan. The dust-laden air impacts the layered-screen bed, which is wetted by a full-cone water spray. As the dust particles impact the wet screen, the force of impact causes a high percentage of them to become encased in the water droplets wetting the screen. This air/dirty-water mixture then travels through a demister, which consists of a group of parallel, sinuous layers of PVC sheets. As the dirty water impacts the folds of the demister, it falls to the black water sump. Relatively clean, dry air is discharged through the scrubber outlet.

Typical fan sizes for continuous miner dust scrubbers range from 10 to 30 kW (13–40 hp), which produces an airflow of 1.65–4.72 m^3/s (3500–10,000 cfm). The mesh consists of 10 to 30 layers of 89-μm, woven steel-mesh screens; the water spray is typically applied at a rate of 0.41 l/s (6.5 gpm) at a pressure of 310 kPa (45 psi).

Two operational characteristics are typically used to define scrubber performance: *capture efficiency*, which is the portion of the airborne dust that is captured by the scrubber, and *cleaning efficiency*, which is the percentage of dust removed from the captured air [4]. Because flooded-bed dust scrubber technology is mature technology, the scope of work for this project did not include evaluating or improving scrubber cleaning efficiency. Instead, effort was focused on developing a scrubber system that is effective at capturing dust near the longwall shearer headgate cutting drum. For this reason, a standard continuous miner scrubber mesh and demister were used in conjunction with a 37.3 kW (50 hp) centrifugal fan.

The scrubber used is composed of a 20-layer mesh, with dimensions of 64.1 × 79.4 cm (22.5 × 31.3 in). The demister is composed of 21 layers and has dimensions of 62.2 × 54.6 × 31.8 cm (24.5 × 21.5 × 12.5 in.). With this scrubber and demister, the fan provided a maximum airflow of 6.47 m3/s (13,700 cfm). Table 1 provides a summary of the scrubber components.

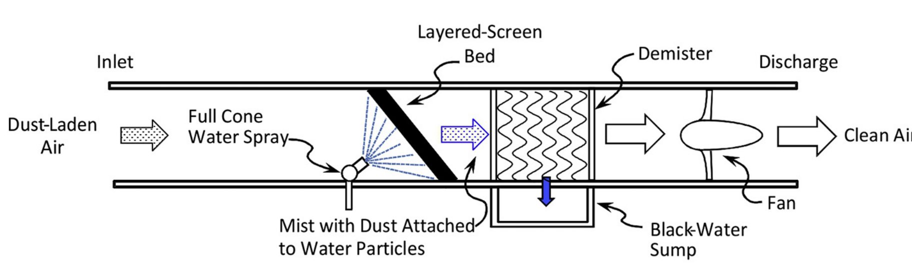

Fig. 4. General arrangement of a flooded-bed dust scrubber.

Table 1
Experimental dust scrubber specifications.

Component	Description
Scrubber fan power	37.3 kW (50 hp)
Scrubber capacity	6.47 m^3/s (13,700 cfm)
Scrubber spray	0.41 l/s (6.5 gpm) single-nozzle, full cone
Mesh	20 layers, 89 μm woven mesh
Demister	21 layers

2.3. Longwall dust gallery

Fig. 5 shows the general layout of the NIOSH Pittsburgh Mining Research Division (PMRD) Longwall Dust Gallery. The dust gallery is a non-functioning representation of a short length of a longwall face. Although the individual components are non-functional, they have been constructed to the same dimensions as typical longwall face equipment so that the airflow along the gallery is very representative of a working longwall section. The gallery face is 38 m (125 ft) in length and consists of 19 roof support shields and a spill plate. (There is no armored face conveyor in the gallery.) For these experiments, the ceiling was set to its lowest height, approximately 2.4 m (94 in.) to match, as closely as possible, the height of the Tunnel Ridge Mine. Fig. 6 shows the relevant dimensions along the dust gallery face. (Readers wanting more information about longwall mining can find additional information in references [11, 12].)

2.4. Test protocol

2.4.1. Dust sampling devices

Dust concentration measurements were made with a combination of ThermoFisher Scientific Personal Dust Monitor (PDM) Model 3600 and Model 3700 devices, shown in Fig. 7. The PDM 3600 is the precursor to the PDM 3700, with the primary difference being that the PDM 3600 includes a cap lamp, a battery to power the cap lamp, and a dust inlet mounted to the cap lamp. Each is a real-time dust monitor approved for underground use, with the PDM 3700 meeting the sampling requirements of the latest MSHA Dust Rule. Details of the PDM 3700 operation and specifications can be found in the Instruction Manual [13]. Both Model 3600 and 3700 PDMs were used because of the number of sampling locations desired and instrument availability.

2.4.2. Dust sampling locations

Sixteen PDMs were used to measure dust concentrations. Fig. 8 (a) shows the 12 dust-measurement locations along the longwall gallery face and Table 2 shows the distances of the dust monitors relative to the face, floor, and hub of the headgate drum. It is noted here that the yellow portion of Fig. 8 shows brattice cloth that was laid near the headgate drum to represent recently cut coal that would be piled on the armored face conveyor near the headgate drum. Fig. 8(b) shows the positions of the four PDMs hung in the return relative to the floor, ceiling, and sides of the return airway.

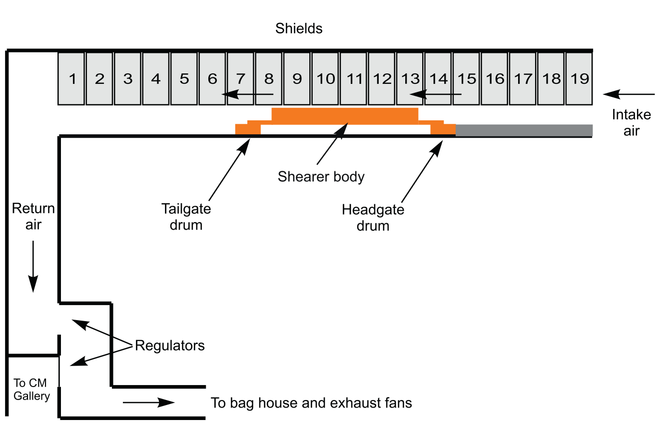

Fig. 5. Layout of the NIOSH PMRD Longwall Dust Gallery replicating a tail-to-head cut.

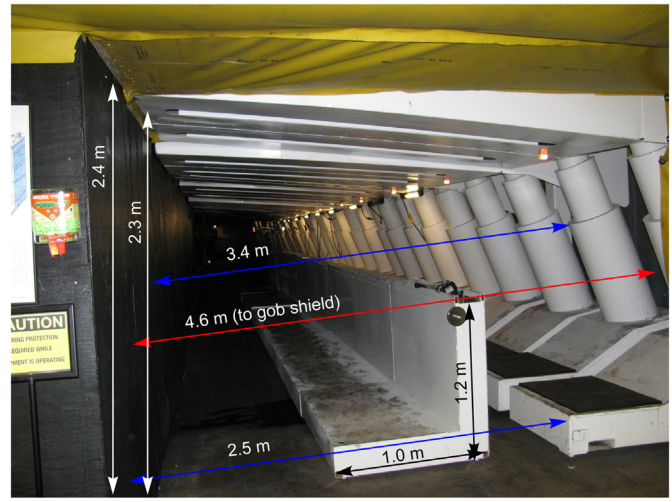

Fig. 6. Dimensions along the Longwall Dust Gallery Face.

2.4.3. Respirable dust and dust injection locations

The dust used for the study is Keystone Mineral Black 325BA, a low specific gravity, finely ground material, manufactured by Keystone Filler and Manufacturing Company. Table 3 provides the relevant physical properties of the Keystone Mineral Black, and Fig. 9 shows the cumulative size distribution.

Observations of operating longwalls were made and videos of operating longwalls were studied to determine suitable dust injection locations for the tests conducted at the longwall dust gallery. These observations indicated that the observed dust patterns could be obtained by injecting dust at three locations, shown in Fig. 10. Dust injection point 1 is located in the middle of the arced surface representing the active coal-cutting location of the headgate drum. Injection point 2 is a 102 mm (4.0 in.) diameter corrugated pipe located 0.45 m (18 in.) from the coalface, 1.02 m (40 in.) from the floor, and approximately 0.53 m (21 in.) from the center of the arc. Dust injection point 3 is from a 7.6 × 30.5 cm (3 × 12 in.) rectangular an opening at the bottom of a wooden box mounted on the headgate ranging arm. Locations 2 and 3 represent dust entrained into the air by the action of the cut coal flowing from the headgate drum onto the armored face conveyor (AFC).

Dust was gravity fed from a screw feeder into a 19.05 mm (0.75 in.) diameter hose transporting compressed air at a pressure of 414 kPa (60 psi) into a six-port dust manifold that had ball valves attached to each

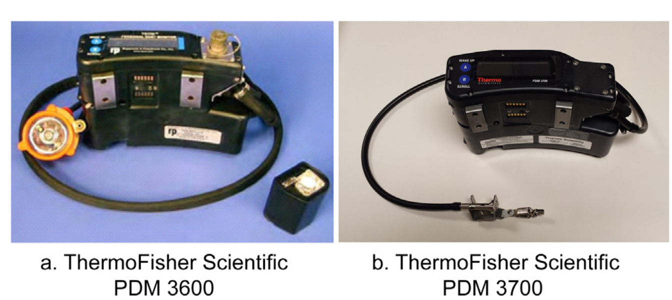

Fig. 7. ThermoFisher Scientific Personal Dust Monitors.

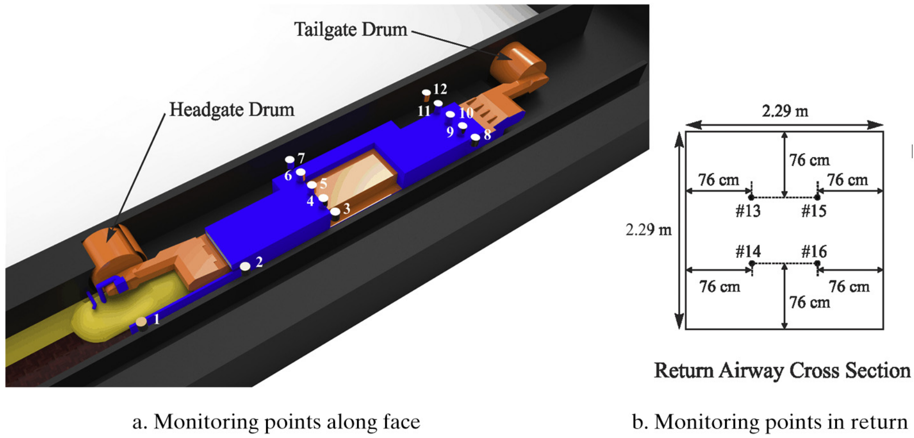

Fig. 8. Dust monitoring locations along longwall face and return airway.

Table 2
Relevant dust monitoring distances.

Identifier	Distance from face	Distance from center of headgate drum	Distance from floor
Splitter arm (1)	3.18 m (125 in.)	1.27 m (50 in.)	1.70 m (67 in.)
Inlet (2)	3.18 m (125 in.)	2.84 m (112 in.)	1.70 m (67 in.)
Scrubber walkway (3)	3.18 m (125 in.)	6.48 m (255 in.)	1.88 m (74 in.)
Scrubber mid-walkway (4)	2.54 m (100 in.)	6.48 m (255 in.)	1.88 m (74 in.)
Scrubber mid-shearer (5)	1.91 m (75 in.)	6.48 m (255 in.)	1.88 m (74 in.)
Scrubber mid-face (6)	1.27 m (50 in.)	6.48 m (255 in.)	1.88 m (74 in.)
Scrubber face (7)	0.64 m (25 in.)	6.48 m (255 in.)	1.88 m (74 in.)
Tailgate walkway (8)	3.18 m (125 in.)	12.12 m (477 in.)	1.88 m (74 in.)
Tailgate mid-walkway (9)	2.54 m (100 in.)	12.12 m (477 in.)	1.88 m (74 in.)
Tailgate mid-shearer (10)	1.91 m (75 in.)	12.12 m (477 in.)	1.88 m (74 in.)
Tailgate mid-face (11)	1.27 m (50 in.)	12.12 m (477 in.)	1.88 m (74 in.)
Tailgate face (12)	0.64 m (25 in.)	12.12 m (477 in.)	1.88 m (74 in.)
Return: top-left (13)	NA	NA	NA
Return: bottom-left (14)	NA	NA	NA
Return: top-right (15)	NA	NA	NA
Return: bottom- right (16)	NA	NA	NA

dust line. Three of the six ports were used to carry the dust to the three dust injection locations described above. The ball valve of the dust line carrying dust to the wooden box (injection location 3) was fully open (100%) while the ball valves carrying dust to the other two locations were half open (50%). The dust lines feeding injection locations 2 and 3 were connected to 102 mm (4.0 in.) corrugated pipes. A blower was used in these pipes to provide dust injection at an air velocity of 24.4 m/s (4800 fpm) at location 2 and 14.22 m/s (2800 fpm) at location 3. Dust at injection point 1 was from a nozzle fed from one of the lines connected to the dust manifold. This configuration produced dust flow patterns closely matching those observed at longwall operations.

2.4.4. Experimental factors and levels

The tests were developed to follow a full factorial experiment to determine main effects and interaction. Because of the limitations in time available at the NIOSH longwall gallery, tests were limited to three factors at two levels. All tests were conducted by NIOSH personnel using NIOSH PDMs and associated software. The factors included the scrubber inlet, the scrubber capacity, and the face-air velocity, discussed below.

2.4.4.1. Scrubber inlet. The scrubber inlet was used with and without an extension. Without the extension, the inlet is 2.77 m (109 in.) from the

Table 3
Typical properties of Keystone Mineral Black 325BA dust.

Typical properties	
Specific gravity	1.22
Color	Black
Moisture	1% maximum
Total sulfur	1.20%
Free sulfur	<0.5%

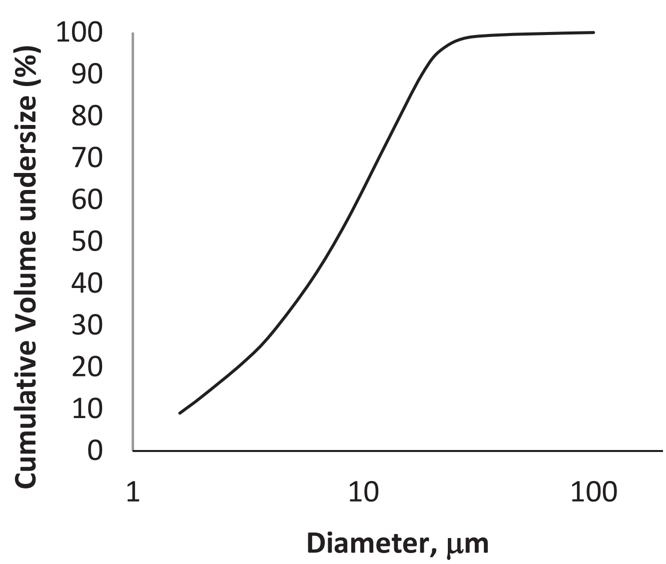

Fig. 9. Approximate cumulative size distribution of Keystone Mineral Black 325BA.

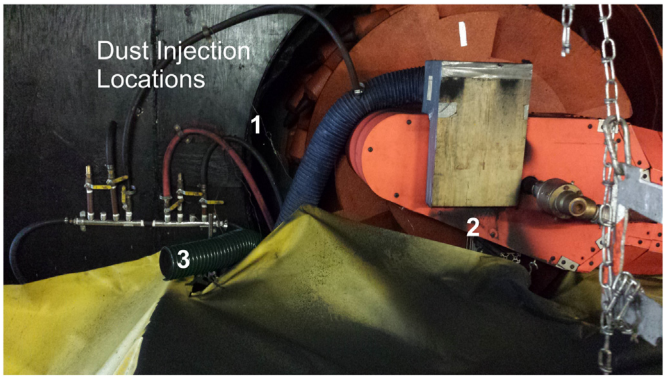

Fig. 10. Dust injection locations.

hub of the headgate drum. With the extension, the inlet is 1.91 m (75 in.) from the hub of the headgate drum. The inlet extension is angled 14° upward from the horizontal. Fig. 11 shows the location of the scrubber inlet with and without the extension on the software model of the shearer. The low level is with the extension removed and the high level is with the extension included.

2.4.4.2. Scrubber capacity. The scrubber fan was operated at full voltage at two frequencies by using a variable-frequency motor drive (VFD) to establish the high and low levels of scrubber capacity. The high-level operation was at 60 Hz, and the low level was at 30 Hz. At 60 Hz, the scrubber capacity is approximately 6.47 m^3/s (13,700 cfm). At 30 Hz, the scrubber capacity is approximately 2.97 m^3/s (6300 cfm). Scrubber spray water flow was maintained at 0.41 l/s (6.5 gpm).

2.4.4.3. Face air velocity. The third factor is the velocity of the longwall face air. The high level is based on the maximum airflow that can be produced at the NIOSH longwall gallery – approximately 3.05 m/s (600 fpm) with a velocity of 3.56 m/s (700 fpm) near the center of the dust gallery. The low level average velocity is 2.03 m/s (400 fpm) with a velocity of 2.54 m/s (500 fpm) near the center of the dust gallery. The Tunnel Ridge ventilation plan calls for a minimum velocity of 2.54 m/s (500 fpm) along the face at a distance of 30.5 m (100 ft) from the headgate. Table 4 shows the factors and levels for the experiments.

2.4.5. Test conditions

Table 5 shows the sequence of operating conditions for each experiment. For each day that testing was conducted, the PDMs were programmed to record dust concentrations throughout the day. However, results were based on the average values measured over 10-min intervals during each operating condition. In addition, there was a three-minute period after the transition from one condition to the next, to allow the system to reach steady-state at the new condition. For example, each test would begin with dust ON (step 1 in Table 5). After three minutes, data from the next 10-min would be used to determine the dust concentrations. Next, the scrubber fan would be turned ON (step 2 in Table 5). After a three-minute wait period, data recorded for the next 10-min time interval would be used to determine the dust concentrations for dust + scrubber fan. This process would be continued in the sequence of steps shown in Table 5 until the completion of step 4. At this point, the scrubber fan, scrubber sprays, and splitter arm sprays would all be turned OFF, and dust only would be run again for 13 min, with data from the last ten minutes used to determine the concentration for dust-only again. Five replicates were run for each test condition, for a total of $(2)^3(5) = 40$ tests.

Because the primary objective of the experiments was to determine the dust-capture effectiveness of the scrubber, it was decided to first study the results with the splitter arm sprays OFF. Splitter arm sprays should improve the performance of the scrubber because the sprays direct dust away from the walkway and toward the scrubber inlet where it can be captured. And, although it is recognized that longwall systems are equipped with splitter arm sprays, it was felt that the initial analysis should be conducted with the splitter arm sprays OFF. Note that the sequence of steps shown in Table 5 makes this analysis possible by using the dust concentrations recorded during step 3 instead of those recorded during step 4. Subsequently, analysis with the splitter arm water sprays ON was conducted.

Each test lasted 62 min and the mean respirable dust used per test was 2.52 kg, with a standard deviation of 0.28 kg. This feed rate provided dust concentrations between five and 45 mg/m^3 (depending on the location) with the scrubber and splitter arm sprays turned off. Although the feed rate of the dust injection was targeted for a constant

Table 4
Factors and levels for NIOSH longwall gallery experiments.

Factor	Label	Low level	High level
Scrubber inlet extension	A	Removed	Included
Scrubber capacity	B	2.97 m^3/s (6300 cfm)	6.47 m^3/s (13,700 cfm)
Face air	C	2.03 m/s (400 fpm)	3.05 m/s (600 fpm)
		15.4 m^3/s (32,640 cfm)	23.1 m^3/s (49,000 cfm)

Table 5
Operating conditions for experimental study.

Step	Operating condition	Duration, min
1	Dust only	13
2	Dust + scrubber fan	13
3	Dust + scrubber fan + scrubber sprays	13
4	Dust + scrubber fan + scrubber sprays + splitter arm sprays	13
5	Dust only	13

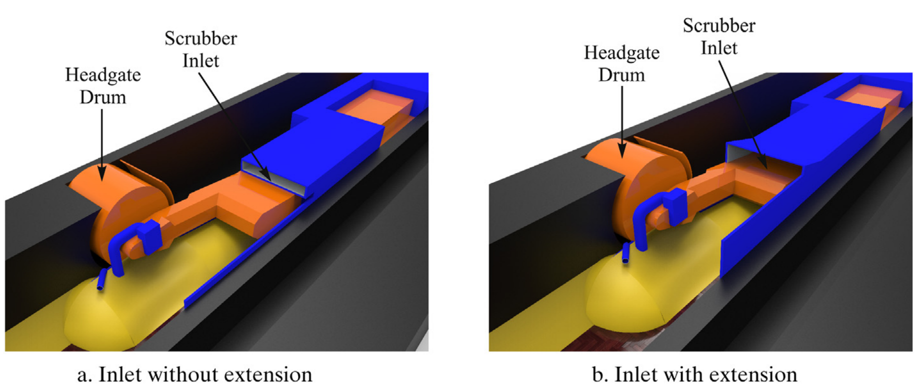

Fig. 11. 3-D model of shearer mockup showing the two inlet locations.

flow rate, it was not possible to produce a fixed dust concentration during the experimental program. Therefore, the results were standardized to the average dust-only value (i.e., on the basis of the average dust concentration of steps 1 and 5 in Table 5) for each particular test. Performance is evaluated as the reduction in dust, in percent, as shown in (1).

$$\text{Dust Reduction} = \left(1.00 - \left[\frac{C_S}{(C_{01} + C_{02})(0.5)}\right]\right)(100\%) \quad (1)$$

where,

C_S = dust concentration measured with the scrubber fan and sprays ON and splitter arm sprays OFF (Step 3 in Table 5).

C_{01} = dust-only concentration at beginning of test (Step 1 in Table 5).

C_{02} = dust-only concentration at end of test (Step 5 in Table 5).

During the tests, the pressure drop across the scrubber mesh and demister was monitored to determine if there was evidence of dust accumulating on the surface of either device. In addition, a viewport was built into the scrubber that permitted visual examination of the scrubber mesh. Pressure drop measurements and visual examination of the mesh showed that the water flow in the system was sufficient to prevent any accumulation of caked dust. In addition, the mesh and demister were periodically inspected for evidence of dust accumulation or damage.

2.4.6. Analysis

The primary objective of the analysis was to determine the performance of the flooded-bed dust scrubber and also to determine those factors that have the greatest impact on performance. Identifying any significant interaction was also important. This analysis is typically done by determining the sums of squares, mean squares, effects, and estimates of the coefficients. Subsequently, a significance test is conducted to determine which coefficients are significantly different from zero. The significant coefficients are then used to create a regression model.

Generally, an *F*-test can be used to determine the level of significance. Alternatively, the *t*-statistic can also be used to determine the level of significance. This is because a *t* random variable with *d* degrees of freedom is an *F* random variable with one numerator and *d* denominator degrees of freedom. Consequently, a test that compares the absolute value of the *t*-statistic to the *t* distribution is equivalent to the *F*-test. For this study, analysis was conducted using *JMP Statistical Analysis Software*, and the *t*-test was used to determine the level of significance, with a *P*-value of <0.01 indicating significance.

3. Results

As previously described, 12 PDMs were used to monitor dust reduction at various locations along the longwall gallery face plus four PDMs in the return airway (as was shown in Fig. 8). This is a very comprehensive set of monitoring locations, and determining the dust reduction at each of these points is valuable for validating software models, e.g., CFD (computational fluid dynamic) models. However, attempting to analyze the scrubber performance at each of these locations is impractical for evaluating performance. Therefore, the analysis focused on the following groups of locations:

- Return airway with splitter arm sprays OFF
- Walkway (locations 1, 2, 3, 8) with splitter arm sprays OFF
- Face area (locations 7, 12) with splitter arm sprays OFF
- Area above shearer body near the headgate module (locations 4, 5, 6) with splitter arm sprays OFF
- Return airway with splitter arm sprays ON
- Walkway (locations 1, 2, 3, 8) with splitter arm sprays ON

As mentioned, the primary emphasis of this study was to develop a scrubber system with high capture efficiency, rather than focusing on the cleaning efficiency. This is because scrubber and demister design is very mature technology, so the development of a scrubber and demister for the flow rates used in this study is beyond the project scope of work. If the integrated dust scrubber is effective at capturing dust, then a manufacturer of scrubbers could develop and manufacture a system for higher airflow rates. Monitoring locations 1–12 measure the scrubber capture efficiency. They are upwind of the scrubber exhaust so they measure the amount of dust captured, but not necessarily cleaned, by the scrubber. However, monitoring points 13–16, located in the return, measure the combined capture and cleaning efficiency of the scrubber.

3.1. Results with splitter-arm sprays OFF

3.1.1. Dust concentration reduction in return airway

Table 6 shows the dust reduction in the return airway for each of the 40 runs, the average values for each treatment combination, and the summation for each combination. Yates notation is used in the treatment combinations column, i.e., the presence of a letter that represents a particular factor indicates that the factor is at the high level, while the absence of the letter indicates that the factor is at the low level. The number one in parenthesis, (1), is the symbol used to indicate all factors are at the low level. For example, the treatment combination (1) indicates the following: scrubber inlet extension removed, scrubber capacity at 50%, and face air velocity at 2.03 m/s (400 fpm).

This information is presented in the form of percent dust reduction of four PDMs; therefore, it is appropriate to show how these values

Table 7
Run 1 dust concentration measurements in return airway with all factors at the low level.

PDM #	Measured dust concentration, mg/m^3		
	Dust + scrubber fan + scrubber sprays	Dust only	Dust only
13	7.169	9.072	9.259
14	4.103	4.878	5.098
15	6.149	8.459	8.383
16	7.309	7.369	7.681
Mean	6.183	7.445	7.605

Table 6
Summary of results for return airway with splitter arm sprays OFF.

Treatment combinations	Design factors			Reduction in dust concentration (%)						
	A	B	C	Run 1	Run 2	Run 3	Run 4	Run 5	Average	Sum
(1)	−1	−1	−1	17.84	27.05	19.27	22.07	19.60	21.17	105.83
a	1	−1	−1	17.53	19.86	18.91	31.34	21.73	21.87	109.37
b	−1	1	−1	42.41	45.36	37.62	40.64	48.96	43.00	214.99
c	−1	−1	1	21.54	24.46	27.67	24.82	19.35	23.57	117.83
ab	1	1	−1	52.53	47.11	48.87	54.49	46.16	49.83	249.17
ac	1	−1	1	31.70	32.39	33.88	35.45	32.56	33.19	165.97
bc	−1	1	1	50.95	51.05	47.05	45.78	53.29	49.63	248.13
abc	1	1	1	56.31	60.43	56.02	54.76	57.41	56.99	284.93

A = scrubber inlet extension, B = scrubber capacity, C = face air velocity.

Table 8
Regression model parameter estimates for return airway – splitter arm sprays OFF.

Term	Estimate	Std error	T-ratio	Critical value	P-value	R^2
Intercept	37.4054	0.5643	66.28	2.739	< 0.0001*	0.95
A	3.0667	0.5643	5.43	2.739	< 0.0001*	
B	12.4549	0.5643	22.07	2.739	< 0.0001*	
C	3.4374	0.5643	6.09	2.739	< 0.0001*	
AB	0.4824	0.5643	0.85	2.739	0.3990	
AC	1.1807	0.5643	2.09	2.739	0.0444	
BC	0.0074	0.5643	0.01	2.739	0.9896	
ABC	−1.0495	0.5643	−1.86	2.739	0.0721	

A = scrubber inlet extension, B = scrubber capacity, C = face air velocity.

were determined from the raw data. Table 7 shows the 10-minute dust concentration values for steps 1, 3, and 5 (as described in Table 5) for each of the four PDMs suspended in the return airway for Run 1 of five replicates with all factors at the low level. Eq. (2) shows how the dust reduction of 17.84%, shown in Table 6, was determined.

$$\text{Dust Reduction} = \left(1.00-\left[\frac{6.183}{(7.445+7.605)(0.5)}\right]\right)(100\%) = 17.84\% \quad (2)$$

The results were then used to determine main effects, interaction, and to develop the regression model for the dust reduction in the return. Table 8 shows the regression model parameter estimates for this situation. Table 8 also shows the coefficient of determination, R^2, which is 0.95, meaning (loosely) that the model predicts 95% of the observed variability.

Inspection of Table 8 shows that there are three main effects and that the most significant one is the scrubber capacity. Further inspection shows that there is no significant interaction, making interpretation of the results for the dust reduction in the return airway straightforward to interpret. Specifically, the most significant factor is the scrubber capacity, with a coefficient of 12.5. The coefficients for the inlet extension and face air velocity are 3.1 and 3.4, respectively. With all factors at the high level, the model (Eq. 3) predicts a dust reduction of 56.4%. Inspection of Table 6 shows an average reduction of 56.99% for each factor at the high level, which compares very well with the model using the three main effects.

$$\hat{y} = 37.405 + 3.067a + 12.455b + 3.437c \quad (3)$$

This result is interesting because one would expect the best scrubber performance to be with the inlet extension included (because the inlet is closer to the dust source), the scrubber at the higher capacity (because more air is cleaned by the scrubber), and the face-air velocity at the lower level (because the scrubber cleans a larger fraction of the total air). For example, with the scrubber capacity at the high level, 42% of the face air is scrubbed at the lower face-air velocity compared with 28% being scrubbed at the higher face-air velocity. However, scrubber performance is actually better at the higher face-air velocity (when the inlet extension is included and the scrubber capacity is at the high level). A reasonable explanation is that, although the scrubber cleans a smaller fraction of air at the higher face-air velocity, the action of the increased face-air velocity helps to direct the dust-laden air toward the scrubber inlet.

3.1.2. Dust concentration reduction in walkway, face area, and area above shearer body

The remaining areas studied for dust reduction with the splitter arm sprays OFF include the walkway, the face area, and the area above the shearer body. As previously mentioned, reducing dust concentration in the walkway is important because this is the area where miners will commonly be working. Therefore, a reduction of dust in the walkway is significant for reducing dust exposure to miners. Analysis of dust reduction along the face and above the shearer body have been done to help gain some insight into the effect of the scrubber on the airflow near the shearer and also for comparison with CFD (computational fluid dynamics) models that will be developed in the future. Table 9 shows the PDM locations (referring to Fig. 8), regression model, and correlation coefficient for each of these areas.

3.1.2.1. Walkway. Inspection of the regression model shows that there is a large main effect associated with the scrubber capacity with a coefficient of 12.7. The coefficients for the inlet extension and face air velocity are 7.2 and 3.6%, respectively.

There is also a relatively small negative scrubber capacity/face-air velocity interaction effect, with a coefficient of −2.9. This interaction suggests that the scrubber performance is not affected much by the face-air velocity when the other factors are at their high level (at the levels tested). For example, with the scrubber capacity and inlet extension at their high levels, the model predicts a 73% reduction in dust concentration with the face-air at the low level and a 74% reduction in dust concentration with the face air at the high level. This is an important result, because face-air velocity cannot be controlled for the sake of improving scrubber performance. In addition to carrying dust away from the face and into the return, the air on a longwall face must also be adequate to dilute methane concentrations to safe levels.

3.1.2.2. Face area and area above shearer body. Although emphasis is on dust reduction in the return and walkway, it is interesting to analyze the impact of the scrubber in the area above the shearer body and between the shearer and face (i.e., the face area). In both cases, there is extension/scrubber capacity interaction and scrubber capacity/face-air velocity interaction. Because of these interactions, the scrubber performance is significantly higher with all factors at the high level compared with other combinations of levels. For example, at the face area, the dust reduction with all factors at the high level is 65%. The next best performance is with the inlet extension removed and other factors at the high level, with a dust reduction of 41%. All other combinations result in dust reductions of <30%. For the area above the shearer body, the dust reduction with all factors at the high level is 60%. All other combinations of levels result in a dust reduction of 31%, or less.

3.2. Results with splitter-arm sprays ON

Recall that the shearer clearer system is used to help reduce dust in the walkway by using a physical barrier and water sprays to direct dust toward the face. However, this system is not designed to remove respirable dust from the airstream, i.e., the splitter-arm sprays primarily direct dust away from the walkway, but do not capture a significant portion of dust in the water droplets. Therefore, one would expect a significant reduction in dust concentrations in the walkway and a modest reduction in dust concentration in the return with the splitter arm sprays ON.

Table 9
Regression models and coefficients of determination for areas near the shearer with splitter arm sprays OFF.

Location	PDM locations	Regression model	R^2
Walkway	1, 2, 3, 8	$\hat{y} = 53.590 + 7.176a + 12.717b + 3.597c - 2.887bc$	0.92
Face area	7, 12	$\hat{y} = 25.714 + 7.519a + 9.558b + 10.200c + 4.268ab + 7.809bc$	0.95
Area above shearer body	4, 5, 6	$\hat{y} = 23.031 + 10.294a + 6.487b + 10.841c + 4.636ab + 5.352bc$	0.90

Table 10
Regression models and coefficients of determination for the return and walkway with splitter arm sprays ON.

Location	PDM locations	Regression model	R^2
Return	13, 14, 15, 16	$\hat{y} = 43.645 + 4.069a + 12.098b + 0.103c + 2.636ac$	0.94
Walkway	1, 2, 3, 8	$\hat{y} = 91.492 + 0.692a + 2.524b - 1.571c + 1.853ac$	0.60

3.2.1. Return

Table 10 shows the regression model for the dust reduction in the return. Inspection of the model shows that the face air velocity is not a significant factor, except for a small inlet extension/face air velocity interaction. Best performance is with all factors at the high level, with a predicted dust reduction of 62.6%. Comparing this result to 56.4% reduction with the splitter arm sprays OFF shows a modest improvement in performance. The coefficient of determination of 0.94 is very good.

These results show that the use of splitter arm sprays results in an 11% improvement in dust reduction in the return; however, it is not known how much of this improvement is due to the sprays directing dust toward the scrubber inlet and how much is due to dust capture by the water droplets of the splitter arm sprays.

3.2.2. Walkway

Table 10 also shows the regression model for dust reduction in the walkway with the splitter arm sprays ON. Inspection of the model shows a mean dust reduction of 91.5% and relatively small main effects and interaction. The coefficient of determination for this model is 0.60, which is the lowest of all the models and indicates that less variability is explained by this model compared to the others. Best scrubber performance is with the scrubber capacity at the high level, the inlet extension removed, and face air velocity at the low level. A possible explanation for this follows. The splitter arm sprays direct dusty air toward the face. Because the sprays are approximately perpendicular to the face airflow, the sprays should be more effective redirecting the air at lower face-air velocities. The action of the scrubber, particularly with capacity at the high level, will assist in pulling air away from the walkway because of the negative pressure at the scrubber inlet. The effect of the inlet extension is not as clear in this situation. With the extension included, dust can be captured before it disperses. However, with the extension removed, particularly at higher face-air velocities, the negative pressure of the scrubber pulls dust away from the walkway for a longer distance, thereby aiding the effect of the splitter-arm sprays.

4. Conclusion

The study indicates that a dust scrubber integrated into a longwall shearer in a laboratory environment can be effective at reducing airborne respirable dust. Test results showed a reduction in the respirable dust concentration in the return airway of up to 56% without splitter arm sprays and up to 63% with splitter arm sprays. Results also show that the scrubber helps to reduce dust concentrations in the longwall walkway, with a maximum dust concentration reduction of 74% without splitter arm sprays and over 90% with splitter arm sprays. In each case, the scrubber capacity at the high level is the most significant factor for removing dust. The inclusion of the inlet extension is also a significant factor in dust capture. An unexpected result is that the scrubber performance is not very dependent on face air velocity; in fact, performance is generally better at the higher face air velocity. It is also noted that these results are based on dust generated near the headgate cutting drum of the shearer.

Although the scrubber was designed considering the mining environment, it is recognized that the tests were conducted under very controlled conditions. Future emphasis needs to be placed on modifying the design so that the scrubber would be capable of handling the larger coal/rock particles that are present on longwall faces. Specifically, additional research needs to be conducted on the inlet design to keep large particles from overloading or damaging the scrubber.

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