

EXAMINATION OF A NEWLY DEVELOPED MOBILE DRY SCRUBBER (DS) FOR COAL MINE DUST CONTROL APPLICATIONS

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ABSTRACT

A self-tramming remotely controlled mobile Dry Scrubber (DS) was developed by J. H. Fletcher and Co. under a contract with the National Institute for Occupational Safety and Health's Office of Mine Safety and Health Research (NIOSH OMSHR) to reduce exposure of miners to airborne dust. NIOSH OMSHR laboratory testing showed that the DS averaged greater than 95% dust removal efficiency with the disposable filters and averaged 88% and 90%, respectively, for the optional washable filters in their pre-washed and post-washed test conditions. Although the washable filters could be reused, washing them generated personal and downstream respirable dust concentrations of 1.2 and 8.3 mg/m³, respectively, for a 10-minute washing period. The DS's velocity pressure regulated variable frequency drive (VFD) fan maintained a relatively consistent airflow near the targeted 1.43 and 4.25 m³/s (3000 and 9000 ft³/min) airflow rates during most of the laboratory dust testing until reaching its maximum 60 Hz fan motor frequency or horsepower rating at 2610 Pa (10.5 in. w.g.) of filter differential pressure and 3.97 m³/s (8420 ft³/min) of scrubber airflow quantity. Laboratory sound level measurements of the DS also showed that the outlet side of the scrubber was noisier and the loaded filters increased sound levels as compared to clean filters at the same airflow quantities. With loaded filters the scrubber reached a 90 dB(A) sound level at 2.83 m³/s (6000 ft³/min) of scrubber airflow, indicating that miners should not be overexposed in relation to MSHA's permissible exposure level (PEL) of 90 dB(A) at or below this airflow quantity (1). The DS's washable filters were not used during field testing because of their lower respirable dust removal efficiency and the airborne dust generated from filter washing. Field testing the DS with the disposable filters at two underground coal mine sections showed that it can clean a portion of the section return air and provide about a 50% dust reduction at the face area downstream of the continuous miner (CM) operation.

INTRODUCTION

Coal mine worker overexposure to coal and quartz dust continues to be a problem at underground coal mining operations in the U.S. The U.S. Mine Safety and Health Administration (MSHA) recently changed the standard for coal mine worker respirable dust exposure from 2.0 mg/m³ average during an eight-hour shift to 1.5 mg/m³ average over the actual working shift, effective as of August 1, 2016 (1). If more than 0.1 mg/m³ quartz mass is found in the coal mine worker dust sample, the applicable respirable dust standard is further reduced to the quotient of 10 divided by the percentage of the quartz in the sample (1). Over 90% of the mechanized mining units operating in U.S. underground coal mines are continuous mining machines (2). MSHA inspector dust samples from 2009 to 2012 showed that 3.7% of continuous miner operators exceeded the 2.0 mg/m³ dust standard, while 8.8% of these dust samples exceeded the new 1.5 mg/m³ dust standard and 9.7% of these samples exceeded the reduced quartz standard (3). Additionally, roof bolter dust samples at these mechanized mining units during this same period have exceeded the 2.0 mg/m³, 1.5 mg/m³, and reduced quartz levels at 1.1%, 3.7%, and 10.6%, respectively (3).

On-board flooded bed scrubbers on continuous mining machines are proven, efficient collectors of respirable dust (4-7). However, dust by-passing the scrubber may expose roof bolter operators who work downwind of the continuous miner to high levels of respirable dust (7). Respirable dust concentrations downwind of the continuous miner can greatly exceed regulatory standards and overexpose roof bolter operators, especially when the continuous miner does not employ a flooded bed scrubber (7). To combat the upstream continuous miner dust source, a portable stand-alone scrubber can be strategically placed to clean the dust-laden air before it enters the roof bolter workplace entry, providing the bolter operators with a cleaner air supply and thereby reducing their dust exposures.

J. H. Fletcher and Co. (Fletcher) of Huntington, WV has developed a self-tramming stand-alone Dry Scrubber (DS or simply referred to as "scrubber" throughout this report) under NIOSH Contract No. 200-2010-36164, "The Development of Dust Control Units for Underground Coal Mines" (8). This prototype scrubber shown in Figure 1 was delivered to NIOSH OMSHR for operational and dust collection efficiency testing. The general specifications of this prototype DS are:

- Machine Dimensions : 1.22 m wide x 1.22 m high x 4.79 m long (4 ft wide x 4 ft high x 15.7 ft long)
- Air Mover: 22.4 Kw (30 hp.) vane axial fan (480 V) with variable frequency drive (VFD) speed controller
- Filtration: Dual 71-cm (28-in.) O.D. cylindrical air filters rated at 99% efficiency for 2- μ m particles
- Tram System: Crawler tram hydraulically controlled via remote transceiver
- Hydraulic System: Remote transceiver controlled, 12 V pilot solenoid function operation, variable flow axial piston pump with designated 30 hp. electric motor (480 V)



Figure 1. Picture of the self-tramming Dry Scrubber (DS) prototype.

Laboratory testing was initially conducted at NIOSH OMSHR to examine the DS's respirable dust collection efficiency and its operational performance with disposable or washable filter cartridges. Functional and operational modifications were made during and after the laboratory testing to prepare it for further underground field testing.

Field testing was conducted at two sections in an underground mine to examine its effectiveness in reducing dust levels at the face area downstream of the continuous mining machine. This report describes the results from both the DS laboratory and field testing.

LABORATORY TESTING

The Fletcher DS was tested for operational performance and dust collection efficiency in the continuous miner gallery at NIOSH OMSHR's laboratory in Pittsburgh, PA. DS testing was conducted in the intake entry of the continuous miner dust gallery as shown in Figure 2. Airflow measurements were initially made on the DS to validate its fan-controlled variable frequency drive response to its internal pitot tube velocity pressure measurement. Several modifications were initially made by Fletcher to the velocity pressure transducer and the VFD fan controller to improve agreement with the preset DS airflow quantity and the amount delivered as the filter loaded with dust. After the DS's airflow controller response was improved, dust removal efficiency and filter loading tests were performed with the disposable filter cartridges and the alternative washable (re-useable) filter cartridges.

Airflow Measurements

Eight air velocity sampling holes were drilled 7.6 centimeters (3 inches) downstream of the fan discharge transition point along the top cross section of the 121.9-cm-wide by 30.5-cm-high (48-in.-wide by 12-in.-high) discharge duct. This provided a stationary 32-point equal area air velocity sampling grid at 4 measurement heights and 8 horizontal locations across the duct for determining the average air velocity and air flow quantity of the DS. The DS's fan had a VFD controller which was regulated by a pitot tube velocity pressure transducer measurement at the center of the discharge duct. A TSI Model 8346 VelociCALC hot wire anemometer (TSI, Inc., Shoreview, MN) was used by NIOSH to measure the air velocities across the sampling grid, which were averaged and multiplied by the 0.372-m² (4-ft²) duct area to determine the air quantity of the DS at planned dust testing quantities of 1.42 and 4.25 m³/s (3000 and 9000 ft³/min). A one-minute moving traverse was also made across the scrubber's 0.372-m² (4-ft²) discharge area before and after the hot wire measurements with a high-speed vane anemometer (Davis Instrumentation Mfg. Co., Baltimore, MD) mounted on a 121.9-cm (4-ft) extension wand to measure its average air velocity and quantity at the preset airflows. Finally, a Series 166T telescoping stainless steel pitot tube with a 0 to 1.0" water gage magnehelic differential pressure gage (Dwyer Instruments, Michigan City, IN) was also used to measure the velocity pressures and average air velocity across the sampling grid in conjunction with additional vane anemometer measurements at the scrubber discharge. These pitot tube measurements were also used to identify several stable velocity pressure monitoring grid locations for continuous monitoring of DS airflow during NIOSH's dust removal efficiency and filter loading tests.

Dust Testing Procedures

Dust efficiency testing was conducted on the DS at a low and high airflow quantity of 1.42 and 4.25 m³/s (3000 and 9000 ft³/min), respectively. The targeted airflow of 1.43 m³/s (3000 ft³/min) is the minimum ventilation airflow quantity allowed to a working coal face where coal is being cut, mined, drilled for blasting, or loaded (1). The targeted airflow of 4.25 m³/s (9000 ft³/min) is the minimum ventilation airflow quantity allowed at the last open crosscut of each set of entries or rooms (1), which is the planned operating location for the DS to clean a portion of the airflow for the roof bolting machine when operating downstream of the CM.

During laboratory dust testing, the velocity pressure inside the exhaust duct and the differential pressure across the filters were continuously monitored and recorded during the dust efficiency testing. The negative differential pressure across the filters was measured with either a 0- to 2490-Pa (0- to 10-in w.g.) or a 0- to 4980-Pa (0- to 20-in w.g.) magnehelic pressure instrument with a 4- to 20-mA output (Dwyer Instruments, Inc., Michigan City, IN) connected with Tygon tubing to a copper tube inserted inside the filter cartridges between the gasket seals. The velocity pressure was measured with a 0- to 249-Pa (0- to 1-in w.g.) magnehelic pressure instrument with a 4- to 20-mA

output (Dwyer Instruments, Inc., Michigan City, IN) connected to a Dwyer Series 166T telescoping stainless steel pitot tube inserted into the exhaust duct. The pitot tube was initially inserted at grid location 12 where its velocity measurement was close to the grid average and later placed at a higher air velocity location of 14 during most of the dust testing to increase the velocity pressure resolution at the lower scrubber quantity of 1.42 m³/s (3000 ft³/min). These instruments were electronically recorded by a Telog R-3307 seven-channel data acquisition system (Telog Instruments, Inc., Victor, NY).

Coal dust was introduced at the entrance of the intake entry of the continuous miner gallery as shown in Figure 2. The coal dust used was Pulverized Keystone Mineral Black 325BA (Keystone Filler & Manufacturing Co., Muncy, PA), which is -325 mesh (-44 μm) Pocahontas No. 3 coal dust, with 45% of this dust less than 10 μm in size. This pulverized coal dust was fed into the gallery through a screw feeder (Vibra Screw, Inc., Totowa, NJ) and two LH-1/2 brass eductors (Penberthy, Prophetstown, IL) operating between 4 and 6 psig of compressed air. The eductors aerosolized and discharged the dust through two hoses at mid-entry height located 1/3 of the entry width away from the left and right side of the entry. The dust cloud was drawn down the entry by the scrubber operating at air quantities of 1.42 and 4.25 m³/s (3000 and 9000 ft³/min). A sealed curtain wall was constructed around the scrubber (with a door) to separate the inlet and outlet ends of the scrubber, thereby isolating the upstream (dirty) and downstream (cleaner) airstreams inside the gallery (see Figure 2). An entrance door near the continuous miner gallery face area was left open during testing so that the pressure differential across the temporary wall around the scrubber would remain neutral when operating both the scrubber and gallery fan. The gallery's ventilation airflow quantity was set at approximately 0.47 m³/s (1000 ft³/min) higher than the targeted scrubber airflow quantity by adjusting the regulator doors in the shared return air course between NIOSH's longwall and continuous miner galleries (see Figure 2). Airflow quantity of the gallery was determined and adjusted by measuring the average velocity across the 18.9 ft² entrance area of the continuous miner gallery return with a vane anemometer (one minute moving traverse), before the operation of the scrubber. After the gallery airflow quantity was preset for the test, the scrubber airflow was preset to the desired airflow quantity and measured with a vane anemometer traverse of the scrubber discharge before and after each test. All dust efficiency testing was conducted with the straight exhaust configuration. An optional 90-degree angled discharge duct is available to redirect the exhaust air to either side of the scrubber but was not used during the laboratory dust testing.

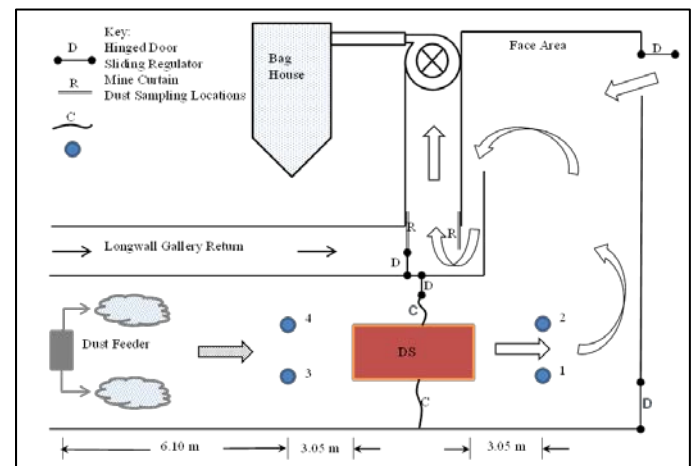


Figure 1. Plan view of Dry Scrubber (DS) testing location in continuous miner gallery (not to scale).

Respirable concentrations were measured at two locations downstream and upstream of the DS as shown in Figure 2. Location numbers 1 and 2 were positioned 3.05 m (10 ft) downstream of the scrubber exhaust at mid-entry height and 1/3 of the entry width away from the left and right side walls of the entry. Location numbers 3 and 4

were positioned 3.05 m (10 ft) upstream of the scrubber inlet at mid-entry height and 1/3 of the entry width away from the left and right side walls of the entry. Gravimetric respirable dust concentrations were measured with coal mine dust personal sampling units (CMDPSU), comprised of an ESCORT-Elf constant flow air sampling pump pulling dust-laden air at 2.0 L/min through a 10-mm nylon cyclone (respirable dust classifier) and depositing the respirable fraction onto a pre-weighed 37-mm filter cassette (Zeffon International, Ocala, FL). A pair of dust samplers (CMDPSU) and one real-time Personal Data Ram (PDR model 1000) instrument were placed and operated at each of the 4 sampling locations during each test. The average of the gravimetric dust concentrations measured downstream (from locations 1 and 2) and upstream (from locations 3 and 4) of the DS were used to determine the DS respirable dust removal efficiency for each test. Respirable gravimetric concentrations used in this analysis were not adjusted to MSHA's MRE compliance sample equivalents (multiplied by 1.38).

DS dust testing was performed with a set of disposable and washable filter cartridges. The washable filters were also tested in their pre- and post-washed conditions. Each set of scrubber filters were successively tested during 4 one-hour test replicates at two scrubber preset airflows of 1.43 and 4.25 m³/s (3000 and 9000 ft³/min). After completion of the one-hour tests, the filters were further evaluated during two-hour tests at the scrubber preset airflow of 4.25 m³/s (9000 ft³/min) to observe for diminished scrubber performance from additional filter dust loading. The number of additional 2-hr tests performed on the disposable, pre-washed, and post-washed filters were 2, 3, and 1, respectively. The dust concentrations generated for these tests varied somewhat between the different airflow tests but averaged 17.8 ± 3.3 mg/m³, 17.4 ± 3.7 mg/m³, and 19.1 ± 3.9 mg/m³ (at the 95% confidence level), respectively, for the disposable, pre-washed, and post-washed filter tests. After the pre-washed filter tests were completed, the filters were removed from the scrubber and back-flushed from the inside of the filter cartridge with a standard garden hose and twist nozzle, until the water running off the filters was relatively clear. A real-time Personal Data Ram (PDR model 1000) instrument was worn by the person washing the filter and another PDR was placed 10-ft downstream in the gallery from where the filters were washed over a 10-minute period. These PDR dust concentrations were adjusted or calibrated to the CMDPSU's gravimetric concentrations measured during these laboratory tests. The post washed filters were set out and air dried for about 24 hours (filter media damp to the touch) and run for about another hour in the scrubber at 1.43 m³/s (3000 ft³/min) to completely dry them out before post-washed filter dust testing.

Sound Level Measurements

Sound level measurements were also taken on the DS operating inside the dust gallery with an unloaded disposable filter before dust testing and with a loaded washable filter at the completion of dust testing. A tripod-mounted Larson Davis LxT sound level meter was used to measure the equivalent continuous sound level 3.05 m (10 ft) from the inlet side of the scrubber and 3.05 (10 ft) from the outlet side of the scrubber at a height of 1.5 m (59 in.) with the microphone pointing at the scrubber. The measurement locations were approximately centered on the width of the scrubber. Initial sound level measurements were made at three scrubber airflow settings with the unloaded disposable filters (clean filters) before dust testing began. A second set of sound level measurements were made for eight scrubber airflow settings with the loaded washable filters (loaded filters) after completion of all dust testing. A vane anemometer was swept across the discharge of the scrubber to determine the airflow at each scrubber operating point. For each airflow setting, three 15-second-long sound level measurements were taken and the logarithmic average of the three sound level measurements was calculated by equation 1 shown below.

$$\overline{L_{Aeq}} = 10 \log \left(\frac{1}{3} \left(10^{L_{Aeq,1}/10} + 10^{L_{Aeq,2}/10} + 10^{L_{Aeq,3}/10} \right) \right) \quad (1)$$

LABORATORY TEST RESULTS

Table 1 shows the airflow quantities measured with the hot wire, pitot tube, and vane anemometer as compared to the preset DS airflows of 1.42 and 4.25 m³/s (3000 and 9000 ft³/min). This table shows that there was initial disagreement between the lower DS airflow target and the measured airflow quantities. After Fletcher visited NIOSH OMSHR's laboratory and made velocity pressure transducer and VFD fan controller modifications, better agreement was achieved between the preset DS airflow quantity and airflow measurements. Once the DS's airflow controller response was improved, dust removal efficiency and filter loading tests were performed with the disposable filter cartridges and the washable filter cartridges.

Table 1. Comparison of hot wire and pitot tube measurements to vane anemometer discharge measurements.

Airflow Instrument, Quantity	Testing Period	DS Target of 1.42 m ³ /s	DS Target of 4.25 m ³ /s
Hot Wire (Vane Anemometer), m ³ /s	Initial DS	1.05 (1.11)	4.32 (4.33)
Pitot Tube (Vane Anemometer), m ³ /s	Initial DS	1.01 (1.16)	4.04 (4.38)
Hot Wire (Vane Anemometer), m ³ /s	Modified DS	1.42 (1.45)	4.34 (4.18)
Pitot Tube (Vane Anemometer), m ³ /s	Modified DS	1.34 (1.42)	4.03 (4.19)

Figures 3 and 4 show the DS's dust collection efficiency results and average scrubber airflow measurements (vane anemometer) with the disposable filter cartridges and washable filters tested, respectively. Figure 5 shows the differential pressures of the filters tested with respect to the filter dust loading. Filter dust loading is the accumulated respirable dust mass that was put through the scrubber during the individual filter tests, amassed from the upstream respirable dust concentrations, average DS airflow quantities, and test times.

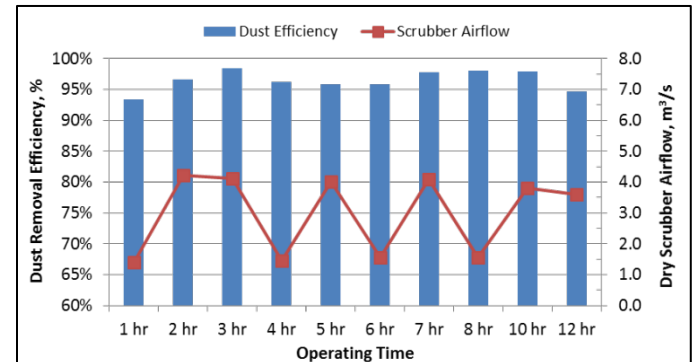


Figure 2. Disposable filter dust efficiency and airflow test results with respect to operating time.

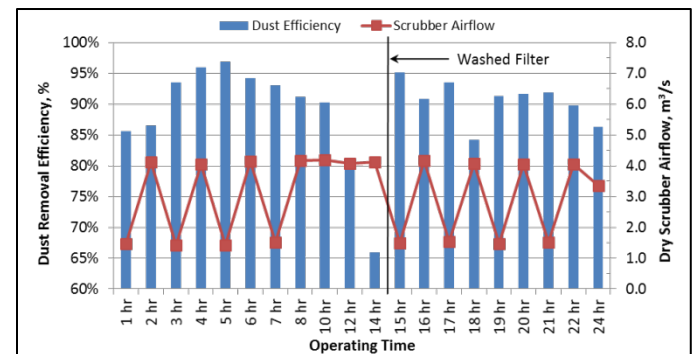


Figure 3. Washable filter dust efficiency and airflow test results with respect to operating time.

The DS averaged greater than 95% dust removal efficiency with the disposable filters and had consistent dust removal efficiencies for the two airflows tested (see Figure 3). After 8 hours of operation, the scrubber airflow quantity with the disposable filters could not be maintained above 4.00 m³/s (8500 ft³/min), indicating that the fan

reached its maximum 60 Hz fan motor frequency or horsepower rating. After the 8th hour of dust testing, the maximum scrubber airflow quantity that could be achieved was 3.97 m³/s (8420 ft³/min) at a filter differential pressure of 2610 Pa (10.5 in. w.g.). Figure 5 further illustrates decreasing DS airflow quantities with additional filter dust loading after 8 hours of testing. DS airflow quantities decreased to 3.80 m³/s (8056 ft³/min) for 1.98 kg of filter dust loading and 2690 Pa (10.8 in. w.g.) of filter differential pressure, and decreased to 3.60 m³/s (7630 ft³/min) for 2.27 kg of filter dust loading and 2750 Pa (11.0 in. w.g.) of filter differential pressure.

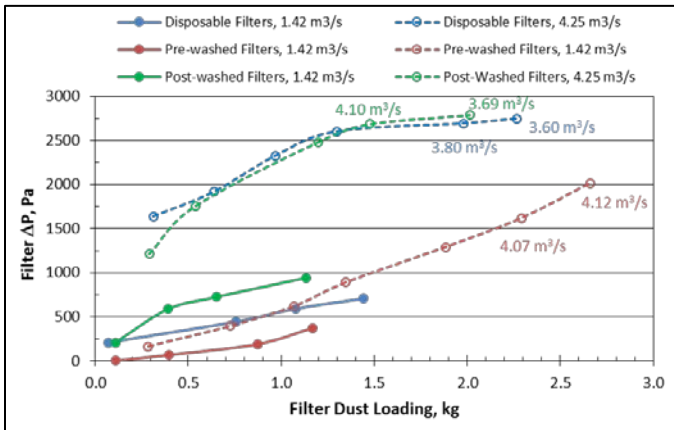


Figure 5. Differential pressure of scrubber filters with respect to filter dust loading (labeled points show the average scrubber airflow quantities measured for the last two filter dust tests).

Operating the DS with the washable filters showed them to be less efficient and more inconsistent than the disposable filters (see Figure 4). The dust removal efficiency of these filters averaged 88% and 90%, respectively, for their pre-washed and post-washed test conditions. The efficiency of the pre-washed filters initially started at 86%, peaked at 97% after 5 hours of testing, and dropped off to 66% after 14 hours of testing. Scrubber airflow remained fairly steady during all the prewashed filter dust testing. The efficiency of the post-washed filters initially started at 95% and inconsistently dropped to 86% at which time the airflow decreased noticeably to below 4.00 m³/s (8500 ft³/min) for the final test. When washing these filters between the pre- and post-testing periods, the average personal and downstream PDR dust concentrations measured were 1.2 and 8.3 mg/m³, respectively.

Figure 5 further illustrates that the pre-wash filters had lower differential filter pressures as compared to the disposable filters and experienced no significant scrubber airflow reductions from 2.6 kg of filter loading with 2010 Pa (8.1 in. of w.g.) of filter differential pressure. The post-washed filters exhibited notably higher filter differential pressures during testing, and scrubber airflow notably decreased to 3.69 m³/s (7820 ft³/min) for 2.01 kg of filter dust loading and 2690 Pa (10.8 in. w.g.) of filter differential pressure for the final test.

The results of the sound level measurements are shown in Figure 6. This graph clearly shows that the scrubber operating with loaded filters had higher sound levels than with clean filters for similar scrubber airflow quantities. Sound levels were also higher at the scrubber outlet location as compared to the scrubber inlet location. Because 90 dB(A) is MSHA's permissible exposure level, the sound levels (labeled in the graph) at 2.83 m³/s (6000 cfm) of scrubber airflow indicate that miners should not have noise exposures that exceed the PEL for airflow rates at or below at 2.83 m³/s (6000 cfm) (1). If the machine is used at airflows near the upper end of its operating range, miners working nearby could be overexposed to noise. However, miners' exposure would vary depending on the distance from and the time spent near the scrubber.

UNDERGROUND FIELD TESTING

After laboratory testing the scrubber was returned to Fletcher's research facility for inspection and preparation for underground testing. Several modifications were made to the DS prototype to facilitate

completion of the underground coal mine testing portion of the NIOSH contract. The primary modification needed was substituting and reprogramming an existing MSHA-approved remote control unit for the desired remote control unit tested in the laboratory, which was currently pending an MSHA approval for underground coal mine use. It was also decided to use only the disposable filters during underground testing, since they provided the highest respirable dust removal efficiency and they eliminated the option of generating respirable dust from being cleaned underground. NIOSH visited Fletcher's research facility to examine these modifications and to re-measure the DS airflow quantity output as compared to the machine-selected airflow quantity with the new remote control unit. These pitot tube measurements were used to correlate a reliable sample location for measuring the scrubber airflow quantity underground. Scrubber field testing was conducted at two continuous miner sections in an underground coal mine.

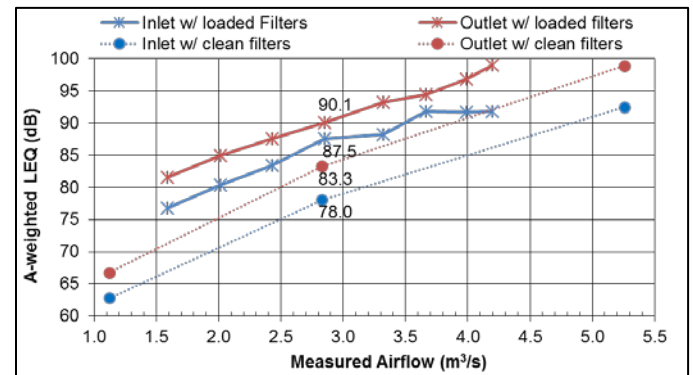


Figure 6. Sound level measurement results for the Dry Scrubber with clean and loaded filters.

Airflow Measurements

NIOSH airflow measurements made at Fletcher's research facility were again made along the 32 equal area sampling grid inside the 121.9-cm-wide by 30.5-cm-high (48-in.-wide by 12-in.-high) discharge duct using a Series 166T telescoping stainless steel pitot tube and a 0 to 1.0" water gage magnehelic differential pressure gage (Dwyer Instruments, Michigan City, IN). The DS's VFD controller was operated at preset airflow quantities of 1.42, 2.83, and 4.25 m³/s (3000, 6000, and 9000 ft³/min). Pitot tube measurements at the three DS preset air quantities were conducted with the straight exhaust duct and with the optional 90° angled discharge duct. Average duct velocity to grid point velocity ratios were examined for the most consistent and reliable sample locations for underground scrubber airflow measurements. A pitot tube measurement at a reliable sampling location was used to determine the scrubber airflow velocity during the underground field studies.

Airflow quantities to the face area cleaned by the scrubber were also measured during the study to indicate the scrubber's operational impact on face airflow quantity. A one-minute moving traverse was made over the cross-sectional area of the face curtain opening with a vane anemometer (Davis Instrumentation Mfg. Co., Baltimore, MD) without and with the scrubber turned on.

Underground Dust Sampling

Underground field testing investigated the dust reductions realized from operating the DS downstream of the continuous miner at two producing mining machine units (MMUs). One MMU was on the right side of a 9-entry super section and the other MMU was on the right side of another 12-entry super section. Fish tail ventilation was used at both super sections to supply intake air to the MMUs studied. The MMUs used blowing face ventilation with flooded-bed scrubbers on the continuous miners. In order to increase the DS operating time and data collection underground, the DS was placed in the last open crosscut of the section return to examine its effectiveness on lowering respirable dust concentrations at the face areas of entries 9 and 12, downstream of all mining activities. This test strategy minimized moving the DS around in the section while providing the least

interference with production. Figure 7 illustrates the DS location in the last open crosscut of entry 9 at the first super section studied and the areas that were dust sampled during the field studies. The optional 90° angled discharge duct was used during the underground studies to direct the DS's exhaust air along the blowing face ventilation curtain. Dust sampling locations sampled during the study included (as shown in Figure 7): A) the intake to the bolting machine; B) the bolting machine near the left-side operators' location; C) the last open crosscut just upstream of the DS; D) the downstream face area cleaned by the DS (entry 9 or 12); and E) the section return entry. The bolting machine was monitored to examine the respirable dust concentrations at this location when working upstream and downstream of the continuous miner during the production shift. The other dust sampling locations were used for evaluating the respirable dust reductions realized from operating the scrubber. The sampling instrumentation used at each sampling location during this field study was identical to those used in the laboratory (two CMDPSUs and one PDR) as described above. Respirable gravimetric concentrations used in this analysis were not adjusted to MSHA's MRE compliance sample equivalents (multiplied by 1.38).

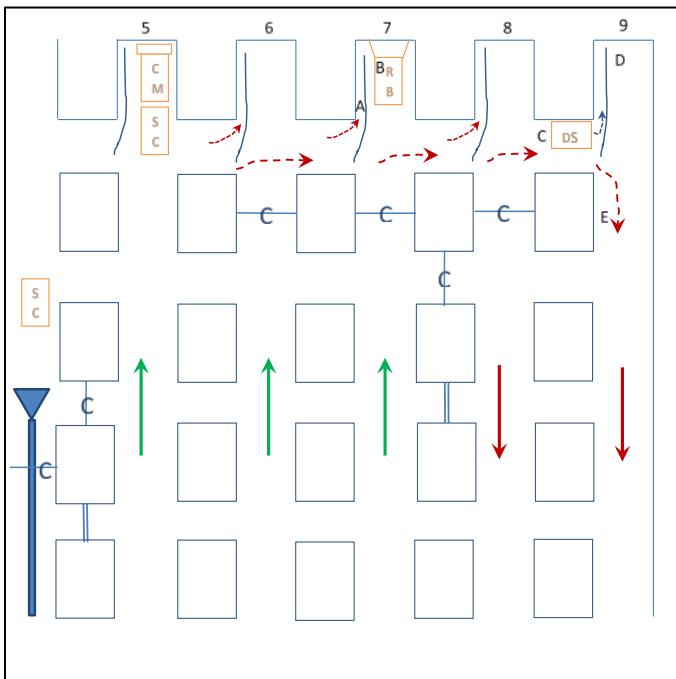


Figure 7. Plan view of DS operation downstream of the continuous mining machine on the 9-entry super-section studied using blowing face ventilation (right-side MMU, capital letters indicate dust sampling locations).

The PDRs' instantaneous dust concentration data was time-recorded every 10 seconds in its internal memory and was downloaded to a computer after the sampling shift. The PDR real-time dust concentrations were gravimetrically calibrated by multiplying each 10-second reading by a gravimetric to PDR dust concentration ratio, determined by dividing their average concentrations measured over identical sampling periods. These adjusted PDR dust concentrations were used to determine dust concentrations during the particular mining activities. Time study and section location of the continuous miner and roof bolter machines were recorded during each sampling shift. This information was used to coordinate and determine the gravimetrically adjusted PDR dust concentrations during time segments of the scrubber operation and roof bolter activities with respect to the continuous miner operation. The DS was moved and parked outby in the section return entry when the continuous miner was cutting in return entries 9 and 12 so as not to inhibit shuttle car haulage. The dust samplers in the last open crosscut, the face area, and the section return were also relocated while mining in return entries 9 and 12.

Field Test Results

The pitot tube measurements made inside the exhaust duct of the scrubber at Fletcher's research facility showed the average duct velocity to grid velocity ratios were the most consistent near the center of the duct for the average airflow quantities of 1.42, 2.73, and 3.90 m³/s (3000, 5790, and 8260 ft³/min) measured with both exhaust configurations (straight and 90 degree). Figure 8 shows the average, minimum, and maximum velocity ratios for each of the stationary 32-grid sampling locations (4 measurement heights at 8 horizontal locations across the exhaust duct). As can be seen in this figure, some of the smallest velocity ratio variations were at grid locations 15, 16, and 19, having duct velocity/grid velocity ratios of 0.76, 0.85, and 0.71, respectively, with the lowest measured velocity ratio ranges of 0.04. Since the airflow velocity ratio at location 16 was nearest the grid average, it was selected as the pitot tube location for measuring the DS airflow quantity underground. The DS airflow quantity was determined from multiplying the airflow velocity measurement by the 0.85 ratio and 4-ft² duct area.

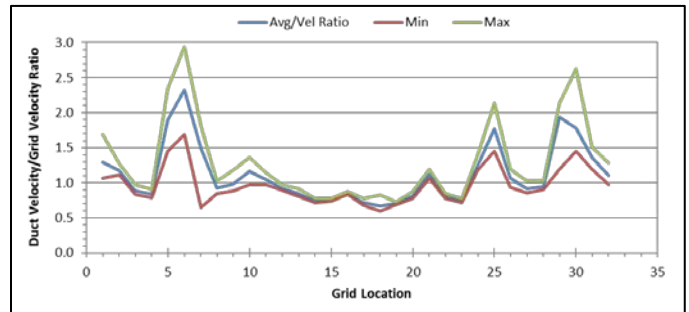


Figure 8. Average duct velocity to grid velocity ratios measured along the DS's exhaust duct sampling grid.

Table 2 shows the time-weighted average respirable dust concentrations measured with respect to the continuous mining activities at both of the sections studied. These concentrations represent gravimetrically calibrated PDR dust levels averaged for the time periods when roof bolting machine was operating upstream and downstream of the continuous mining machine. Average dust concentrations at the roof bolting machine at sections 1 and 2 were 0.59 and 0.17 mg/m³, respectively, when operating upstream of the CM as compared to 1.80 and 1.60 mg/m³, respectively, when it was operating downstream of the CM and upstream of the DS. The dust concentrations at the last open crosscut of the scrubber location at sections 1 and 2 were 2.77 and 2.43 mg/m³, respectively, when the roof bolting machine was upstream of the CM as compared to 1.85 and 1.35 mg/m³, respectively, when the bolting machine was downstream of the CM. The higher crosscut dust concentrations measured when the roof bolter was upstream of the continuous miner was likely due to the CM operating physically closer to the last open crosscut sampling location, thereby reducing the time for dust dilution and dispersion of the CM return concentrations by the section ventilation.

Table 2. Time-weighted averages of roof bolter and DS dust concentrations with respect to the CM location.

Bolter Location	Mine Test Section	Intake Dust Conc. to Roof Bolter A	Roof Bolter Dust Conc. B	Crosscut Dust Conc. Up-stream DS C	Face Dust Conc. Down-stream DS D	Section Return Dust Conc. E	¹ DS Face Dust Reduction Efficiency
		mmu mg/m ³ (cuts)	mg/m ³ (cuts)	mg/m ³ (cuts)	mg/m ³ (cuts)	mg/m ³ (cuts)	%
Upstream CM	¹ 1	0.54 (6)	0.59 (6)	2.77 (6)	1.32 (6)	1.99 (6)	52.9
	2	0.22 (9)	0.17 (9)	2.43 (5)	0.91 (5)	0.96 (5)	59.9
Downstream CM & Upstream DS	¹ 1	1.96 (6)	1.80 (6)	1.85 (7)	0.99 (7)	1.51 (7)	46.3
	2	1.58 (4)	1.60 (4)	1.35 (3)	0.86 (3)	1.20 (3)	50.7
Downstream CM & Downstream DS	¹ 1	NA (0)	NA (0)	NA (0)	NA (0)	NA (0)	NA (0)
	2	1.00 (4)	1.10 (4)	1.69 (4)	1.06 (4)	1.25 (4)	36.8
Average of All Cuts	¹ 1	1.32 (12)	1.26 (12)	2.24 (13)	1.13 (13)	1.72 (13)	49.1
	2	0.71 (17)	0.71 (17)	1.90 (12)	0.88 (12)	1.11 (12)	50.5

¹The DS scrubber intermittently kicked off and was restarted during nearly half of the cuts studied.

NA – Not Available

²Determined as the time-weighted average of the DS face dust reduction efficiencies for the individual cuts.

Table 2 also shows that the scrubber reduced the dust concentrations at the face areas downstream of the CM for all cuts by

49.1 and 50.5% at sections 1 and 2, respectively. At section 2, when the roof bolter was in entry 12 downstream of the CM and DS, the dust reduction at the face was somewhat lower at 36.8%. The average roof bolter machine dust concentration (1.10 mg/m³) was nearly identical to the average face dust concentration (1.06 mg/m³) when downstream of the CM and DS. The lower percent dust reduction realized at the face when the bolting machine was present may have been due to some additional dust generated by the bolting machine in this face area.

In order to ascertain the DS's respirable dust collection efficiency underground, the face area sampling package was placed directly into the DS exhaust discharge air for short period of time (2 to 5 minutes) at the end of several shifts to determine its respirable dust collection efficiency (concentrations not shown in Table 2). The measured DS exhaust concentrations at sections 1 and 2 averaged 0.13 and 0.01 mg/m³, respectively, while their corresponding upstream dust concentration averaged 1.87 and 1.08 mg/m³, thereby yielding DS dust collection efficiencies of 93.2 and 99.2%, respectively. These dust collection efficiencies were found to be very similar to the scrubber's laboratory test results with similar disposable filters. Consequently, the scrubber's reduced dust reduction effectiveness at the face sampling locations demonstrate that its clean exhaust discharge air was being mixed with some of the dustier section return air to ventilate the face area.

Airflow quantity measurements at the last open crosscut and face areas likewise showed that the scrubber cleaned a small amount of the section return air and mixed this cleaned air with some of the return air for ventilating the face. Airflow quantities in the last open crosscut during these studies ranged from 5.32 to 13.1 m³/s (11270 to 27720 ft³/min), while the scrubber was operated at airflow quantities of 1.28 to 2.31 m³/s (2720 to 4900 ft³/min). Initial ventilation airflow quantities delivered to the face areas ranged from 0.784 to 2.31 m³/s (1660 to 4890 ft³/min) without the scrubber operating and were enhanced by the scrubber to an operating range of 1.09 to 3.88 m³/s (2300 to 8220 ft³/min), thereby providing a 1.4 to 1.7 increase over the initial face ventilation airflow quantities without the scrubber. These face airflow changes from operating the scrubber also indicate that its exhaust airflow was being mixed with some of the dusty return airflow.

Several DS operation issues were observed during the study at section 1. The scrubber unexpectedly shut down and was restarted during nearly half of the cut periods at section 1, and sometimes its measured airflow quantity deviated up to nearly 2760 cfm from its preprogrammed targeted amount. These operational malfunctions were attributed to communication issues encountered from the substitution of an approved MSHA underground coal mine remote control unit with the original unapproved scrubber remote control unit, which had been thoroughly and successfully tested in the lab. The original scrubber remote control unit was pending an MSHA approval and could not be used during the underground coal mine field testing. During the second field study at section 2, the DS was operated more continuously by using the fan motor's frequency control mode, thereby eliminating the intermittent DS shutdowns experienced during the first field study. The DS's fan motor was operated at 25 to 35 Hz to deliver scrubber airflows of 1.28 to 2.13 m³/s (2720 and 4510 ft³/min) at differential filter pressures of 473 to 971 Pa (1.9 and 3.9 in. w.g.).

The DS operating parameters measured at Section 2 indicate that the disposable filter cartridges did not reach their fully loaded dust capacity during underground testing. At section 1 the DS was operated for 461 minutes with an average dust concentration of 2.24 mg/m³, and at section 2 the DS was operated for an additional 509 minutes with an average dust concentration of 1.90 mg/m³. Previous laboratory testing indicated that the disposable filters approach their useful life when they were loaded with an average dust concentration of 17.8 mg/m³ for 729 minutes. An accumulated filter dust mass loading of 2.27 kg was determined from this laboratory testing to reach the maximum differential filter pressure of 2750 Pa (11.0 in w.g.) at 3.60 m³/s (7630 ft³/min) of airflow quantity. Estimation of filter dust loading times or useful filter life at various scrubber airflows and dust concentrations less than or equal to these maximum laboratory DS operating parameters can be calculated by using equation 2 shown above. Thus, operating the scrubber at 4000 ft³/min in dust concentrations of 2

mg/m³ (comparable to the underground field study conditions) indicates a longer filter dust loading time of 167 hours as compared to the 16.2 hours of actual underground field testing time. Given that the DS on the last shift of testing exhibited a maximum filter differential pressure of 971 Pa (3.9 in. w.g.) at 2.13 m³/s (4510 ft³/min) while operating at 35 Hz, these filters did not appear to be at their maximum filter life as compared to laboratory test results.

(2)

$$\text{Filter Dust Loading Time (hr)} = \frac{2.27(\text{kg}) \times 1,000,000 \left(\frac{\text{mg}}{\text{kg}} \right)}{\text{Dust Concentration} \left(\frac{\text{mg}}{\text{m}^3} \right) \times \text{Airflow Quantity} \left(\frac{\text{m}^3}{\text{s}} \right) \times 3600 \left(\frac{\text{s}}{\text{hr}} \right)}$$

CONCLUSIONS

NIOSH laboratory testing of the Fletcher Dry Scrubber showed that it averaged greater than 95% dust removal efficiency with the disposable filters and averaged 88% and 90%, respectively, for the washable filters in their pre-washed and post-washed test conditions. Although the washable filters could be reused, washing them generated notable amounts of dust. The personal and downstream dust concentrations measured averaged 1.2 and 8.3 mg/m³, respectively, over the 10-minute washing period. Laboratory dust testing showed that the scrubber fan also maintained a relatively consistent airflow near the targeted 1.43 and 4.25 m³/s (3000 and 9000 ft³/min) airflow rates until reaching 2610 Pa (10.5 in. w.g.) of filter differential pressure at 3.97 m³/s (8420 ft³/min) of scrubber airflow quantity. At this point the scrubber airflow decreased with additional dust loading because the fan had reached its maximum horsepower rating with the VFD operating the fan at 60 Hz motor frequency. Sound level measurements made on the scrubber in the lab showed that the outlet side of the scrubber was noisier and the loaded filters increased sound levels as compared to clean filters at the same airflow quantities. With loaded filters the scrubber reached a 90 dB(A) sound level at 2.83 m³/s (6000 ft³/min) of scrubber airflow, indicating that miners should not be overexposed in relation to MSHA's permissible exposure level (PEL) of 90 dB(A) at or below this airflow quantity (1).

Field testing the DS with the disposable filters at two underground coal mine sections showed that it can clean a portion of the section return air and provide about a 50% dust reduction at the face area downstream of the continuous miner operation. The average roof bolting machine dust concentrations at sections A and B were 0.59 and 0.17 mg/m³, respectively, when operating upstream of the CM as compared to 1.80 and 1.60 mg/m³, respectively, when it was operating downstream of the CM and upstream of the DS. A 36.8% dust reduction was measured at section B when the roof bolter was operating downstream of the CM in the face area being cleaned by the DS. The DS's dust collection efficiencies at sections A and B were 93.2% and 99.2%, respectively, showing that the exhaust airflow was mixed with some of the dusty return airflow being delivered to the face. This airflow mixing was further exhibited by the DS's 1.4 to 1.7 face airflow quantity improvement over the initial airflow quantities without the scrubber operating. Therefore, the DS appears to be a new viable dust control method to combat roof bolter dust exposures when operating downstream of the continuous miner.

REFERENCES

1. CFR (2015), "Code of Federal Regulations," Washington, DC: US Government Printing Office, Office of the Federal Register.
2. MSHA (2015), Information provided by Philip Lindahl, Mine Safety & Health Specialist, Coal Division of Health, Mine Safety & Health Administration, Headquarters, Arlington, Virginia.
3. U.S. Department of Labor (2013), Mine Safety and Health Administration, Program Evaluation and Information Resources, MSHA Standardized Information Systems, Arlington Virginia.
4. Fields, K.G., Atchison, D.J., and Haney, R.A. (1990), "Evaluation of Combined Face Ventilation System Used with a Remotely Operated Mining Machine," Proceedings of the 3rd Symposium on Respirable Dust in the Mineral Industries, Oct. 17-19, 1990, Pittsburgh, PA, Published by the Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO, Chapter 43, pp. 349-353.

5. Colinet, J.F. and Jankowski, R.A. (1996), "Dust Control Considerations for Deep-Cut Faces when Using Exhaust Ventilation and a Flooded-Bed Scrubber," SME Transactions, Vol. 302, Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc., pp. 104-111.
6. NIOSH (2011). Evaluation of Face Dust Concentrations at Mines Using Deep-Cutting Practices. By: Potts, J.D., Reed, W.R., Colinet, J.F. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2011-131, Report of Investigations 9680, 2011 Jan, pp. 1-94.
7. NIOSH (2013). Impact on Respirable Dust Levels When Operating a Flooded-bed Scrubber in 20-foot Cuts. By: Colinet J.F., Reed W.R., and Potts J.D. Pittsburgh, PA: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2014-105, RI 9693, 59 pp.
8. Kendall, B. (2015). Final Report for Fletcher Mobile Dry Scrubber (DS). NIOSH Contract No. 200-2010-36164, "The Development of Dust Control Units for Underground Coal Mines," available from NIOSH, Office of Mine Safety and Health Research, 22 pp.

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