1st Solicitation for Single Investigator Research Grants

(AFC113)

ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Final Technical Report

1.0 Cover Page

Project Title: The Application of Flooded Bed Dust Scrubbers to Longwall Mining Systems

Grant Number: AFC113-10

Organization: University of Kentucky

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Period of Performance: November 1, 2013 – December 31, 2016

Acknowledgement/ Disclosure: This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the ALPHA FOUNDATION, its Directors and staff.

Table of Contents

List of Figures

List of Figures (Continued)

Figure Page

List of Tables

2.0 Executive Summary

Dust is an undesirable consequence of all types of mining. It is particularly problematic in underground coal mining. Coal workers' pneumoconiosis, commonly referred to as *black lung*, is a debilitating and irreversible lung disease, which results from the excessive inhalation and deposition of coal dust in the lungs. Although its prevalence has steadily and significantly declined since the Federal Coal Mine Health and Safety Act of 1969, a study by the National Institute for Occupational Safety and Health (NIOSH) indicates that health hazards associated with *respirable dust* still exist within the coal mining industry.

Besides being a health hazard, coal dust can also create a potentially catastrophic safety hazard. Airborne dust, if not removed near its source, is dispersed and transported downwind throughout a mine by the ventilation airstream. This *float dust* is deposited on all mine surfaces as it permeates through the mine airways. A potential safety hazard occurs if an insufficient amount of rock dust is applied to mine surfaces and the settled coal dust is not adequately diluted to an inert mixture. If a methane ignition occurs, the resulting shockwave propels the settled dust into the airstream, creating an explosive dust cloud, and the initial methane ignition can transition to a dust explosion. Since the shockwave of a dust explosion travels faster than its accompanying flame front, it continuously generates and extends the explosive cloud, which in turn feeds the slower moving flame. This perpetuating explosion continues to propagate throughout mine airways until its fuel (explosive dust) is exhausted.

The overall research objective is the reduction of *respirable dust* and *float dust* in longwall mining systems through the application of flooded-bed dust scrubbers. Using scrubbers to capture and remove dust, addresses two focus areas of the Alpha Foundation – health and safety. Longwall mining, which accounts for more than one-half of the coal produced by underground mines in the U.S., exhibits greater difficulty in maintaining compliance with federally mandated dust regulations, as compared with continuous mining. Moreover, the newly enacted federal dust rule has exacerbated these difficulties for longwall mine operators.

Researchers at the University of Kentucky worked with a longwall equipment manufacturer, a longwall operator, and other experts to design and fabricate a full-size mockup of a longwall shearer with an integrated 50-hp flooded-bed dust scrubber. The shearer mockup was transported to the NIOSH Pittsburgh Research Laboratory and installed in the Longwall Dust Gallery. This gallery replicates a portion of an actual longwall face with 19 roof-support shields and dust-generating mechanisms for simulating respirable dust produced by a shearer while cutting coal. Forty tests, plus 10 base-case tests, were conducted using ThermoFisher Scientific Personal Dust Monitors to measure the dust-dust levels during the experiments. Three factors at two levels were used in the experiments: the presence and absence of an extension to the scrubber inlet, the scrubber capacity at 6300 cfm (2.97 m^3/s) and 13,700 cfm (6.47 m^3/s), and face-air velocities of 500 fpm (2.54 m/s) and 700 fpm (3.56 m/s).

The results of the tests indicate that a flooded-bed dust scrubber integrated into a shearer could be very effective at reducing levels of airborne respirable dust. Results indicate that up to 56% of the respirable dust released near the headgate drum could be captured and cleaned, without the assistance of splitter arm (or shearer clearer) water sprays. The most significant factor is the scrubber capacity. The maximum dust reduction in the return with the assistance of splitter arm sprays was 62%.

Results also show that the scrubber can reduce dust concentrations in the longwall walkway where mine personnel are likely to be located. Without assistance of splitter arm water sprays, results indicate that the scrubber reduced dust concentrations in the walkway by up to 74%.

3.0 Statement of the Problem and Objectives

For organizational purposes, this major heading is divided into two separate subheadings – Statement of the Problem and Objectives.

3.1 Statement of the Problem

Dust is a detrimental, but inherent, consequence of any mining process. 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. Although the prevalence of CWP has steadily and significantly declined over the three decades following the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173, 1969), a study by the National Institute for Occupational Safety and Health (NIOSH, 2008) indicates that significant health hazards associated with respirable dust still exist within the coal mining industry. According to the NIOSH study, the declining trend in CWP ended around 1995, and its prevalence has since begun to rise, as shown in Figure 3.1 (NIOSH, 2008). 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. The report 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 coal mining industry.

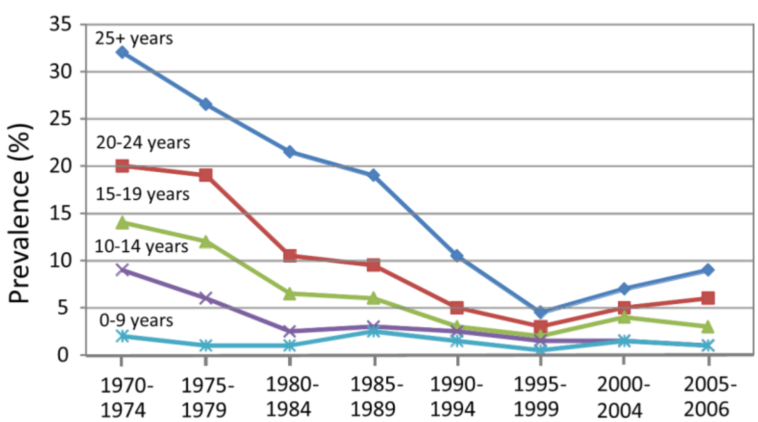


Figure 3.1. Prevalence of CWP among examinees employed at underground coal mines (NIOSH, 2008).

Coal dust, besides being a respiratory health hazard, has the potential for creating a catastrophic safety hazard because of its explosibility (Field, 1982; Cross and Farrer, 1982; Nagy and Verakis, 1983; Cashdollar and Hertzberg, 1987; and Cashdollar, 1996). Airborne dust that is not removed close to its source is transported downwind throughout the return airways of a mine by the ventilation airstream. This dust remains in suspension for extended periods and is thus referred to as *float dust*. The float dust is deposited on all mine surfaces (roof, ribs, and floor) as it permeates through the mine airways. A potential safety hazard occurs when an insufficient amount of rock dust is applied to mine surfaces for the purpose of diluting the settled coal dust to an inert mixture (Sapko, et al., 2007). If a methane ignition occurs with this non-inert condition, the resulting shockwave propels the settled dust into the airstream, creating an explosive dust cloud. The flame front of a dust explosion travels at a relatively slow speed, around 30 – 35 ft/s (10 m/s), compared with that of its associated shock wave [up to 1115 ft/s (340 m/s)]. Therefore, the shockwave travels ahead of the flame front and continuously extends the explosive dust cloud which subsequently feeds the slower-moving flame. This chain reaction creates a perpetuating explosion that propagates throughout mine airways until it runs out of fuel (explosive dust). The Mine Safety and Health Administration (MSHA) concluded that this type of explosion occurred at the Upper Big Branch Mine, resulting in the death of 29 mineworkers in 2010 (U.S. Department of Labor, 2011). Therefore, capturing and removing coal dust at its source mitigates the probability of two major hazards that continue to plague the mining industry – respirable dust and float dust, thus, covering two focus areas of the Alpha Foundation, namely, health and safety.

The following subsections provide dust-control information specific to longwall mining. These sections address the problems, challenges, and prior attempts at applying scrubbers to longwall shearers.

Dust Sources in Longwall Mining. The research discussed in this report specifically addresses dust-control problems associated with longwall mining systems. Longwall mining is the most productive underground coal mining method in the United States. Since its introduction to the U.S. (in its modern form) in the early 1970s, the percentage of underground coal production from longwall mining has steadily increased. In 1993, longwall operations accounted for 40% of underground coal production (Colinet et al., 1997), which increased to 51% in 2004 (Rider & Colinet, 2004). Currently, over 59% of underground coal is produced from longwall mines (U.S. Energy Information Administration, 2015). The increase in coal production from a longwall face obviously corresponds with an increase in dust generation, particularly respirable dust. As a consequence, longwall mines frequently find it difficult to maintain consistent compliance with mandated dust regulations (Rider & Colinet, 2004).

A NIOSH study highlights the following six main sources of dust in longwall mining in the United States (Colinet, et al., 2010).

1. Shearer operation,
2. Shield advancement,
3. Stage loader/crusher operation,
4. Face spalling and armored face conveyor (AFC) operation,
5. Contamination of intake ventilation air, and
6. Caving in the gob.

The majority of dust on a longwall mining section is generated by the longwall shearer while it is cutting coal from the coal face. The cutter-head bits impact the coal face, break the coal, and crush it. The amount of dust generated during cutting depends on the cut depth, bit condition, and cutter-head rotational speed. A deep cut tends to reduce dust generation, while a blunt bit and high cutter-head speed increase dust generation. A significant portion of the dust generated by a shearer adheres to the surfaces of cut coal. The ventilation airflow can disperse this dust causing it to become airborne while the cut coal is transported to the stage loader by the armored face conveyor (AFC). Shield advancement, which occurs after the coal is extracted from the face, causes crushing of roof and floor strata, resulting in considerable dust liberation. As the load of the strata above a shield increases, the amount of dust generated increases. Roof caving behind the hydraulic supports (shields) also contributes to dust generation at a longwall face. Leakage paths between adjacent shields allow dust to enter the face area, with the dust volume being dependent on the size of the roof fall.

A dust survey conducted on 13 longwall faces indicates that shearer operation is the primary source of dust and the major contributor to respirable dust in the face area, followed by shield movement (Colinet, et al., 1997). As shown in Table 1, the shearer accounts for over 50% of the dust generated on the longwall face.

Table 3.1. Dust contributions from major longwall dust sources (Source: Colinet et al., 1997)

Source	Average Percent	Contribution Median (mg/m^3)	Contribution Range (mg/m^3)
Intake	9	0.33	0.07-1.1
Stage loader-crusher	15	0.78	0.29-1.3
Shield	23	1.8	0.67-2.3
Shearer	53	3.5	0.70-8.8

Present-Day Longwall Dust Control. NIOSH conducted benchmark surveys at longwall operations across the country to identify operating practices and the types of control being used. The surveys show that a wide variety of dust-control methods exist (Rider and Colinet, 2004). These variations in methods were mainly attributed to different operating conditions and equipment. Although the dust control methods change from mine to mine, the following approaches are common to all longwall mines in the United States (Wang & Peng, 1991):

1. Dilution with ventilation airflow,
2. Wetting and capture by water sprays, and
3. Confinement and isolation by water sprays.

Dilution of a dust concentration with ventilation air provides the simplest method of dust control at a longwall face. The basic principle entails adjusting the quantity of intake air to dilute an initial concentration of the generated dust to a lower final concentration. Over the years, with increases in production and hence dust generation, longwall ventilation quantities have also increased (Jankowski et al., 1990). A survey by NIOSH showed that longwall mines in the United States had an average face air quantity of 67,000 cfm (31.6 m^3/s), with a range between 51,000 to 83,000 cfm (24.3 to 39.1 m^3/s) (Rider and Colinet, 2004). The variation in air quantity depends on coal production, dust generation, and methane liberation. Today's average air quantity represents approximately a 65% increase when compared with that of a mid-1990 longwall study. The average face velocity was found to be 665 fpm (3.4 m/s).

While a higher air quantity improves the dilution of dust concentration, it may also have a negative impact of entraining settled dust, particularly respirable dust, if the air velocity is too high. According to Kissel, 2003, the critical velocity appeared to be approximately 600 fpm (3 m/s). A laboratory study to evaluate shield-dust entrainment in high velocity airstreams found significant increases in both total and respirable dust concentrations as air velocity was increased from 400 to 1,600 fpm (2.0 to 8.2 m/s) (Listak, et al., 2001). However, more recent in-mine surveys by NIOSH do not support the laboratory findings; seven of the eight longwalls surveyed having face air velocities exceeding 600 fpm (3 m/s) did not experience any entrainment problems (Rider and Colinet, 2004).

The use of water sprays for dust control has two main purposes: wetting of the broken material and capture of the airborne dust. Of the two purposes, wetting is more effective. Most dust particles generated by the shearer adhere to the surfaces of the cut coal. Wetting the dust particles on these surfaces discourages their entrainment by the ventilation air, thus reducing the occurrence of airborne dust during coal haulage by the AFC or the discharge of coal at the stage-loader transfer point (Kissell, 2003). An investigation of the amount of dust adhering to the surface of run-of-face broken bituminous coal showed that about 16 lb (7.25 kg) of ordinary run-of-face broken bituminous coal had enough adhering respirable dust to contaminate 1,000,000 ft^3 (28,316 m^3) of air at a level of 2 mg/m^3, if all adhering dust particles became airborne (Cheng & Zukovich, 1973). The best dust-control result is achieved when the surface of the cut coal is uniformly wetted by aiming water nozzles at broken material during the breaking process. Additionally, wetting agents can be added to the spray water to improve coal wetting and assist with dust capture (Organiscak, 2014). A wetting agent lowers the surface tension of water droplets and allows better spreading over the broken material (McDonell, 2009).

The capture of airborne dust occurs when the water droplets from the water sprays collide with, and encase or adhere to, the airborne dust particles, thus causing the water droplets and dust particles to fall out of the air due to gravity. Dust capture is most effective when the water-droplet size is comparable to that of a dust particle.

In the past, fine mist atomizing sprays have been used to control dust at longwall faces (McDonell, 2009). The aim was to produce water droplet sizes comparable to those of respirable dust particles. Although this method offers improved dust capture, its lacks reliability when used in dirty underground mining environments. Because of the small orifices required to produce an atomized mist, the nozzle is prone to clogging (Kissell, 2003). Figure 3.2 shows airborne capture performance of four different spray nozzle types at different water pressures. The atomizing nozzle is the most effective, followed by the hollow-cone nozzle. However, the hollow cone sprays are more popular because of their larger orifice size and decreased likelihood of clogging.

Despite the many advantages of using water sprays, there are circumstances where sprays can increase dust exposure to workers. In addition to capturing dust, the spray from a nozzle displaces air and creates air currents, and these currents may have a negative impact on dust control. As an example, Figure 3.3 shows a shearer operator exposed to airborne dust resulting from a dust cloud moving from the face to the walkway caused by air currents created by the sprays (Kissell, 2003). A high pressure spray can displace a large volume of air and result in dispersion of the dust instead of its capture (Kissell, 2003).

Water sprays are mounted on the shearer drum with the intent of controlling dust at its point of generation, as shown in Figure 3.4. The sprays are placed on the top of the drum vanes, either in front of or behind the cutter bits. They are aimed at the tip of the bits to achieve wetting of the coal prior to it being broken, as well as immediately after the coal is broken. Furthermore, the sprays work to cool the bits to help prevent a methane ignition.

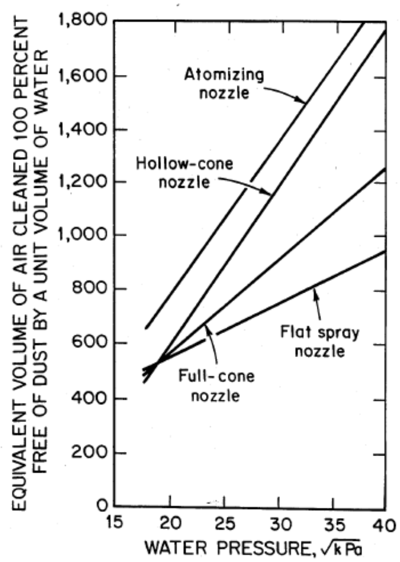


Figure 3.2. Performance of different nozzle types capturing airborne dust (Source: Kissell, 2003).

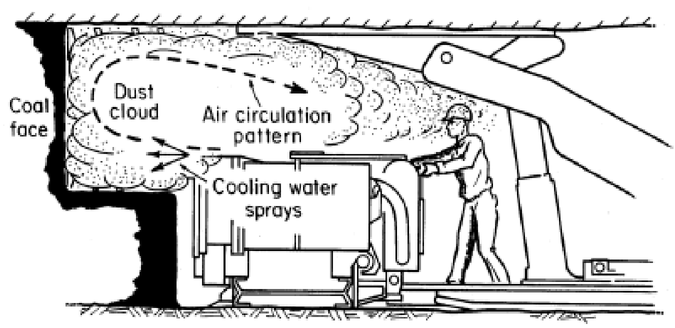


Figure 3.3. Dust exposure to the operator from air currents created by water sprays. (Source: Kissell, 2003).

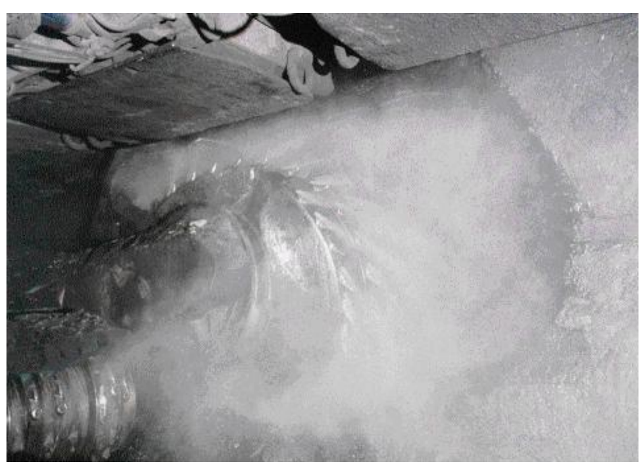


Figure 3.4. Drum sprays in operation at a longwall face.

The amount of water supplied to the shearer drum in this process is approximately 100 gpm (6.3 liter/s) (Colinet, et al., 1997). The spray pressure is maintained between 80 and 100 psi (551.5 and 689.4 kPa) (Kissell, 2003). Too high of a water pressure can blow the dust into the walkway and expose the shearer operator to dust (Pimentel, et al., 1984). The number and type of sprays mounted on the shearer drum also affect the control of dust. Studies (Kissell, 2003) have shown that the larger the number of water sprays, the better the wetting; thus, the better the dust control.

The final approach to present-day longwall dust control consists of the confinement and isolation of dust. A shearer-clearer system was developed by the U.S. Bureau of Mines that uses a spray bar (a long pipe with attached water sprays) in parallel with the ranging arm of the shearer and extending beyond the cutter drum. As mentioned earlier, water spays create air currents resulting from the spray displacing air. The intent here is to use these air currents to contain the dust cloud to the coal face and prevent it from migrating into the walkway (Kissell, 2003). Additionally, the remote control, used for operating the shearer, enables the operator to run the shearer from 15-20 feet (4.57 – 6.10 m) upwind and avoid direct exposure. The remote location of the shearer operator can reduce the operator's dust exposure by 68% (Kissell, 2003).

***Dust Control Using a Flooded-Bed Dust Scrubber*.** The greatest source of dust in underground coal mining occurs at the machines where coal extraction occurs, namely a continuous miner or longwall shearer. Methods of dust control for both continuous and longwall mining systems consist of ventilation-airflow dilution and water sprays. Additionally, most continuous mining operations utilize flooded-bed dust scrubbers, which are incorporated into the continuous miners and provide a very effective means for capturing and removing airborne dust. Dust scrubbers, however, are not used in longwall mining operations because longwall operating conditions are not conducive to the application of scrubbers.

The general arrangement of a flooded-bed scrubber is illustrated in Figure 3.5. Two operational characteristics define the performance of a dust scrubber – *capture efficiency*, which is the percentage of the generated dust that is captured by the scrubber, and *cleaning efficiency*, which is the percentage of dust removed from the captured air (Wirch & Jankowski, 1991). The captured dust-laden air is drawn into the scrubber inlet by the negative pressure created by an exhausting vane-axial fan located near the discharge. Fan sizes typically range from 13 hp (9.70 kW) to 40 hp (29.8 kW), with an accompanying airflow range from 3.5 kcfm (1.65 m^3/s) to 10 kcfm (4.72 m^3/s). A full-cone water spray, typically delivering 6.5 gpm (0.41 l/s) at 45 psi (310 kPa), wets the bed which consists of 10 to 30 layers of woven, 0.0035-in. (88.9 µm), steel-mesh screens. A higher number of layers increases the probability that a dust particle will impact the screen and become encased by a water droplet. The screen is angled, rather than being perpendicular to the duct surfaces, to increase the surface area of the bed. After the dust-laden air passes through the bed, a high percentage of dust particles becomes encased by water droplets. The air/water mist then flows through a demister, which consists of parallel, sinuous layers of plastic-type material; and the water (and encased dust) is removed from the air. The dirty water then drains into a collection sump while the cleaned air flows through the fan to the scrubber discharge. The black water is usually pumped from the sump to an appropriate discharge point, such as the chain conveyor on a continuous miner. A NIOSH study shows that a flooded-bed scrubber with a 30-layer bed can achieve a cleaning efficiency significantly greater than 90% with respect to the removal of respirable dust that enters the scrubber inlet (NIOSH, 1997).

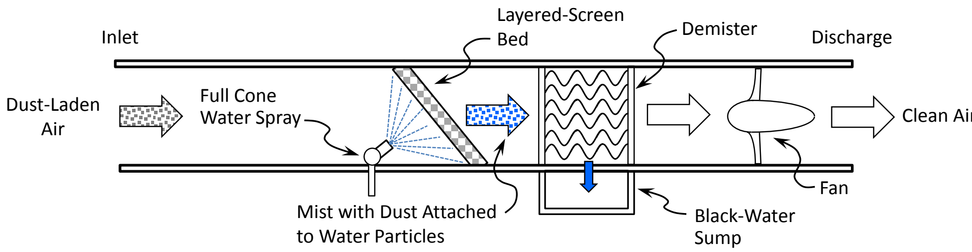


Figure 3.5. General arrangement of a flooded-bed scrubber.

The application of flooded-bed dust scrubbers to continuous miners was patented in 1983 (Campbell, et al., 1983). These scrubbers are typically applied to a remote-controlled continuous miner in an extended-cut operation, as shown in Figure 3.6. The remote control permits the machine operator to remain under supported roof, while the continuous miner advances a mine opening up to a maximum depth of 40 ft (12.2 m) inby the last roof support. The depth of the extended cut must be approved by MSHA in the roof-control and ventilation plans for a specific mine.

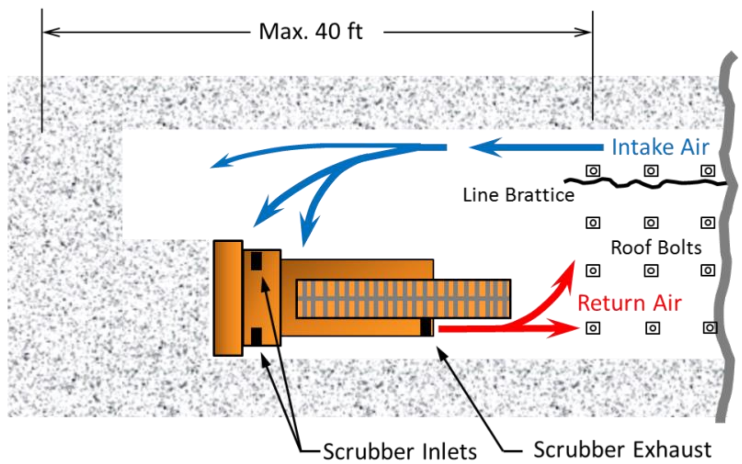
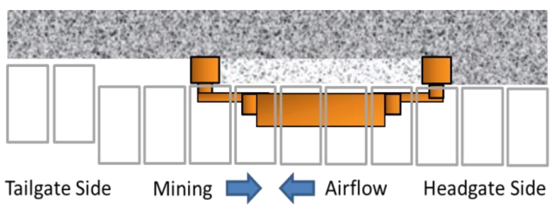


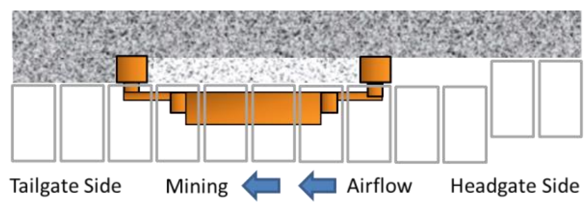
Figure 3.6. Plan view of a continuous miner with a dust scrubber in an extended-cut operation.

Federal Law (30 CFR 75.325) requires a minimum air quantity of 3 kcfm (1.42 m^3/s) for ventilating an active continuous-mining face; in practice, however, the actual air quantity is usually much higher to achieve adequate methane and dust dilution (Listak, 2010). MSHA recommends that the ventilation quantity equals or slightly exceeds the rated, air-handling capacity of the scrubber. The intent for this recommendation is to have most of the working-place ventilation air flow through the scrubber without recirculation, allowing for high capture efficiencies. Figure 3.6 shows that the line brattice cannot be extended much beyond the last roof support, because workers are not permitted to work under unsupported roof. Because of this limitation in advancing the line brattice, the pressure difference created by the scrubber fan becomes a primary means for ventilation airflow to reach the face area, as the entry is extended. Given this extended-cut arrangement, it is obvious that the capture efficiency of the scrubber should be high when the quantity of ventilation air matches the scrubber capacity.

The ventilation characteristics of a longwall mining system are not nearly as conducive to the application of a dust scrubber as those for a continuous mining system. Historically, longwall operations have had difficulty in maintaining consistent compliance with the federal dust standard (Rider and Colinet, 2010). Longwall ventilation practices and equipment arrangement make the effective application of scrubbers extremely challenging. Figures 3.7 (a) and (b) show the general arrangement, and commonly used bidirectional mining process, for a longwall system in the United States. The ventilation airflow is always in the same direction, from headgate to tailgate; whereas, the mining direction changes with each pass across the longwall face. A major issue for the application of a scrubber relates to the large quantity of intake air flowing along the longwall face, which can be an order of magnitude higher than that delivered to a continuous-miner face. A NIOSH study in 2007 found the average air velocity along a longwall face to be 665 fpm (3.38 m/s), with an average quantity of 67 kcfm (31.6 m^3/s) (Rider and Colinet, 2010). Airflows of this magnitude make it impractical to match the air-handling capacity of a scrubber to the longwall ventilation airflow, as is done with continuous mining systems. The placement of a scrubber inlet is critical if reasonable capture efficiency is to be realized. Capture must occur before the dust cloud disburses and is diluted by the ventilation air. Thus, an inlet must be placed as close as practical to a cutter drum. However, if the inlet is positioned too close, large coal particles can be sucked into the inlet and clog the scrubber screen. A scrubber inlet and its associated ductwork must also be positioned so that they are protected from spalling coal and rock, and do not interfere with moving components, such as a ranging arm or cutter drum.



(a) Mining from tailgate to headgate.



(b) Mining headgate to tailgate.

Figure 3.7. General arrangement of a longwall.

Prior Attempts at Using Scrubbers on Longwalls**.** Past attempts at applying scrubbers to longwall systems provide evidence for the need to improve dust control on longwall faces. Research related to the application of dust scrubbers to shearers in the United States began in the 1970s and continued into the 1980s (Wirch and Jankowski, 1991). Four approaches have been used for incorporating a scrubber into a longwall shearer: ventilated-drum, ventilated-cowl, water-powered, and flooded-bed scrubbers.

With a ventilated-drum scrubber (French, 1983), 12 water-powered dust-capture tubes were incorporated into the design of a shearer drum around its hub, as shown in Figure 3.8. A spray-ring manifold, mounted on the face side of the drum, provided high-pressure water to hollow-cone water sprays that performed two tasks – induce dust-laden air through the tubes and scrub the dust-laden air. A deflector plate directed the spray away from the shearer operator. Maximum capture required a high water pressure of approximately 1000 psi (689 kPa). According to Divers, 1987, in-mine tests showed a 50% reduction in dust for an average ventilation quantity of 28 kcfm (13.2 m^3/s), and the estimated quantity through the drum was 3.5 kcfm (1.65 m^3/s). On a practical note, the ventilated drum required excessive daily maintenance and was only applicable on drum diameters greater than 52 in. (1.32 m). Research on this type of scrubber ceased over 30 years ago. Additionally, a face-ventilation quantity of 28 kcfm (13.2 m^3/s) is low compared with today's standards.

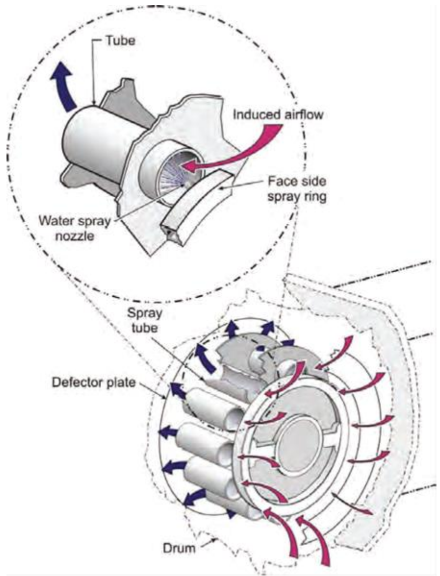


Figure 3.8. Ventilated-drum scrubber (Rider and Colinet, 2010).

Patent US 4351567 – "A Cowl-like scrubber for a long-wall shearer" was awarded in 1982. With this patent, the cowl of a shearer cutter drum was enlarged and modified to accommodate an entire dust scrubbing system within its housing, as show in Figure 3.9. A screen-like barrier was mounted over the air inlet to prevent large coal particles from passing through and clogging the scrubber. Water sprays were used to intermittently flush the outside screen surface. Back-flush sprays, which were automatically activated by a pressure-sensing switch located in the downstream scrubber, were provided behind the screen. The operation of the scrubber, within the cowl housing, was similar to that of a flooded-bed scrubber, although this specific terminology was not used in the patent. Jet sprays, instead of a fan, were used to induce air movement. According to Wirch and Jankowski, 1991, ventilated cowls had reliability and maintenance issues similar to the ventilated-drum scrubber because of the requirement of high pressure pumps for the jet sprays. Furthermore, tests showed that dust reduction was less than 50% under ideal performance conditions.

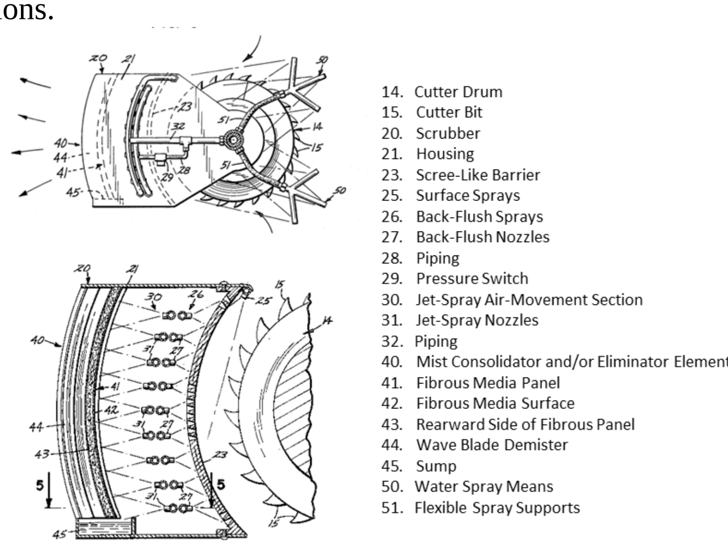


Figure 3.9. Ventilated-cowl scrubber (From Patent US 4351567).

A less-complicated approach for using high-pressure water-powered scrubbing was also attempted in the early 1980s. High pressure sprays were mounted in a rectangular box to induce airflow as well as remove dust, as shown in Figure 3.10. This scrubber, which measured approximately 2 ft x 2 ft x ½ ft, was developed by the U.S. Bureau of Mines and was referred to as a *spot scrubber* (Kelly, 1982). Under ideal conditions, laboratory tests indicated that the scrubber required airflow of at least 20% of the primary airflow to perform adequately. Tests also showed the best performance location was the face side of the shearer body, where it would have a high probability of being damaged (Wirch and Jankowski, 1991). Along similar lines, Patent US 5219208 A – "Scrubber for dispersing dust generated by longwall shearers," was awarded in 1993, and its application was intended for a unidirectional longwall system. It used numerous small wet scrubbers, with each scrubber employing three twin-fluid atomizers that consisted of water sprays in conjunction with compressed air. The patent states that a plurality of scrubbers is required and that the available space dictates the actual number. A fan was not used to move air from the rotating drums to the scrubbing apparatus. As an alternative, the system relied on the momentum induced by the twin fluid atomizers, which also served as the scrubber.

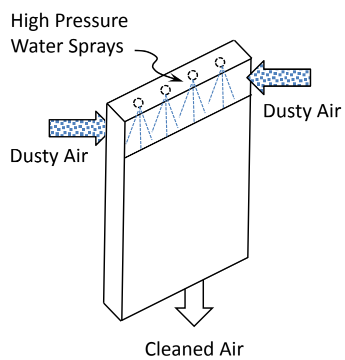
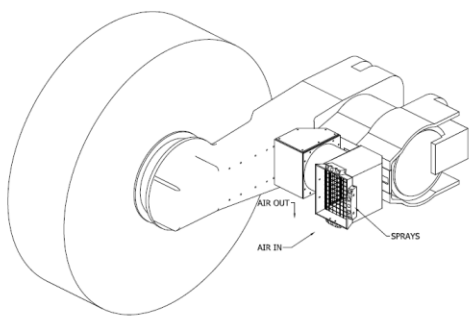


Figure 3.10. Water-powered *spot* scrubber (Wirch and Jankowski, 1991).

The application of a fan-powered flooded-bed scrubber, similar to the one described earlier, was also attempted by the U.S. Bureau of Mines (Jayaraman, 1977). Tests were performed on a longwall face using unidirectional cutting and having a very low ventilation quantity of 12.2 kcfm (5.76 m^3/s). The fan and bed were located on the downwind side of the shearer body, with the ductwork located under the shearer body. The rated throughput of the scrubber was 5.0 kcfm (2.36 m^3/s). With this system, dust reduction of up to a 66% occurred in the longwall return (Wirch and Jankowski, 1991). However, the complexity of incorporating the ductwork into the shearer, along with increasing the shearer dimensions, caused future research in this area to be abandoned.

More recently, the Australian Coal Association Research Program (ACARP) funded a project entitled "Dust control technology for longwall faces – shearer scrubber development and field trials" (Ren, et al., 2009), with CSIRO Exploration and Mining conducting the research. The program was directed toward applying an add-on dust scrubber to a shearer operating in a coal-seam height of 16 ft (5 m). Computational fluid dynamics (CFD) modeling indicated that a minimum scrubber air-handling capacity of 17 kcfm (8 m^3/s) was needed for a face ventilation of 170 kcfm (80 m^3/s). A diagram and photograph of the final design is shown in Figures 3.11 (a) and (b), respectively. Because the shearer cuts coal only in one direction (unidirectional mining) in Australia, only one scrubber was mounted on the headgate side of the shearer. Test results showed dust reductions ranging from 14% to 56%, depending on the sampling instruments used and the operating conditions. Ren et al., 2009, indicated that the major challenge of the project was designing the scrubber to withstand the harsh longwall mining environment.

The results of the ACARP project were somewhat encouraging and suggested that flooded-bed dust scrubbers might be applied to the lower seam heights encountered in longwall operations in the United States. However, the reduced space concerns associated with lower seam heights and the common practice of bidirectional mining in the U.S. created new challenges. Although bidirectional mining is commonly used in the U.S., the research presented in this report only focuses on the application of a scrubber to the head-gate cutter drum. This limited approach increased the probability of a successful outcome, and, if successful, future research can be directed toward applying a scrubber to the tailgate side of the shearer.



(a) Diagram of scrubber location.

(b) Photograph of scrubber.

Figure 3.11. Scrubber location for ACARP Project C14036.

Federal Dust Regulations. Despite significant progress made in reducing Coal Workers' Pneumoconiosis (CWP) over the three decades following the Health and Safety Act of 1969, the uptick in CWP trends after 1995 provided the incentive for MSHA to initiate a campaign to eradicate black lung disease. In 2010, MSHA proposed a new dust standard for coal mines. After a comment period, the newly proposed regulations were modified, resulting in the final dust rule, which went into effect on August 1, 2014. The key provisions of the final rule for an underground coal mine are as follows:

1. Lowers the existing concentration limits for respirable coal mine dust 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.
2. Establishes requirements for the use of the Continuous Personal Dust Monitor (CPDM). The final rule mandates the use of 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 minute running average, and the percentage of the permissible exposure limit.
3. Redefines the term "normal production shift" as the production shift which has at least 80% of average production, as compared with the earlier value of 50% of the average

production. A respirable dust sample is only valid when coal production for the shift is at least 80% of the average production for 30 recent production shifts.

4. Requires collecting respirable dust samples for the full-shift that a miner works regardless of the shift duration. Earlier, a maximum eight hours of sampling was required.
5. 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.
6. Guides MSHA inspectors to use a single, full-shift sample to determine compliance.
7. Adds spirometry testing, occupational history, and symptom assessment to the periodic chest radiographic (x-ray) examinations required to be offered by mine operators to underground miners under NIOSH's existing standards.
8. Adds requirements for certified persons to complete an MSHA course of instruction for performing dust sampling, and maintaining and calibrating the sampling device.
9. Requires re-examination every three years for certified persons to maintain certification.
10. Allows decertification of a certified person for not performing his/her duties properly.

The implementation of the final dust rule causes an additional level of difficulty for longwall-mine operators in maintaining compliance with existing dust-control technology.

3.2 Objective

The overarching objective of this research project is the reduction of *respirable dust* and *float dust* in longwall mining systems through the incorporation of an effective, flooded-bed dust scrubber into a shearer.

The following are specific research aims in support of the objective:

1. The design of a full-scale flooded-bed scrubber system that can be incorporated into a longwall shearer by a longwall equipment manufacturer.
2. The involvement of a longwall mine operator and longwall equipment manufacturer in the project to provide critical information and practical feedback related to the scrubber design.
3. The fabrication of a functional, full-scale physical model (mockup) of a longwall shearer that accurately replicates a Joy 7LS shearer with the flooded-bed scrubber incorporated into the body of the shearer mockup. The mockup must be capable of being used for realistic proof-of-concept testing.
4. The transportation of the shearer-mockup compartments to the NIOSH Pittsburgh Research Laboratory (PRL), and the assembly and installation of the mockup in the NIOSH Longwall Dust Gallery.
5. The development of research protocols and the subsequent dust-reduction testing at the Longwall Dust Gallery.
6. The analyses of the experimental data for investigating the effects of various experimental factors on dust capture effectiveness, and their inter-relationships.

7. The development of computational fluid dynamics (CFD) models of the shearer and its test environment at the NIOSH-PRL Longwall Dust Gallery.
8. The validation of the CFD models using experimental data, and the use of the validated CFD models to predict effects of various factors on the capture efficiency of the scrubber and to improve future designs of the system.

4.0 Research Approach

The research approach is divided into five subsections – Information Gathering and Analysis, Computer-Generated Design of the Shearer, Scale Modeling and CFD Verification, Fabrication of the Full-Scale Mockup, NIOSH Test Gallery, Experimental Factors and Levels, Dust Injection, Dust Concentration Measurements, Experimental Procedure, and Results.

4.1 Information Gathering and Analysis

The research approach for the project was directed toward a site-specific application of a flooded-bed dust scrubber to a longwall mining system. Because of variations in coal-seam thicknesses, dimensions of longwall equipment, and face ventilation requirements, it was determined that attempting the development of a general system that was applicable to all longwall systems throughout the United States was impractical. Instead, the research focused on a specific longwall operation to demonstrate the concept and improve the probability of success. Thus, the research investigators solicited and obtained the cooperation of Alliance Coal, LLC and Joy Global, Inc. to narrow the operating conditions and equipment used for this initial application. Alliance Coal owns and operates three longwall mines, and the longwall system at its Tunnel Ridge Mine, which uses a Joy 7LS shearer, provided the test and information-gathering site. The Tunnel Ridge Mine is a relatively new mine with production beginning in May 2012. It operates in the Pittsburgh coal seam, which has an average seam height of 7 ft (2.13 m), and is located near Wheeling, West Virginia in Ohio County, West Virginia and Washington County, Pennsylvania. Joy Global manufactured the shearer, and its engineering office is located in Franklin, Pennsylvania.

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 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-control branch in Pittsburgh, Pennsylvania. Joy Global shared detailed engineering data for the 7 LS shearer in electronic format with the research team. The obtained data and information from Alliance and Joy were invaluable for constructing computer and physical models of the longwall system.

4.2 Computer-Generated Design of Shearer

The research team obtained 2-D and 3-D (.stl files – non-editable) drawings of the original Joy 7LS shearer. To create an editable 3-D model of the shearer, it 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. Figures 4.1 and 4.2 show the original and simplified drawings of the shearer, respectively.

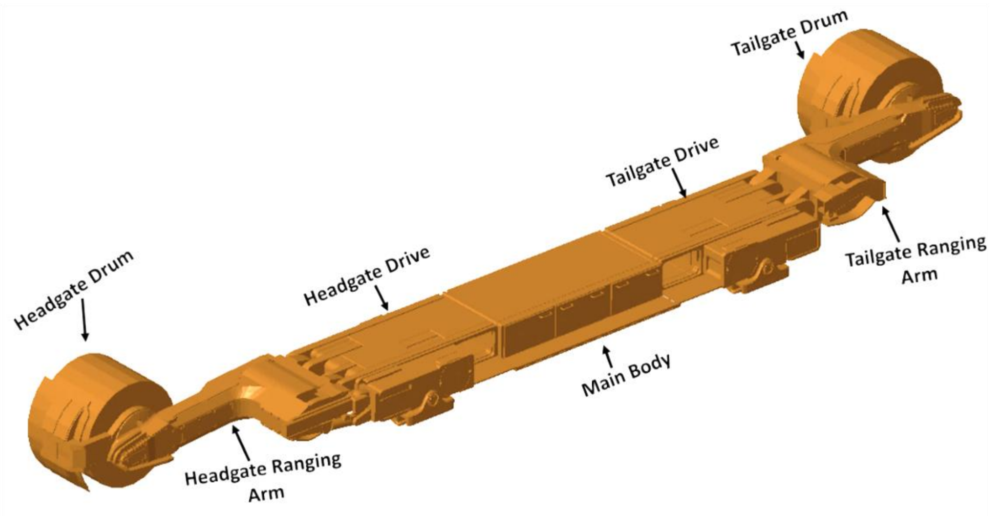


Figure 4.1. Original computer-generated shearer drawing obtained from Joy Global, Inc.

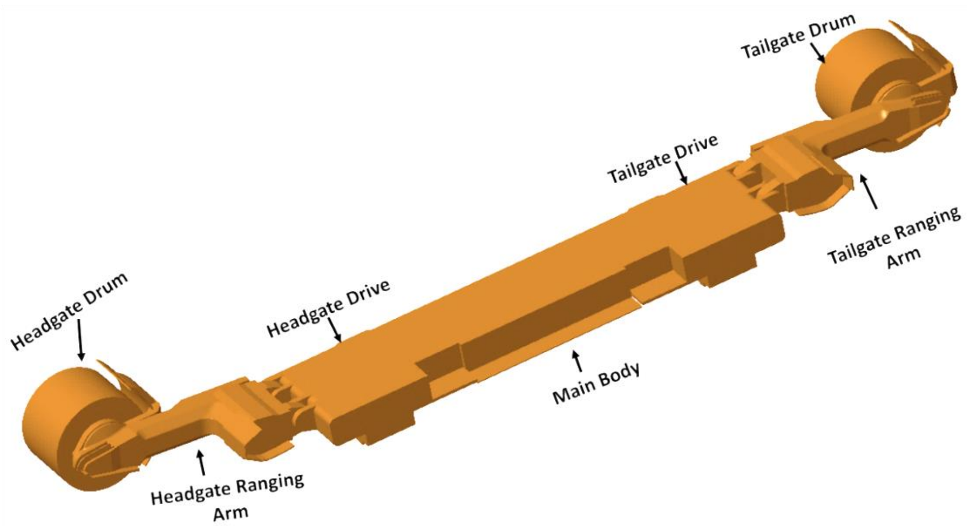


Figure 4.2. Simplified shearer drawing developed at the University of Kentucky.

The next step after constructing the 3-D model was to incorporate a flooded-bed dust scrubber into the shearer assembly. This process consisted of the following four main design issues:

1. Maximum vertical height of the modified shearer so that it would not interfere with mining operations and/or obstruct the view of the shearer operator,
2. Locations for the four flooded-bed scrubber components (screen, demister, ductwork, and fan) that would not interfere with mining or maintenance operations,
3. Scrubber inlet location, and
4. Fan size and type.

The vertical height of the modified shearer had to be sized so that it did not interfere with lowering of the shields and did not block the visibility of the shearer operator. After several iterations with the manufacturer, it was determined that a maximum height of 10 in. (25 cm) above the shearer frame was acceptable. After arriving at this height restriction, the research team eliminated the approach of placing the entire scrubber system on the top of the shearer body as add-on components, because the dimensions of the four components (screen, demister, ductwork, and fan) would easily exceed the 10-in. (25-cm) limitation.

Because of the large difference between the ventilation and scrubber air quantities, the inlet of the scrubber must be as close to the headgate drum as practical. Furthermore, the outlet of the flooded-bed scrubber should be well downwind towards the tailgate drum. The three scrubber compartments – the flooded-bed panel and demister, the fan and motor, and the connecting ductwork were added to the shearer body, as shown in Figure 4.3. The width of the connecting duct extends 20 in. (51 cm) beyond the control-compartment frame towards the coal face and has a vertical dimension of 36-$^{1}/_{8}$ in. (92 cm). A commercialized version of this duct would require robust construction, similar to that of the shearer compartments, because it would be subjected to spalling coal and rock from the face. Furthermore, the vertical distance from the bottom of the duct to the floor needs to be coordinated with the cutter-drum diameter to prevent interference by the coal bench left by the lead cutter drum. The additional compartments increase the overall length of the original shearer by approximately 7 ft (2.13 m), which should not create problems unless the shearer is operating in a coal seam with significant undulations. Figure 4.4 shows the scrubber inlet and discharge ducts, along with the associated airflow directions.

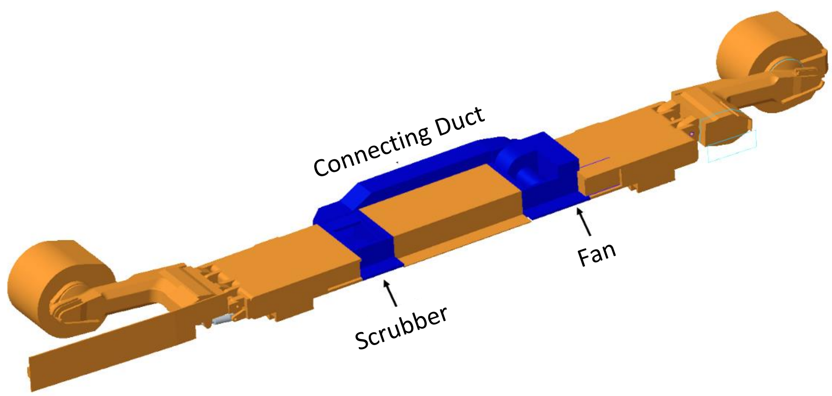


Figure 4.3. Shearer computer model with the scrubber compartments added.

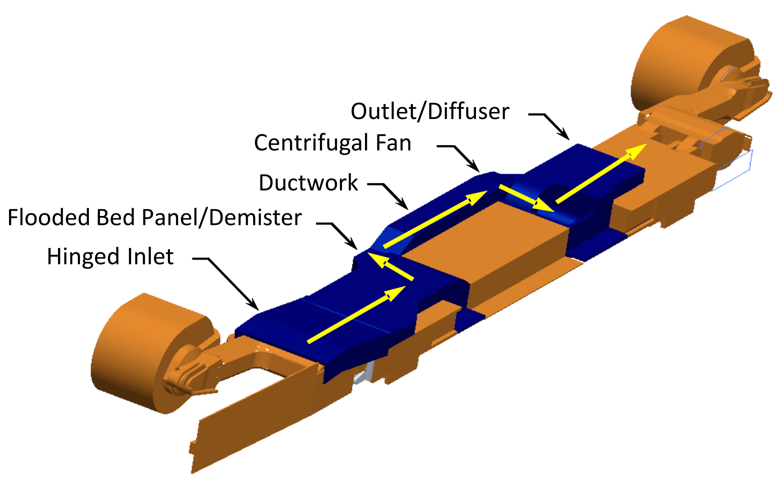


Figure 4.4. Final shearer computer model with the inlet and discharge ducts.

4.3 Scale Modelling and CFD Verification

A 1/20th scale model of the shearer and longwall face was developed to verify initial results from the CFD modeling. The scale model was built to replicate the design of the scrubber and scaled conditions at the Tunnel Ridge Mine. The model, including the shearer, scrubber ductwork, and AFC, was constructed using a MakerBot 3D printer. A wind tunnel was constructed of wood and polycarbonate to house and test the scaled equipment. The wind tunnel is connected to an exhausting fan, with variable-frequency-drive (VFD) motor control, for controlling the quantity of air along the simulated longwall face. Figure 4.5 shows a layout of the shearer body and scrubber components of the model. The orange components represent the original 7LS shearer, while the blue components represent the scrubber system incorporated into the design. The model is required to simulate the airflow through the actual scrubber; therefore, a plastic device attached to the scrubber inlet allowed for tubing to be connected to the ductwork. A shop vacuum was used to pull air through the simulated scrubber system. The shop vacuum moves approximately 32 cfm (0.015 m^3/s) of air through the scrubber ductwork. The longwall-face air velocity at the Tunnel Ridge Mine is approximately 500 fpm (2.54 m/s). A vane-axial fan was used to create this flow, and a thermo-anemometer was used to the measure the velocity through the wind tunnel.

To simulate dust-laden air, CO_2 was injected as a tracer gas into the system. The CO_2 was emitted through the simulated coalface, which is designed with holes spaced approximately 1 cm apart to allow the gas to escape into the simulated mine environment near the shearer drum. The shearer was positioned at the face to simulate the actual cutting position. Figure 4.6 shows the total layout of the model, which is completely sealed within the wind tunnel.

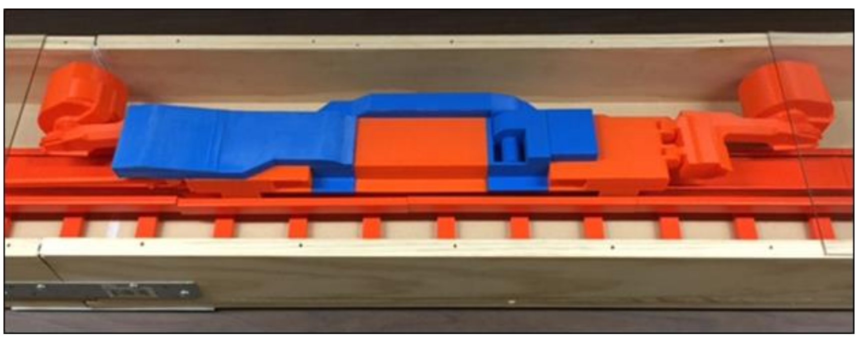


Figure 4.5. Scale model of the shearer body and scrubber unit.

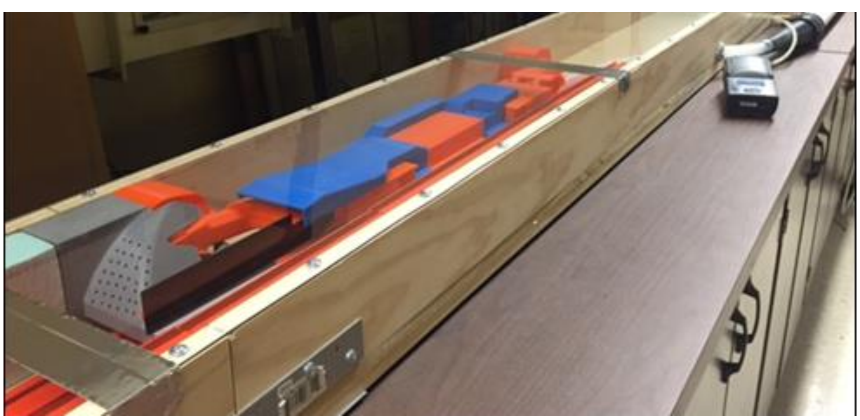


Figure 4.6. Scale model of the wind-tunnel testing layout.

A gas monitor was placed downwind of the system and was used to measure the concentration of CO_2. First the CO_2 was released with the scrubber off, and its concentration was measured. Once the scrubber was activated, the ventilation air velocity was adjusted to the value occurring prior to scrubber activation, because the scrubber caused an additional airflow, which increased the velocity across the face. The adjustment kept the experiments consistent. After the adjustment and scrubber activation, the CO_2 concentration was measured again.

For this experiment, measurements were taken at five different air velocities. These velocities included 400 fpm (2.0 m/s), 450 fpm (2.3 m/s), 500 fpm (2.5 m/s), 550 fpm (2.8 m/s), and 600 fpm (3.0 m/s). Two separate trials were conducted to verify repeatability. The results from the scale-model testing are given in Tables 4.1 and 4.2, which represent Trials 1 and 2, respectively.

Table 4.1. Capture Efficiencies for Trial 1

Trial 1						
No Scrubber w/CO_2			Scrubber w/CO_2			Capture Efficiency
Air Velocity		CO_2 Content (%)	Air Velocity (fpm)		CO_2 Content (%)	
m/s	fpm		m/s	fpm		
2.06	405	0.60	2.06	406	0.08	94.5%
2.32	456	0.52	2.34	460	0.11	87.2%
2.54	500	0.52	2.57	505	0.11	87.2%
2.82	555	0.47	2.79	550	0.14	78.6%
3.07	605	0.41	3.05	600	0.14	75.0%

Table 4.2. Capture Efficiencies for Trial 2

Trial 2						
No Scrubber w/CO_2			Scrubber w/CO_2			Capture Efficiency
Air Velocity		CO_2 Content (%)	Air Velocity (fpm)		CO_2 Content (%)	
m/s	fpm		m/s	fpm		
2.05	403	0.69	2.06	405	0.08	95.3%
2.29	451	0.60	2.32	457	0.11	89.1%
2.54	500	0.52	2.55	501	0.11	87.2%
2.79	549	0.47	2.82	555	0.14	78.6%
3.03	596	0.41	3.07	605	0.14	75.0%

After each measurement at various velocities, the CO_2 content of the laboratory atmosphere was measured. This value was used as a baseline to calculate the capture efficiency. Air generally contains 0.039% CO_2 in a normal atmosphere. A concentration of 0.05% CO_2 was measured in the laboratory throughout the test period. Therefore, this value was used as the baseline. The baseline was subtracted from the recorded concentration to reflect the efficiency. The efficiency is calculated from the percentage of CO_2 before and after the scrubber activation.

A CFD model was developed to replicate the 1:20 scale model and to compare results and help verify the accuracy of the computer analysis. Airflow from the primary ventilation system is represented as a constant velocity at the inlet of the longwall model. The rotation of the shearer drums and the movement of the AFC were neglected, as in the scale model. Three boundary layers were utilized at the walls and surfaces of the CFD model, and a volume mesh was generated. Steady-state simulations were initially performed. Figure 4.7 shows velocity contours at the shearer for four parallel planes, perpendicular to the coal face. Note that the air velocities close to the tailgate drum are significantly lower than those at the headgate drum. This occurs because the shop vacuum, which simulates the scrubber fan, does not return the captured air to the scaled model as an actual scrubber would.

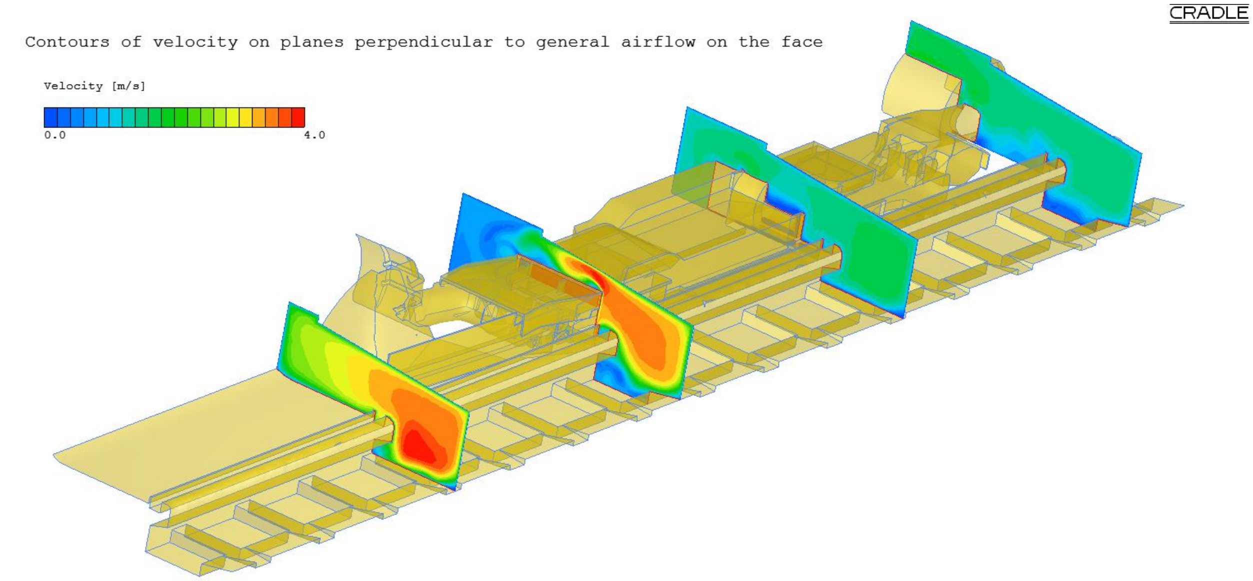
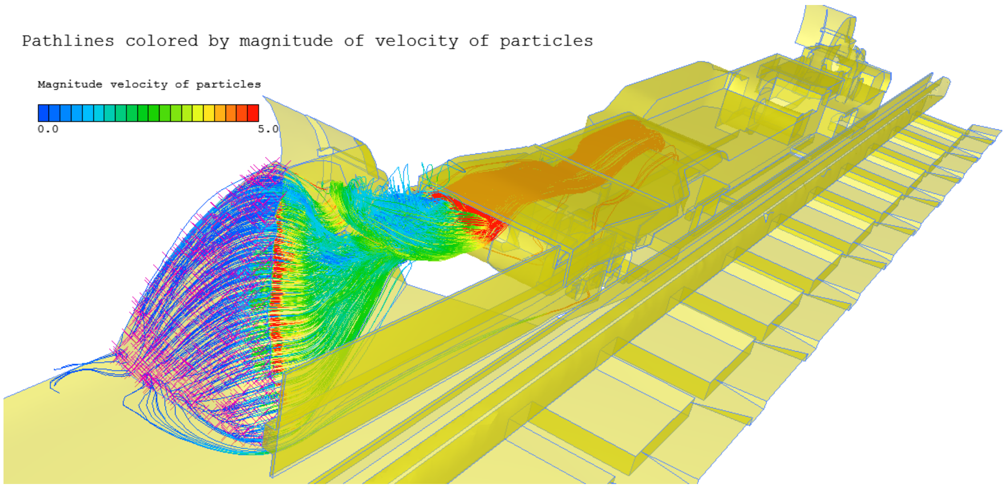


Figure 4.7. Velocity contours for four parallel planes, perpendicular to the coal face along the shearer.

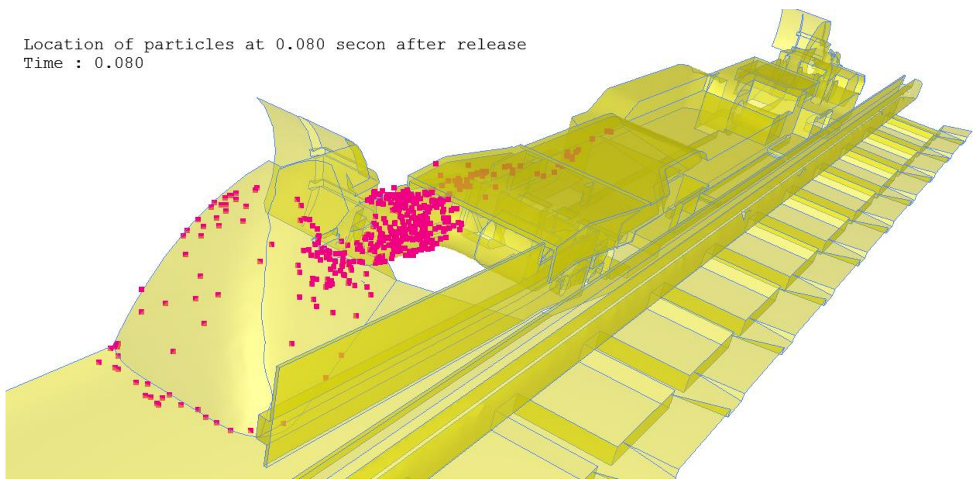
Transient-state simulations were run with small time steps of 20 μs to ensure a low Courant number and precise particle locations for capture. Meshes were generated with different numbers of elements to establish grid independence. A mesh with approximately 2.21 million elements was considered to provide sufficient detail, since further refinement did not improve the results. Furthermore, the CFD results show good agreement with the tracer-gas experiments. Table 4.3 compares the capture efficiencies obtained from the tracer gas experiments with those obtained from the CFD models. Figure 4.8 shows the CFD-generated path lines (a), as well as particle position (b), at 0.080 seconds after release.

Table 4.3. Percent Capture for Tracer-Gas Experiments vs CFD Models

Sl. No.	Air velocity (fpm)	Mean experimental capture	Capture shown by CFD
1	405	94.9	92.2
2	456	88.2	91.8
3	500	87.2	87.6
4	555	78.6	77.6
5	605	75.0	75.2



(a) Simulated path lines followed by the tracer gas.



(b) Simulated particle positions.

Figure 4.8. CFD particle simulations at 0.080 seconds after release.

The tracer-gas experiments and the CFD models showed strong agreement, with the encouraging results that indicate a flooded-bed scrubber can capture a significant amount of dust generated by the headgate drum.

4.4 Fabrication of the Full-Scale Mockup

A full-scale mock-up of a Joy 7LS double-drum shearer with the integrated scrubber was fabricated within the Department of Mining Engineering at the University of Kentucky. The purpose was to test the effectiveness of the flooded-bed scrubber with respect to dust capture and removal. The following steps were performed to fabricate the mockup:

1. 3-D geometric modeling for each compartment of the mockup,
2. Building the aluminum frame structure for each section,
3. Covering each structure with high-density polyethylene (HTPE) sheets, and
4. Assembling the fabricated components of the shearer.

Three-dimensional CAD models for each component of the mockup were created before building the physical model. The primary objective of the CAD model was to have an interactive visual representation of the final physical model. This approach offers design insights and allows the result to be viewed on a computer monitor before construction, thus helping to avoid costly mistakes. The modeling was performed using the editable 3-D models to create the framework and simulate its covering with plastic sheets using CAD software PTC Creo Parametric 3.0. The 3-D model includes all details, such as size and length of the extruded profile, location, quantity of different fasteners and brackets, and dimensions of the plastic needed to cover a specific area. An example of a 3-D CAD model of a shearer component (ranging arm) is shown in Figure 4.9.

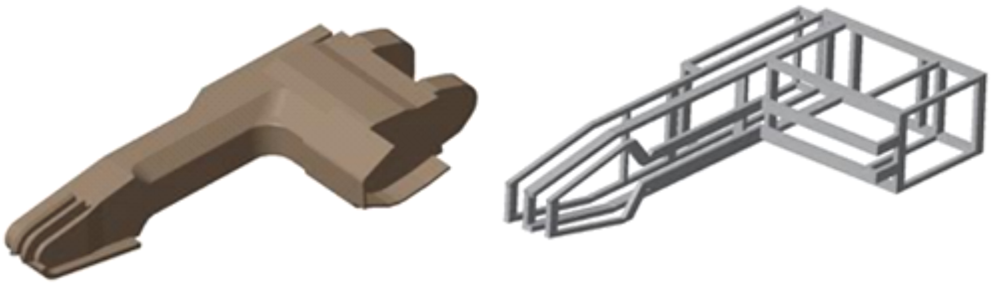


Figure 4.9. Computer generated 3-D model of the ranging arm of the shearer and its corresponding 80/20 structure.

The first step towards constructing the mockup was to fabricate the structure (skeleton) of each component. The 80/20 aluminum, which includes extruded profiles, fasteners, and joining plates, was selected for this purpose, because of its high strength, high strength-to-weight ratio, resilience, and easily machined properties. The manufacturer, 80/20 Inc., uses a modular T-slotted framing system with extruded beams of 6105-T5 aluminum alloy. Figure 4.10 shows an extruded profile, fastener, and joining plate used for building the shearer-component frames.

Figure 4.10. From left to right: 80/20 extrusion, corner bracket, and joining plate.

The photographs in Figures 4.11 and 4.12 show the partially completed headgate and tailgate ranging arms, respectively. Pillow-block bearings were subsequently mounted to the headgate ranging arm for supporting the rotating cutter drum by means of a hollow steel shaft. A hollow drum shaft acts as a pipe for supplying water to 41 spray nozzles mounted on the drum. A nonrotating drum is attached to the tailgate ranging arm.

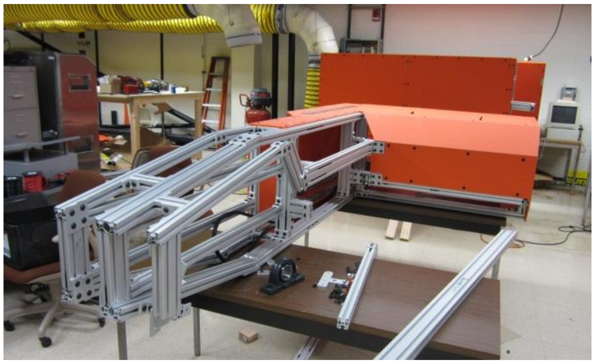


Figure 4.11. Fabrication of the headgate ranging arm.

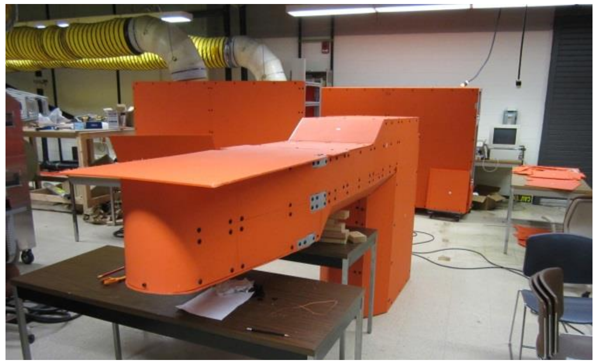


Figure 4.12. Nearly completed tailgate ranging arm.

Light-weight, off-the-shelf components, with the appropriate dimensions and strength, for use as the cylindrical portion of the cutter drum could not be found. Furthermore, the design and fabrication of the spiral scroll, which is mounted to the drum cylinder, presented a complex challenge. The mounting of the bit blocks and bits further complicated the design. A couple of attempts failed until a workable process was finalized. It was decided to construct the cylindrical portion of the drum using expanding urethane foam. The sequence of photographs (Figures 4.13 – 4.20) shows the cutter drum, which was by far the most difficult component of the shearer to fabricate, at various stages of construction. The initial casting of the hollow urethane cylinder had to be turned and smoothed, as shown in Figure 4.13. A lathe-like apparatus, with a wood-working router used as the cutting tool, was designed and constructed in-house in the Ventilation Lab to perform this turning process. A plastic barrel, shown in Figure 4.14, was used as the inner form of the mold for constructing the hollow, urethane cylinder. The barrel remained attached to the urethane to provide additional strength. Aluminum rings with set screws were fabricated with tapped holes for mounting adjustable spokes for attaching the urethane cylinder to the hollow shaft, which also serves as the water-supply line for the drum-mounted sprays.

The scroll was constructed from high-density insulation using a custom-designed jig to cut sectioned pieces. The pieces of insulation were cut with a hot-wire cutter, as shown in Figure 4.16. The sectioned pieces were glued together and attached to the cylindrical portion of the drum to form a continuous scroll. A shearer cutter bit, and its associated block, was printed using a 3-D printer. The printed bit and block was used to create a mold for casting the bits and blocks from high-density urethane.

Figure 4.13. Turning the initial casting.

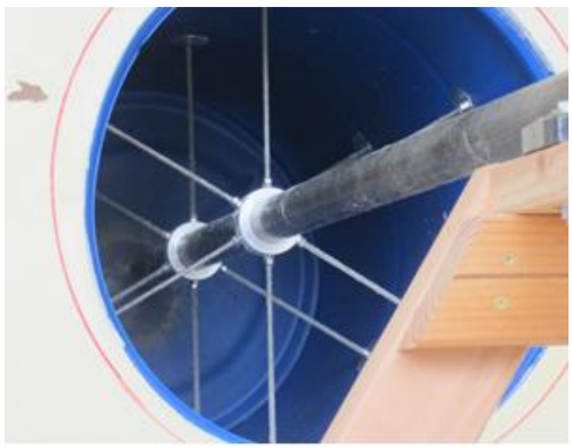


Figure 4.14. Plastic barrel used for inner form of drum.

Figure 4.15. Turned and smoothed hollow cylinder.

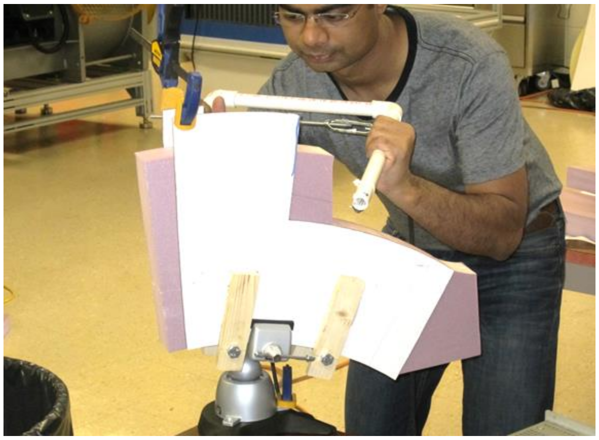


Figure 4.16. Jig for cutting insulation for the shearer scroll.

The unpainted shearer drum, with the scroll, 41 bits and bit blocks, and 41 water sprays, is shown in Figure 4.17. After the fabrication of the shearer drum was complete, it was coated with orange Rhino Lining™ to provide additional strength, as shown in Figure 4.18. Water is supplied to the hollow shaft of the cutter-drum by means of a rotary coupler (Figure 4.19). The 41 water sprays mounted on the drum (Figure 4.20) are connected to the hollow drum shaft through a manifold (Figure 4.21). Water is supplied to the headgate drum and the scrubber by two separate PVC pipes. An electric ball valve, controlled by the programmable automation controller (PAC), adjusts the flowrate for each water circuit.

Figure 4.17. Final assembly of drum prior to painting.

Figure 4.18. Painted drum mounted to the ranging arm.

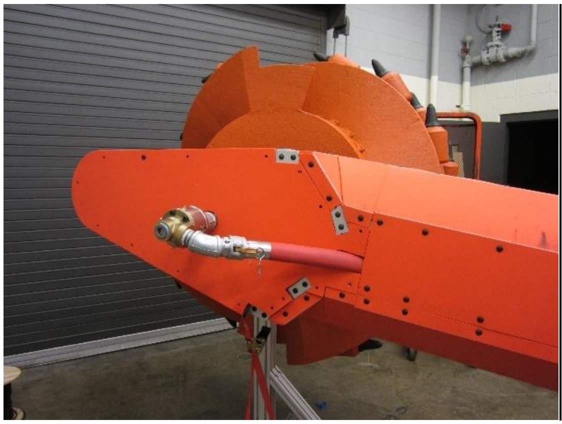


Figure 4.19. Drum water supply via rotary coupler.

Figure 4.20. Water sprays aimed at the bit tips.

A three-phase, 460 V, ¼ hp (186.4 W), 47 rpm gear motor is located within the headgate ranging arm and drives the headgate drum through a belt-pulley arrangement, as shown in Figure 4.22.

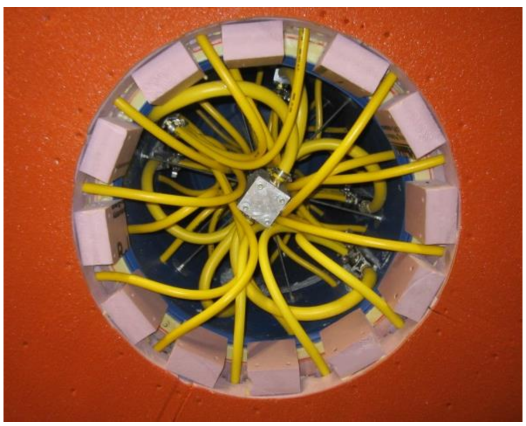


Figure 4.21. Plumbing for the cutter-head sprays.

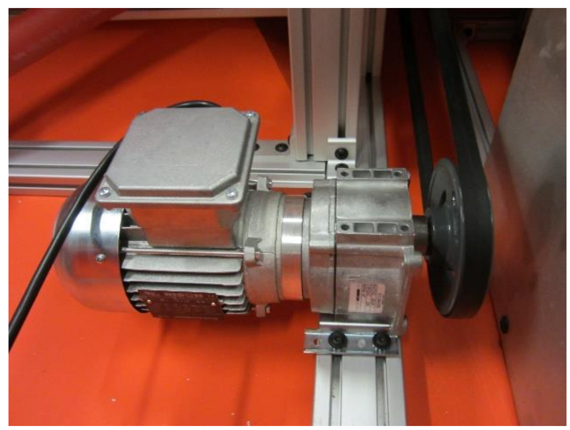


Figure 4.22. Cutter-drum motor with belt drive.

The scrubber compartment consists of an inlet, water spray, screen, demister, water sump, and outlet. A 20-layer woven, 88.9 micron steel mesh screen (Figure 4.23) was installed at an angle of approximately 45^{o} to the airflow direction through the inlet. A full-cone water spray, located upwind of the screen, completely wets the screen. A demister (Figure 4.24) is placed downwind of the screen to remove water from the dense mist exiting the screen. A black-water sump is located under the demister to collect the dirty water as it drains from the demister, and a sump pump removes the black water from the sump.

The fan compartment consists of an inlet, a centrifugal fan, and a discharge. A 50 hp (37.3 kW), 3540 rpm motor drives the fan, which pulls air through the inlet duct of the scrubber. The fan motor and its variable frequency drive (VFD) are shown in Figure 4.25, while the centrifugal fan is shown in Figure 4.26. A rectangular duct on the face side of the control compartment connects the outlet of the scrubber compartment (screen and demister) to the inlet of the fan housing.

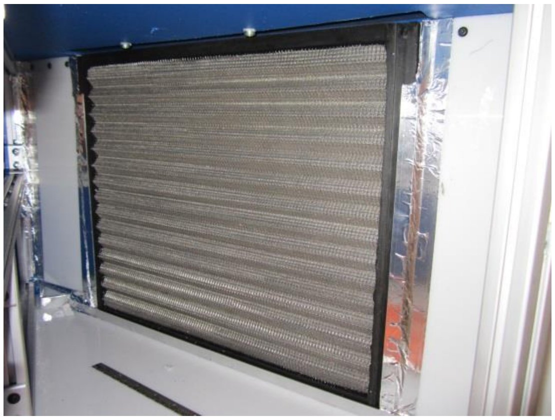


Figure 4.23. Flood-bed screen.

Figure 4.24. Demister.

Figure 4.25. VFD and fan motor.

Figure 4.26. Centrifugal fan.

The electrical/electronic controls for the shearer mockup are shown in Figure 4.27 and primarily consist of the 50-hp variable frequency drive (VFD), the cutter-motor starter, and the seven-slot programmable automation controller (PAC). A touch-screen display (Figure 4.28) provides a remote human-machine interface (HMI) for controlling the system, as well as a display for the operating parameters, such as rotational fan speed, motor currents, pressures, etc. Figure 4.29 shows an example of the HMI display. A three-pole circuit breaker protects the internal electrical components of the mockup. Hard-wired emergency stop buttons are located on the shearer control panel (Figure 4.27) and the remote HMI (Figure 4.28).

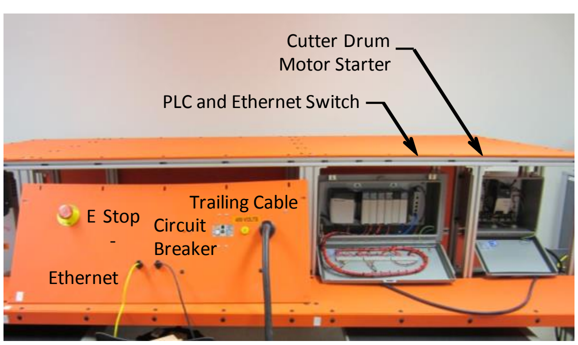


Figure. 4.27. Controls for shearer mockup.

Figure 4.28. Touch screen human-machine interface.

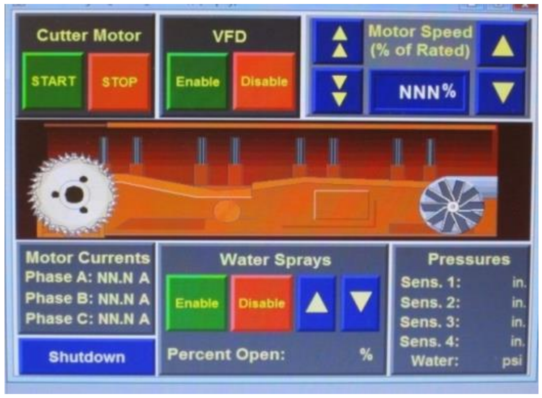


Figure 4.29. Human-machine interface (HMI) display.

Testing of the control functions for the assembled full-scale mockup of the Joy 7LS shearer was conducted at the University of Kentucky, as shown in Figure 4.30. The photograph of the mockup does not include the tailgate ranging arm because of space limitations in the setup area. After testing, the shearer mockup was disassembled and transported to the NIOSH Longwall Dust Gallery (Figure 4.31) in Pittsburgh, Pennsylvania.

Figure 4.30. Physical model of the modified Joy 7LS longwall shearer without tailgate ranging arm.

Figure 4.31. Longwall Dust Gallery at the NIOSH Pittsburgh Research Laboratory.

4.5 NIOSH Longwall Dust Gallery

Significant modifications to the NIOSH longwall gallery had to be made to accommodate the experimental shearer. First, the existing shearer had to be removed and the ceiling lowered to approximately 94 in. (2.4 m) to more closely match the dimensions of the cooperating mine. Next, the material representing the coal bench between the two cutter drums was removed and replaced with material of the proper height for the cutting drums of the experimental shearer. The shearer was then installed and the remainder of the material representing coal was put in place. Power and water were then supplied to the shearer and its functionality was tested. Dust injection points and dust monitor locations were determined and installed (described later). The installation process took several weeks beginning on June 6, 2016. By mid-August, preliminary testing began.

Figure 4.32 shows the general layout of the NIOSH longwall gallery. Fresh (intake) air is introduced near shield 19 and travels along the face to the return airway. The return air is then directed to a bag house and exhaust fan. Regulators in the return are used to control air quantity. Dust is introduced near the headgate drum to simulate the generation of respirable dust, as will be described later.

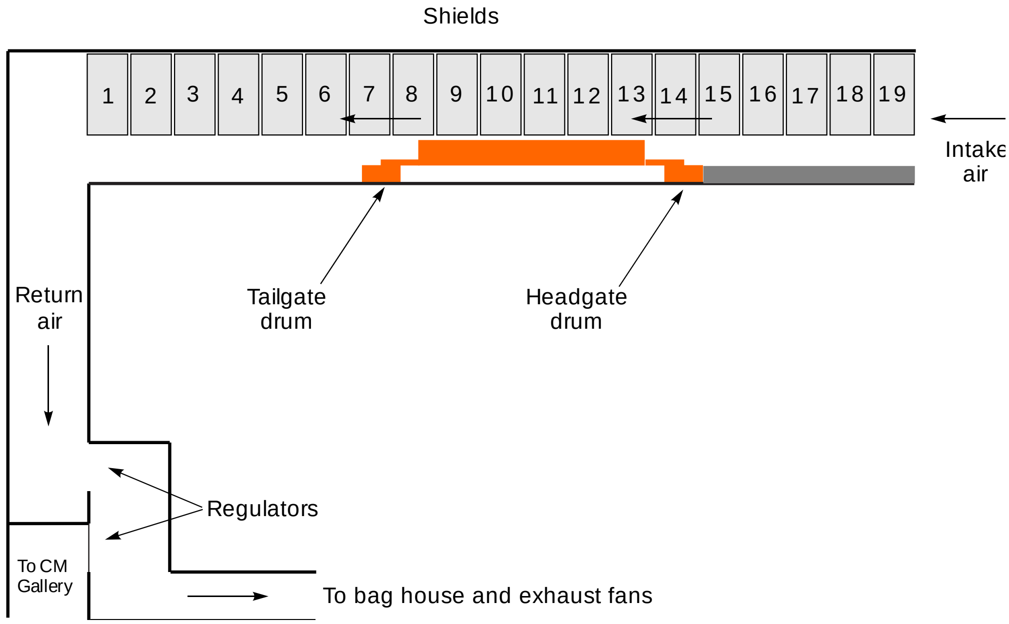


Figure 4.32. Layout of the NIOSH PRL Longwall Dust Gallery.

4.6 Experimental Factors and Levels

The experimental plan was developed during the summer and dust-measurement tests of the shearer-mounted dust scrubber were conducted from approximately September 19 through November 3, 2016. The tests included three factors at two levels, with five replications at each of the test conditions, for a total of 40 tests. Measurements were made over 10-minute intervals.

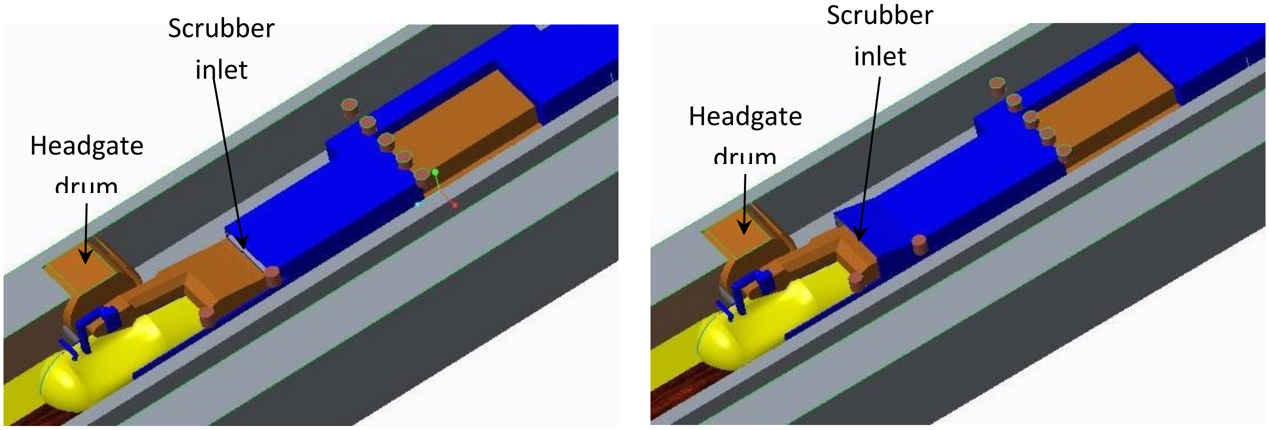
The tests were developed to follow a standard factorial experiment to determine main effects and interaction. Because of the limitations in time available at the NIOSH longwall gallery, tests were limited to three factors and two levels. Tests were conducted by NIOSH personnel.

Scrubber Inlet. The scrubber inlet was used with and without an extension. Without the extension, the inlet is 109 in. (2.77 m) from the hub of the headgate drum. With the extension, the inlet is 75 in. (1.91 m) from the hub of the headgate drum. The inlet extension is angled 14° upward from the horizontal. Figure 4.33 shows the location of the scrubber inlet with and without the extension. The low level is with the extension removed and the high level is with the extension included.

Scrubber Capacity. The scrubber fan was operated at full voltage at two frequencies by using a variable-frequency drive 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 13,700 cfm (cubic feet per minute) (6.47 m^3/s). At 30 Hz, the scrubber capacity is approximately 6300 cfm (2.97 m^3/s). Scrubber spray water flow was maintained at 6.75 gallons-per-minute (0.43 l/s).

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 700 feet per minute (fpm) (3.56 m/s). The low level is 500 fpm (2.54 m/s), which is believed to be representative of low air velocity on modern longwall faces. The Tunnel Ridge ventilation plan calls for a minimum velocity of 500 fpm (2.54 m/s) along the face at a distance of 100 ft from the headgate.

Table 4.4 provides a summary of the factors and levels. Other test conditions include the splitter arm sprays that were OFF during the first series of tests and ON for the second series of tests, and the headgate drum sprays that were ON during the tests.



(a) Inlet without extension. (b) Inlet with extension.

Figure 4.33. 3-D model of shearer mockup showing the two inlet locations.

Table 4.4. Factors and levels for NIOSH experiments

Factor	Low Level	High Level
Scrubber inlet extension	Removed	Included
Scrubber capacity	6300 cfm (2.97 m^3/s)	13,700 cfm (6.47 m^3/s)
Face air velocity	500 fpm (2.54 m/s) 40,800 cfm (19.3 m^3/s)	700 fpm (3.56 m/s) 57,200 cfm (27.0 m^3/s)

4.7 Dust Injection

The dust used for the experimental study was Keystone Mineral Black 325BA, a low specific gravity, finely ground material, manufactured by Keystone Filler and Manufacturing Company. This is the same material used for many years at NIOSH PRL for conducting respirable-dust studies. Table 4.5 gives the relevant physical properties of the Keystone Mineral Black, and Figure 4.34 shows the cumulative size distribution.

Table 4.5. Typical properties of Keystone Mineral Black 325BA dust

Typical Properties	
Specific Gravity	1.22
Color	Black
Moisture	1% Max
Total Sulfur	1.20%
Free Sulfur	<0.5%

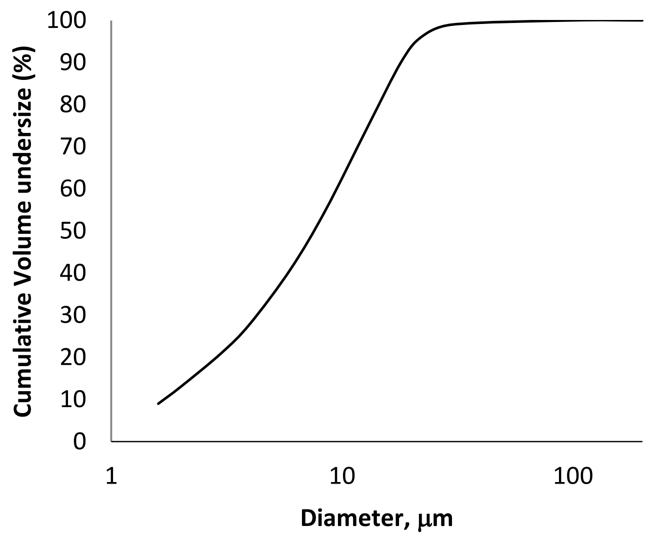


Figure 4.34. Approximate cumulative size distribution of Keystone Mineral Black 325BA.

Figure 4.35 shows the dust injection locations. Dust injection point 1 is located in the middle of the arced surface representing the active coal-cutting location by the headgate drum. Injection point 2 is a 4.0 in. (102 mm) diameter corrugated PVC pipe located 18 in. (0.45 m) from the coal face, 40 in. (1.02 m) from the floor and approximately 21 in. (0.53 m) from the center of the arc. Dust injection point 3 is from a wooden box mounted on the headgate ranging arm. Dust is introduced from the bottom of the wooden box. 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). The dust generation sources were selected based on observations of longwall operations.

The Keystone Mineral Black is gravity fed from a screw feeder into a 0.75 in. (19.05 mm) hose transporting compressed air at a rate of 60 psi (413.6 kPa) into two ends of a six-port dust manifold that has ball valves attached to each dust line. Three ports are open and carry the dust to the headgate drum area, wooden box, and 4.0 in. (102 mm) diameter duct, respectively. The ball valve of the dust line carrying dust to the dust box is fully open while the ball valves carrying dust to the other two locations are half open.

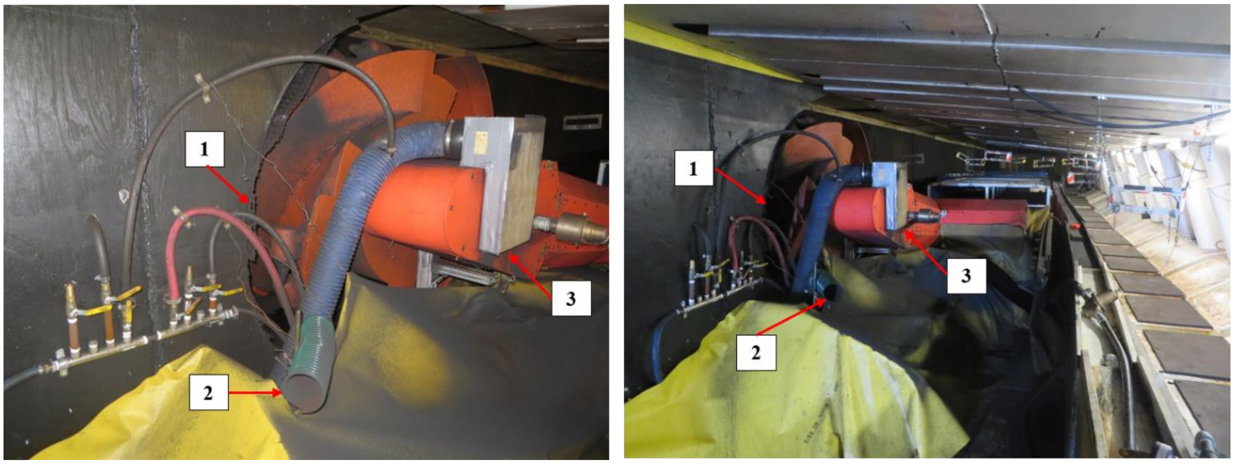


Figure 4.35. Dust injection locations.

4.8 Dust Concentration Measurements

Dust concentration measurements were made with a combination of ThermoFisher Scientific Personal Dust Monitor (PDM) Model 3600 and Model 3700 devices, shown in Figure 4.36. The PDM 3600 is the precursor to the PDM 3700, with the primary difference being that the PDM 3600 includes a cap lamp and associated battery as part of the device. The choice between devices was based on availability. Each is a real-time dust monitor that meets the requirements of the latest MSHA Dust Rule. Dust measurement is accomplished through a tapered-element oscillating microbalance (TEOM) mass sensor. The TEOM uses a Teflon-coated fiberglass filter mounted on one end of a hollow tube vibrating at a known frequency. The dust sample enters through the PDM inlet and is carried to a Higgins-Dewell cyclone, which separates the respirable fraction of dust. As respirable dust particles are deposited on the TEOM's filter, the TEOM frequency changes. The change in TEOM frequency is related to the amount of respirable dust on the filter and hence, gives the respirable dust mass, which is used to calculate dust concentration from a known airflow rate (Page et al., 2008). Dust concentrations are shown on the PDM display and also stored in the PDM memory to be downloaded for analysis at the end of the sampling period. The PDM displays cumulative dust concentration, a 30-minute running average, as well as percentage of the permissible exposure limit.

Sixteen Personal Dust Monitors were used to measure dust concentrations. Figure 4.37 shows the 12 dust-measurement locations along the dust gallery longwall face. Four additional dust monitors were located in the longwall gallery return airway.

Table 4.6 shows the distances of the dust monitors relative to the face, floor, and hub of the headgate drum.

a. ThermoFisher Scientific PDM 3600.

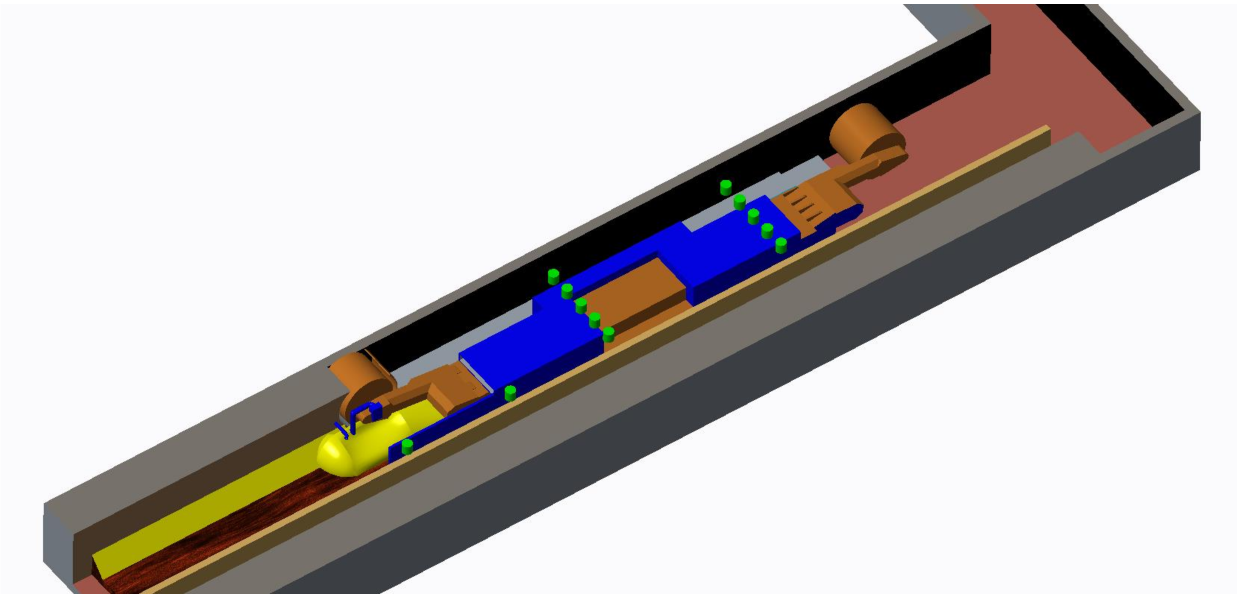
b. ThermoFisher Scientific PDM 3700.

Figure 4.36. ThermoFisher Scientific Personal Dust Monitors.

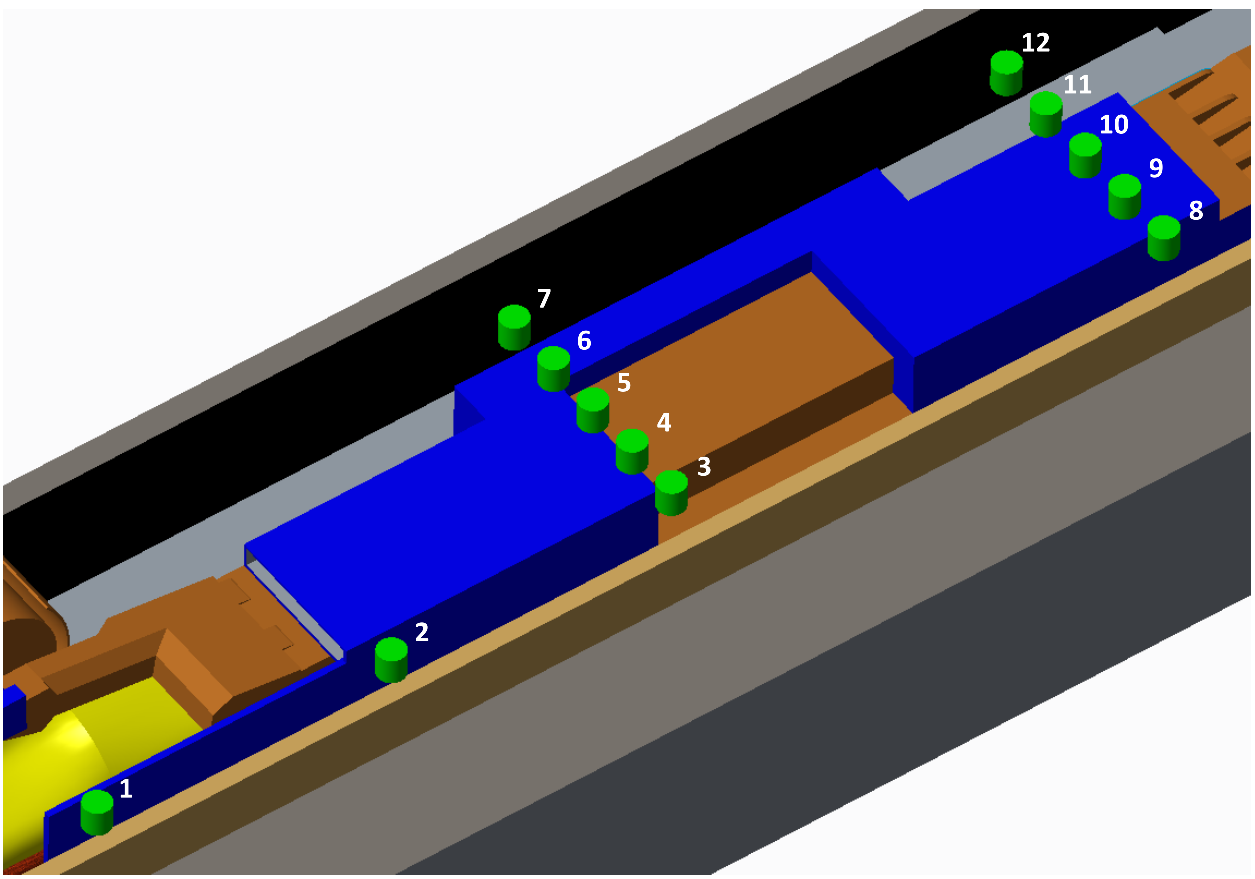
Sixteen Personal Dust Monitors were used to measure dust concentrations. Figure 4.37 shows the 12 dust-measurement locations along the dust gallery longwall face. Four additional dust monitors were located in the longwall gallery return airway. Table 4.6 shows the distances of the dust monitors relative to the face, floor, and hub of the headgate drum.

4.9 Experimental Procedure

Table 4.7 shows the sequence of steps taken for each experiment that was conducted. For each day that testing was conducted, the PDMs were programmed to record dust concentrations throughout the day. However, each test condition consisted of average values over 10-minute intervals. There was a three-minute wait period during the transition from one condition to the next to allow the system to reach steady-state conditions. For example, a test begins with dust ON (step 1 in Table 4.7). After three minutes, the data from the next 10-minute time interval is used to determine the dust concentrations (from the data file that is downloaded at the end of the day). Next, the scrubber fan is turned ON (step 2 in Table 4.7). After a three-minute wait period, data from the next 10-minute time interval is used to determine the dust concentrations for dust + scrubber fan. This process continues in the sequence of steps shown in Table 4.7 until the completion of step 4. At this point, the scrubber fan, scrubber sprays, and splitter arm sprays are turned OFF and dust-only is run again for 13 minutes, with data from the last ten minutes used to determine the concentration for dust-only again.



a. General location of sampling locations.



b. Detailed locations of sampling locations.

Figure 4.37. Dust measurement locations along longwall gallery face.

Table 4.6. Dust monitoring locations

Identifier	Distance from face	Distance from Center of Headgate Drum	Distance from floor
Splitter (1)	125 in. (3.18 m)	47 in. (1.19 m)	61 in. (1.55 m)
Inlet (2)	125 in. (3.18 m)	109 in. (2.77 m)	61 in. (1.55 m)
Scrubber Walkway (3)	125 in. (3.18 m)	252 in. (6.40 m)	74 in. (1.88 m)
Scrubber Mid-walkway (4)	100 in. (2.54 m)	252 in. (6.40 m)	74 in. (1.88 m)
Scrubber Mid-shearer (5)	75 in. (1.91 m)	252 in. (6.40 m)	74 in. (1.88 m)
Scrubber Mid-face (6)	50 in. (1.27 m)	252 in. (6.40 m)	74 in. (1.88 m)
Scrubber Face (7)	25 in. (0.64 m)	252 in. (6.40 m)	74 in. (1.88 m)
Tailgate Walkway (8)	125 in. (3.18 m)	474 in. (12.04 m)	74 in. (1.88 m)
Tailgate Mid-walkway (9)	100 in. (2.54 m)	474 in. (12.04 m)	74 in. (1.88 m)
Tailgate Mid-shearer (10)	75 in. (1.91 m)	474 in. (12.04 m)	74 in. (1.88 m)
Tailgate Mid-face (11)	50 in. (1.27 m)	474 in. (12.04 m)	74 in. (1.88 m)
Tailgate Face (12)	25 in. (0.64 m)	474 in. (12.04 m)	74 in. (1.88 m)
Return: Top-Left	NA	NA	NA
Return: Bottom-Left	NA	NA	NA
Return: Top-Right	NA	NA	NA
Return: Bottom- Right	NA	NA	NA

Table 4.7. Operating conditions for experimental study

Step	Operating Condition
1	Dust only
2	Dust + scrubber fan
3	Dust + scrubber fan + scrubber sprays
4	Dust + scrubber fan + scrubber sprays + splitter arm sprays
5	Dust only

5.0 Summary of Results and Accomplishments

5.1 Experimental Methodology

As mentioned in Section 4, three factors at two levels, with five replications, for a total of $(2^3)(5) = 40$ tests, were conducted to evaluate the scrubber performance. In addition, two base-case situations were run (five replications each). Base cases included face velocities of 500 fpm (2.54 m/s) and 700 fpm (3.56 m/s) with the scrubber off and the splitter arm sprays on. Analysis of variance (ANOVA) is used to determine the level of significance for main effects and level of interaction.

Because the goal of the analysis was to focus on the effectiveness of the scrubber, it was decided to focus on results while the splitter arm (or shearer clearer) sprays were OFF. Clearly, the splitter arm sprays would 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 use 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 4.7 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, as will be described later.

Because of the difficulty in maintaining a fixed concentration of injected dust throughout the experimental program, the results were standardized to the average dust-only value (i.e., the average dust concentration of steps 1 and 5 described in Table 4.7) for each particular test. In addition, performance was described as the reduction in dust, in percent, as shown in EQ 5. 1.

$$\text{Dust Reduction} = \left(1.00 - \left[\frac{C_S}{(C_{01} + C_{02})(0.5)}\right]\right)(100\%) \qquad \text{EQ 5. 1}$$

where,

C_S = dust concentration measured with the scrubber fan and sprays ON and splitter arm sprays OFF

C_{01} = dust-only concentration at beginning of test

C_{02} = dust-only concentration at end of test

The design factors and associated treatments, summarized in Table 4.4, are labeled as shown below:

A = Scrubber inlet extension. Low: scrubber inlet extension removed, High: scrubber inlet extension included,
B = Scrubber capacity with scrubber water sprays on. Low: scrubber fan operating at 50% of rated frequency (30 Hz) [approximately 6300 cfm], High: scrubber fan operating at 100% frequency (60 Hz) [approximately 13,700 cfm], and
C = Face velocity. Low: 500 fpm (2.54 m/s), High: 700 fpm (3.56 m/s).

Before presenting the results, an example is used to illustrate the procedure for determining the significance of the main effects and interaction effects. The example is based on measurements taken in the return airway with splitter arm sprays OFF.

Table 5.1 shows the treatment combinations, design factors, and average dust reduction of the four PDMs that were hung in the return airway for each of the five replications. The presence of a letter that represents a particular factor in the treatment combinations column indicates that the factor is at the high level, while the absence of the letter indicates that the factor is at the low level (i.e., Yates Notation). As is typically done with this notation, the number one in parenthesis, (1), is the symbol used to indicate all factors are at the low level. For example, the treatment combination **ac** indicates the following: scrubber inlet extension included, scrubber capacity at 50%, and face air velocity at 700 fpm (3.56 m/s), while the treatment combination **(1)** indicates the following: scrubber inlet extension removed, scrubber capacity at 50%, and face air velocity at 500 fpm (2.54 m/s). The 40 values in the columns Run 1 through Run 5 are the average reductions in dust concentration of the four PDMs hung in the return airway, as calculated by using EQ 5. 1. The averages column is the average of the five runs and the totals column is the sum of the runs. (Appendix A includes a summary of all of the experimental test results for each of the 16 PDMs.)

Table 5.1. Summary of results for return airway – 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	Averages	Totals
(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

The general procedure for determining the main factors and interaction is as follows:

- Determine the main/interaction effect for each treatment combination
- Determine the coefficient for each treatment combination
- Determine the sum of squares for each treatment combination, SS_A, SS_B, etc
- Determine the mean square for each treatment combination, MS_A, MS_B, etc
- Determine the error sum of squares, SS_E
- Determine the mean square error, MS_E

From this point, the analysis can be conducted in one of two ways. The *f*-statistic can be determined as the mean square of each treatment combination divided by the mean square error. If this value is greater than the critical value, it is an indication that the associated main/interaction effect is significant, and that coefficient is included in the regression model. (The critical value is the value of the distribution associated with the chosen level of significance, where the level of significance is the probability of a Type I error.)

Alternatively, the *t*-statistic can also be used to determine the level of significance of treatment combinations. 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. To apply this approach, the following steps are taken,

- Determine the standard error
- Determine the *t*-statistic as the estimate of the coefficient divided by the standard error.

If the absolute value of the *t*-statistic is greater than the critical value, it indicates that the associated main/interaction effect is significant and that coefficient is used in the regression model. Typically, the level of significance is chosen to be 0.01, 0.05, or (sometimes) 0.10. For these experiments, it was decided to use a level of significance of 0.01.

Evaluation is commonly done by comparing the P-value to the level of significance for rejecting the null hypothesis. In this case, a P-value less than 0.01 is an indication that the factor/interaction is significant.

Because statistical analysis software used in this study uses the *t*-statistic, that approach is illustrated here through a numerical example.

Consider the main effect of factor *A*, the scrubber inlet extension (experimental results shown in Table 5.1). The main effect is determined as the average high-level minus the average low-level for factor *A* (EQ 5. 2).

$$A = \overline{y}_{A+} - \overline{y}_{A-} = \frac{1}{4(n)}[a + ab + ac + abc - (1) - b - c - bc] \qquad \text{EQ 5. 2}$$

$$A = \frac{1}{4(5)}[109.37 + 249.17 + 165.97 + 284.93 - 105.83 - 214.99 - 117.83 - 248.13] = \frac{122.665}{20} = 6.1333 \qquad \text{EQ 5. 3}$$

The estimate of the coefficient, $\hat{\beta}$, is one-half of the effect,

$$\hat{\beta} = 3.0667$$

The sum of squares for *A* is determined as follows:

$$SS_A = \frac{(contrast)^2}{n2^k} \qquad \text{EQ 5. 4}$$

$$SS_A = \frac{(122.665)^2}{5(2)^3} = 376.17 \qquad \text{EQ 5. 5}$$

where the contrast is defined as the numerator of EQ 5. 3.

The *t*-statistic (or *t* ratio) is determined as follows:

$$t = \frac{\hat{\beta}}{\text{standard error } \hat{\beta}} \qquad \text{EQ 5. 6}$$

where the standard error of $\hat{\beta}$ is

$$se(\hat{\beta}) = \sqrt{\frac{MS_E}{n2^k}} = \sqrt{\frac{12.74}{(5)2^3}} = 0.5643 \qquad \text{EQ 5. 7}$$

MS_E in EQ 5.7 is determined as:

$$MS_E = \frac{SS_E}{\text{error degrees of freedom: } abc(n-1)} = \frac{407.64}{32} = 12.74 \qquad \text{EQ 5. 8}$$

From EQ 5. 6,

$$t = \frac{3.0667}{0.5643} = 5.43 \qquad \text{EQ 5. 9}$$

The critical value is the *t*-distribution value corresponding to the probability of the absolute value of *t* being equal to 0.01. For dof (degrees of freedom) = 32, this value is 2.739. Thus, a *t*-ratio greater than 2.739 corresponds to a P-value less than 0.01, and indicates that a particular factor or interaction is significant. For this example, the P-value associated with 5.43 is 5.7×10^{-6}, i.e., practically zero. Therefore, we see that effect of the scrubber inlet extension is significant, and the coefficient associated with it is 3.0667.

In addition to the main effects and interaction, an estimate for the intercept is also determined. The estimate for the intercept is the grand mean of all tests. The *t*-ratio and associated P-value are also calculated for the intercept.

As previously described, 12 PDMs were used to monitor dust reduction along the longwall gallery (locations shown in Figure 4.37) plus four PDMs in the return airway. This is a very comprehensive set of monitoring locations, and using the measured reduction at each of these points is extremely useful 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 the scrubber performance. Therefore, the analysis focused on the following groups of locations:

- Return airway with splitter arm sprays OFF
- Walkway with splitter arm sprays OFF
- Face area with splitter arm sprays OFF
- Area above shearer body with splitter arm sprays OFF
- Return airway with splitter arm sprays ON
- Walkway with splitter arm sprays ON

It is important to note that 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 unnecessary and, therefore, beyond the project scope of work. If the shearer-integrated dust scrubber is shown to be effective at capturing dust, then a manufacturer of scrubber meshes and demisters could develop and manufacture a mesh/demister system for cleaning respirable dust at the appropriate flow rates. Because of this, and budgetary constraints, an existing scrubber system for a continuous miner was used, rather than one developed specifically for the high airflow rates used in this study.

It is also important to note that 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. Monitoring points 13-16, located in the return, measure the combined capture and cleaning efficiency of the scrubber.

5.2 Dust Reduction in the Return Airway – Splitter Arm Sprays OFF

Table 5.2 provides a summary of the results for all of the treatment combinations for the return. (Table 5.1 shows the summary data.) Inspection of this table shows that four terms are significant: the intercept, the inlet extension (A), the scrubber capacity (B), and the face-air velocity (C). Each of these has a positive effect on the dust reduction, i.e., the high level of the factor improves performance. There is no significant interaction among factors. EQ 5.10 shows the resulting regression equation.

Table 5.2. Regression model parameter estimates for return airway – splitter arm sprays OFF

$R^2 = 0.95$					
Term	**Estimate**	**Std Error**	**t-ratio**	**Critical Value**	**P-Value**
Intercept	37.4054	0.5643	66.28	2.739	< 0.0001*
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

$$\hat{y} = 37.405 + 3.067a + 12.455b + 3.437c \qquad \text{EQ 5. 10}$$

Table 5.2 also shows the coefficient of determination, R^2. The coefficient of determination is 0.95, meaning (loosely) that the model predicts 95% of the observed variability.

The best scrubber performance is under the following conditions: inlet extension included, 100% scrubber capacity, and 700 fpm (3.56 m/s) face-air velocity. For these operating conditions, the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 37.405 + 3.067[+1] + 12.455[+1] + 3.437[+1] = 56.36\%$$

Comparing this value with the experimental test result of 56.99% reduction shown for the **abc**, (all factors at the high level) average in Table 5.1 shows very good prediction by the model.

By examination of the regression equation, the lowest performance is when each factor is at the low level, i.e., inlet extension removed, 50% scrubber capacity, and 500 fpm (2.54 m /s) face-air velocity. The regression model predicts the following reduction in dust concentration:

$$\hat{y} = 37.405 + 3.067[-1] + 12.455[-1] + 3.437[-1] = 18.45\%$$

Comparing this value with the experimental test result of 21.17% reduction shown for the (1) average, i.e., all factors at the low level, in Table 5.1, shows good prediction by the model.

5.3 Dust Reduction in Walkway – Splitter Arm Sprays OFF

The second major area that was investigated is the scrubber's potential for reducing dust in the walkway. For this analysis, the regression model was determined from the average dust reduction of locations 1, 2, 3, and 8 combined (locations shown in Figure 4.37), because these are likely locations for mine personnel to be working. Summary data is included in Table 5.3. Note that the summary data for each run is the average of the four PDMs located in the walkway. Appendix B shows how these average values were determined.

Table 5.3. Summary of results for walkway (Locations 1, 2, 3, and 8) – 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	Averages	Totals
(1)	-1	-1	-1	28.76	27.37	32.55	32.93	28.46	30.01	150.07
a	1	-1	-1	39.02	37.45	41.35	40.88	35.12	38.76	193.82
b	-1	1	-1	50.38	56.41	53.62	58.82	59.69	55.78	278.92
c	-1	-1	1	42.22	45.81	39.83	39.24	30.21	39.46	197.31
ab	1	1	-1	78.50	69.52	74.27	76.77	78.00	75.41	377.06
ac	1	-1	1	57.54	46.87	48.38	61.14	62.32	55.25	276.26
bc	-1	1	1	60.62	61.01	54.96	55.71	69.68	60.40	301.98
abc	1	1	1	78.64	82.17	69.21	64.56	73.61	73.64	368.19

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

Table 5.4 shows the regression model estimates and EQ 5.11 shows the regression model. Inspection of this table shows that five terms are significant: the intercept, the inlet extension (A), the scrubber capacity (B), the face-air velocity (C), and the scrubber capacity/face-air velocity (BC) interaction.

Table 5.4. Regression model parameter estimates for walkway (average of locations 1, 2, 3, 8) – splitter arm sprays OFF

$R^2 = 0.92$					
Term	**Estimate**	**Std Error**	**t-ratio**	**Critical Value**	**P-Value**
Intercept	53.590	0.8119	66.01	2.739	<0.0001*
A	7.176	0.8119	8.84	2.739	<0.0001*
B	12.717	0.8119	15.66	2.739	<0.0001*
C	3.597	0.8119	4.43	2.739	0.0001*
AB	1.041	0.8119	1.28	2.739	0.2089
AC	0.0818	0.8119	0.10	2.739	0.9204
BC	-2.887	0.8119	-3.56	2.739	0.0012*
ABC	-1.678	0.8119	-2.07	2.739	0.0469

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

$$\hat{y} = 53.590 + 7.176a + 12.717b + 3.597c - 2.887bc \qquad \text{EQ 5. 11}$$

Inspection of EQ 5.11 shows that the scrubber performance is highest when all factors are at the high level; however, performance with the scrubber inlet extension included, scrubber capacity at 100%, and low face-air velocity is very close to the maximum (because of the **bc** interaction), with the difference being only (2)(3.597-2.887) = 1.42% lower. For example, the best predicted performance (with all factors at the high level) is

$$\hat{y} = 53.590 + 7.176[+1] + 12.717[+1] + 3.597[+1] - 2.887[+1][+1] = 74.19\%$$

compared with

$$\hat{y} = 53.590 + 7.176[+1] + 12.717[+1] + 3.597[-1] - 2.887[+1][-1] = 72.77\%$$

with the face-air velocity at the low level and other factors at the high level.

Comparing these predictions with the experimental results of 73.64% with all factors at the high level and 75.41% with the face-air velocity at the low level and the other factors at the high level shows good prediction by the regression model. (Note that the experimental data shows a slightly higher dust reduction when the face-air velocity is at the low level because of experimental error for which the regression model does not account.)

The practical interpretation of these results is that the face air velocity has very little impact on scrubber performance when the inlet extension is included and the scrubber fan is at 100% capacity.

By examination of the regression equation, the lowest performance is when each factor is at the low level, i.e., inlet extension removed, 50% scrubber capacity, 500 fpm (2.54 m/s) face-air velocity. For these conditions, the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 53.590 + 7.176[-1] + 12.717[-1] + 3.597[-1] - 2.887[-1][-1] = 27.21\%$$

Comparing this value with the experimental test result of 30.01% reduction shown for all factors at the low level, reported in Table 5.3, shows good prediction by the model.

5.4 Dust Reduction in Face Area – Splitter Arms Sprays OFF

Locations 7 and 12 were used to determine dust reduction along the face. (See Figure 4.37.) Table 5.5 shows the summary of experimental results. Note that the average value for each run was determined in a manner similar to that used for the walkway.

Table 5.5. Summary of results for face area (Locations 7 and 12) – 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	Averages	Totals
(1)	-1	-1	-1	17.25	14.19	13.69	5.56	5.51	11.24	56.19
a	1	-1	-1	21.28	12.85	15.07	20.28	11.99	16.29	81.46
b	-1	1	-1	-0.01	-2.56	0.66	2.30	11.88	2.45	12.26
c	-1	-1	1	15.57	14.89	16.04	14.80	11.55	14.57	72.86
ab	1	1	-1	33.96	35.49	34.52	26.44	29.98	32.07	160.37
ac	1	-1	1	22.03	25.27	25.40	23.72	16.20	22.52	112.61
bc	-1	1	1	51.30	50.39	38.64	44.54	37.71	44.52	222.59
abc	1	1	1	66.31	65.10	63.61	54.19	61.01	62.05	310.23

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

Table 5.6 shows the regression model estimates, and EQ 5.12 shows the regression model. Inspection of Table 5.6 shows that six terms are significant: the intercept, the inlet extension (A), the scrubber capacity (B), the face-air velocity (C), the inlet extension/scrubber capacity interaction (AB), and the scrubber capacity/face-air velocity (BC) interaction.

Table 5.6. Regression model parameter estimates for face area (average of locations 7 and 12) – splitter arm sprays OFF

$R^2 = 0.95$					
Term	**Estimate**	**Std Error**	**t-ratio**	**Critical Value**	**P-Value**
Intercept	25.714	0.7360	34.94	2.739	<0.0001*
A	7.519	0.7360	10.22	2.739	<0.0001*
B	9.558	0.7360	12.99	2.739	<0.0001*
C	10.200	0.7360	13.86	2.739	<0.0001*
AB	4.268	0.7360	5.80	2.739	<0.0001*
AC	-1.150	0.7360	-1.56	2.739	0.1282
BC	7.809	0.7360	10.61	2.739	<0.0001*
ABC	-1.874	0.7360	-2.55	2.739	0.0159*

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

$$\hat{y} = 25.714 + 7.519a + 9.558b + 10.200c + 4.268ab + 7.809bc \qquad \text{EQ 5. 12}$$

Inspection of EQ 5.12 shows that the best performance is when all factors are at the high level, i.e., the inlet extension included, the scrubber capacity at 100%, and face velocity at 700 fpm (3.56 m/s). Under these conditions the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 25.714 + 7.519[1] + 9.558[1] + 10.200[1] + 4.268[1][1] + 7.809[1][1] = 65.07\%$$

Comparing this value with the experimental test result of 62.05% (shown in Table 5.5) shows good prediction by the model.

By examination of the regression equation, the lowest performance is for the following conditions: inlet extension removed, 100% scrubber capacity, and 500 fpm (2.54 m /s) face-air velocity. For these conditions, the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 25.714 + 7.519[-1] + 9.558[1] + 10.200[-1] + 4.268[-1][1] + 7.809[1][-1] = 5.48\%$$

Comparing this value with the experimental test result of 2.45% shown in Table 5.5 for these conditions shows good prediction by the model.

5.5 Dust Reduction above Shearer Body – Splitter Arm Sprays OFF

The next area to examine consisted of the six dust monitoring locations above the shearer body. As shown in Figure 4.37, these include locations 4, 5, 6, 9, 10, and 11. As reported in Table 4.6, locations 4-6 are 252 in. (6.40 m) from the headgate drum hub and locations 9-11 are 474 in.

(12.04 m) from the headgate drum hub. Each row, i.e., 4-6 and 9-11 was analyzed separately to determine if there were any trends in dust reduction. The row consisting of monitoring points 4-6 is identified as the scrubber because those points are located above the scrubber module; the row consisting of monitoring points 9-11 is identified as the tailgate because it is located above the tailgate module. Note that all locations are upwind of the scrubber outlet.

Dust Reduction above Scrubber Module. Table 5.7 shows a summary of the experimental results for the shearer body above the scrubber module, locations 4-6.

Table 5.7. Summary of results for shearer body above scrubber (Locations 4, 5, and 6) – 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	Averages	Totals
(1)	-1	-1	-1	16.82	6.92	6.36	-4.04	1.68	5.55	27.74
a	1	-1	-1	21.38	14.78	22.35	14.25	10.06	16.56	82.82
b	-1	1	-1	3.73	-8.67	-8.42	-9.00	5.00	-3.47	-17.37
c	-1	-1	1	15.03	15.19	18.86	18.53	13.51	16.23	81.13
ab	1	1	-1	40.27	26.73	27.74	30.76	25.13	30.12	150.62
ac	1	-1	1	34.34	34.17	26.57	33.87	10.26	27.84	139.21
bc	-1	1	1	31.87	38.24	22.34	34.03	36.76	32.65	163.25
abc	1	1	1	69.08	60.78	57.49	54.32	52.19	58.77	293.86

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

Table 5.8 shows the regression model estimates and EQ 5.13 shows the regression model. Inspection of Table 5.8 shows that there are six terms in the regression model that are significant.

Table 5.8. Regression model parameter estimates for shearer body above scrubber (Locations 4, 5, and 6) – splitter arm sprays OFF

$R^2 = 0.90$					
Term	Estimate	Std Error	t-ratio	Critical Value	P-Value
Intercept	23.031	1.0748	21.43	2.739	<0.0001
A	10.294	1.0748	9.58	2.739	<0.0001
B	6.487	1.0748	6.04	2.739	<0.0001
C	10.841	1.0748	10.09	2.739	<0.0001
AB	4.636	1.0748	4.31	2.739	0.0001
AC	-0.860	1.0748	-0.8	2.739	0.4297
BC	5.352	1.0748	4.98	2.739	<0.0001
ABC	-1.010	1.0748	-0.94	2.739	0.3546

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

$$\hat{y} = 23.031 + 10.294a + 6.487b + 10.841c + 4.636ab + 5.352bc \qquad \text{EQ 5. 13}$$

Inspection of EQ 5.13 shows that the best performance is when all factors are at the high level, i.e., the inlet extension included, the scrubber capacity at 100%, and face velocity at 700 fpm (3.56 m/s). Under these conditions the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 23.031 + 10.294[1] + 6.487[1] + 10.841[1] + 4.636[1][1] + 5.352[1][1] = 60.64\%$$

Comparison of this value with the experimental test result of 58.77% (shown in Table 5.7) shows good prediction by the model.

By examination of the regression equation, the lowest performance is with the scrubber inlet removed, the scrubber at 100% capacity, and face-air velocity at 500 fpm (2.54 m/s). For these conditions, the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 23.031 + 10.294[-1] + 6.487[1] + 10.841[-1] + 4.636[-1][1] + 5.352[1][-1] = -1.61\%$$

Comparing this value with the experimental test result of -3.47%, shown in Table 5.7 for these conditions, shows good prediction by the model.

Dust Reduction above Tailgate Module. Table 5.9 shows a summary of the experimental results for locations 9-11, representing the area above the shearer tailgate module.

Table 5.9. Summary of results for shearer body above tailgate module (Locations 9, 10, and 11)

Treatment Combinations	Design Factors			Reduction in Dust Concentration (%)						
	A	B	C	Run 1	Run 2	Run 3	Run 4	Run 5	Averages	Totals
(1)	-1	-1	-1	33.17	30.38	32.85	34.49	33.66	32.91	164.55
a	1	-1	-1	---	43.02	44.60	41.15	36.23	41.25	165.00
b	-1	1	-1	77.75	71.09	72.25	77.17	70.89	73.83	369.15
c	-1	-1	1	36.11	42.72	40.81	35.22	25.67	36.10	180.52
ab	1	1	-1	87.48	72.97	79.33	83.17	74.66	79.52	397.61
ac	1	-1	1	48.14	48.63	41.70	47.27	40.45	45.24	226.19
bc	-1	1	1	78.98	79.54	62.74	69.29	66.19	71.35	356.74
abc	1	1	1	85.97	83.22	83.04	74.25	79.19	81.13	405.66

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

Table 5.10 shows the regression model estimates and EQ 5.14 shows the regression model. Inspection of Table 5.10 shows that, besides the intercept, the only significant terms are the main effects of the inlet extension and scrubber capacity.

Table 5.10. Regression model parameter estimates for shearer body above tailgate module (Locations 9, 10, and 11)

$R^2 = 0.95$					
Term	**Estimate**	**Std Error**	**t-ratio**	**Critical Value**	**P-Value**
Intercept	57.667	0.8082	71.35	2.744	<0.0001
A	4.119	0.8082	5.10	2.744	<0.0001
B	18.792	0.8082	23.25	2.744	<0.0001
C	0.789	0.8082	0.98	2.744	0.3366
AB	-0.250	0.8082	-0.31	2.744	0.7594
AC	0.611	0.8082	0.76	2.744	0.4555
BC	-1.006	0.8082	-1.25	2.744	0.2224
ABC	0.412	0.8082	0.51	2.744	0.6135

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

$$\hat{y} = 57.667 + 4.119a + 18.792b \qquad \text{EQ 5. 14}$$

Inspection of EQ 5.14 shows that the best performance is with the inlet extension included and the scrubber at 100% capacity. Under these conditions, with the face air velocity at either 500 fpm (2.54 m/s) or 700 fpm (3.56 m/s) the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 57.667 + 4.119[1] + 18.792[1] = 80.58\%$$

Comparing this value with the experimental test results of 79.52%, with face-air velocity at 500 fpm (2.54 m/s) and 81.13% with face-air velocity at 700 fpm (3.56 m/s), shown in Table 5.9, shows good prediction by the model.

By examination of the regression equation, the lowest performance is with the scrubber inlet removed and the scrubber at 50% capacity. For these conditions, the regression model predicts the following reduction in dust concentration:

$$\hat{y} = 57.667 + 4.119[-1] + 18.792[-1] = 34.76\%$$

Comparison of this value with the experimental test results of 32.91% with face-air velocity at 500 fpm (2.54 m/s) and 36.10% with face-air velocity at 700 fpm (3.56 m/s), shown in Table 5.9, shows good prediction by the model.

5.6 Impact of Scrubber with Splitter Arm Sprays ON

The analysis presented thus far was from results while the splitter arm sprays were OFF. This is because researchers are primarily interested in determining the effect of the scrubber without the assistance of the splitter-arm water sprays directing dust away from the walkway and toward the scrubber. In addition, future planned research efforts include CFD modeling of this system, and the initial efforts will be with no splitter-arm sprays because of the difficulty in modeling the water sprays.

However, it is recognized that splitter arm (shearer-clearer) sprays are very common on longwall systems. In addition, because the tests conditions were established in the sequence shown in Table 4.7, it is possible to determine the performance of the scrubber with the splitter-arm sprays ON. Therefore, analysis was conducted on dust reduction in the return and walkway with splitter arm sprays ON. For this analysis, the dust reduction was determined as:

$$\text{Dust Reduction} = \left(1.00 - \left[\frac{C_S}{(C_{01} + C_{02})(0.5)}\right]\right)(100\%) \qquad \text{EQ 5. 15}$$

where,

C_S = dust concentration measured with the scrubber fan and sprays ON and splitter arm sprays ON

C_{01} = dust-only concentration at beginning of test

C_{02} = dust-only concentration at end of test

Note that no other test conditions, i.e., factors or levels, were changed.

Dust Reduction in Return. The first situation studied is the dust reduction in the return with the splitter arm water sprays ON. Table 5.11 shows the summary of the results for each combination of factors plus the averages and totals. Table 5.12 shows the regression model parameter estimates and EQ 5.16 shows the resulting regression model.

Table 5.11. Summary of results for return airway – splitter arm sprays ON

Treatment Combinations	Design Factors			Reduction in Dust Concentration (%)						
	A	B	C	Run 1	Run 2	Run 3	Run 4	Run 5	Averages	Totals
(1)	-1	-1	-1	33.40	34.97	28.56	30.88	27.94	31.15	155.74
a	1	-1	-1	28.26	25.28	31.93	41.44	31.49	31.68	158.41
b	-1	1	-1	52.85	56.41	44.54	53.85	57.70	53.07	265.34
c	-1	-1	1	23.13	22.62	27.61	25.15	20.84	23.87	119.35
ab	1	1	-1	58.09	56.79	59.91	59.73	56.82	58.27	291.34
ac	1	-1	1	39.90	40.17	42.69	35.95	38.72	39.49	197.43
bc	-1	1	1	51.01	50.05	48.25	46.97	54.81	50.22	251.09
abc	1	1	1	63.19	66.66	57.99	58.89	60.37	61.42	307.09

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

Table 5.12. Regression model parameter estimates for return airway – splitter arm sprays ON

$R^2 = 0.94$					
Term	**Estimate**	**Std Error**	**t-ratio**	**Critical Value**	**P-Value**
Intercept	43.645	0.5843	74.70	2.739	<0.0001
A	4.069	0.5843	6.96	2.739	<0.0001
B	12.098	0.5843	20.71	2.739	<0.0001
C	0.103	0.5843	0.18	2.739	0.8610
AB	0.031	0.5843	0.05	2.739	0.9575
AC	2.636	0.5843	4.51	2.739	<0.0001
BC	-0.028	0.5843	-0.05	2.739	0.9618
ABC	-1.135	0.5843	-1.94	2.739	0.0609

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

$$\hat{y} = 43.645 + 4.069a + 12.098b + 2.636ac \qquad \text{EQ 5. 16}$$

Inspection of EQ 5.16 shows that the best performance is with the inlet extension included, scrubber capacity at 100%, and face velocity at 700 fpm (3.56 m/s). Under these conditions, the model predicts a reduction in dust concentration of

$$\hat{y} = 43.645 + 4.069[1] + 12.098[1] + 2.636[1][1] = 62.45\%$$

Comparing this with the experimental result of 61.42% shows very good agreement.

Inspection of EQ 5. 15 shows that the lowest performance is with the inlet extension removed, scrubber capacity at 50%, and face velocity at 700 fpm (3.56 m/s). Under these conditions, the model predicts the following reduction in dust concentration:

$$\hat{y} = 43.645 + 4.069[-1] + 12.098[-1] + 2.636[-1][1] = 24.84\%$$

Comparing this with the experimental result of 23.87% shows good prediction by the model.

Dust reduction in walkway. The other situation studied with splitter arm sprays ON is the dust reduction in the walkway. Table 5.13 shows the summary of the results for each combination of factors plus the averages and totals. Table 5.14 shows the regression model parameter estimates, and EQ 5.17 shows the resulting regression model.

Table 5.13. Summary of results for walkway (locations 1, 2, 3, 8) – splitter arm sprays ON

Treatment Combinations	Design Factors			Reduction in Dust Concentration (%)						
	A	B	C	Run 1	Run 2	Run 3	Run 4	Run 5	Averages	Totals
(1)	-1	-1	-1	93.84	92.78	93.60	92.97	90.68	92.78	463.88
a	1	-1	-1	83.52	81.13	85.45	94.08	88.39	86.51	432.57
b	-1	1	-1	94.93	97.10	93.92	96.31	96.11	95.67	478.37
c	-1	-1	1	89.51	93.65	85.38	79.04	81.81	85.88	429.38
ab	1	1	-1	97.01	97.10	98.33	97.77	96.24	97.29	486.45
ac	1	-1	1	90.65	89.74	93.43	86.93	92.79	90.71	453.53
bc	-1	1	1	88.64	90.35	83.65	88.91	92.83	88.88	444.38
abc	1	1	1	101.20	95.47	90.09	89.25	95.12	94.22	471.12

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

Table 5.14. Regression model parameter estimates for walkway (locations 1, 2, 3, 8) – splitter arm sprays ON

$R^2 = 0.60$					
Term	**Estimate**	**Std Error**	**t-ratio**	**Critical Value**	**P-Value**
Intercept	91.492	0.5709	160.26	2.739	<0.0001
A	0.692	0.5709	1.21	2.739	0.2344
B	2.524	0.5709	4.42	2.739	0.0001
C	-1.571	0.5709	-2.75	2.739	0.0097
AB	1.049	0.5709	1.84	2.739	0.0753
AC	1.853	0.5709	3.25	2.739	0.0027
BC	-0.894	0.5709	-1.57	2.739	0.1270
ABC	-0.920	0.5709	-1.61	2.739	0.1168

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

$$\hat{y} = 91.492 + 2.524b - 1.571c + 1.853ac \qquad \text{EQ 5. 17}$$

Inspection of EQ 5.17 shows that the best performance is with the inlet extension removed, the scrubber capacity at 100%, and face velocity at 500 fpm (2.54 m/s). Under these conditions, the model predicts the following reduction in dust concentration:

$$\hat{y} = 91.492 + 2.524[1] - 1.571[-1] + 1.853[-1][-1] = 97.44\%$$

Comparing this result with the experimental result of 95.67% shows good agreement.

Inspection of EQ 5. 17 shows that the lowest performance is with the inlet extension removed, the scrubber capacity at 50%, and face velocity at 700 fpm (3.56 m/s). Under these conditions, the model predicts a reduction in dust concentration of the following:

$$\hat{y} = 91.492 + 2.524[-1] - 1.571[+1] + 1.853[-1][1] = 85.54\%$$

Comparing this with the experimental result of 85.88% shows good agreement.

Further inspection of EQ 5. 17 shows that the estimate of the intercept is 91.49, and that each of the coefficients is quite small. In addition, the coefficient of determination is 0.60, meaning, loosely, that only 60% of the variability is predicted by the model, which is quite low compared with the previous test results. The interpretation of this is that, under these test conditions, the splitter arm sprays are very effective at preventing dust from entering the walkway, regardless of the treatments used in this study.

5.7 Summary of Experimental Results

Table 5.15 summaries the results of the analyses conducted with the splitter arm sprays OFF, and Table 5.16 summarizes the results with the splitter arm sprays ON. Considering the results with the splitter arm sprays OFF, the scrubber performance is best with the inlet extension included, the scrubber at maximum capacity, and face velocity at 700 fpm (3.56 m/s). One would expect the inlet extension to improve performance because it helps dust to be captured close to where it is liberated. One would also expect performance to be better at the higher scrubber capacity. However, it was somewhat surprising that the best scrubber performance was at the higher face-air velocity. The logical assumption is that the higher face-air velocity helps direct dust to the scrubber inlet compared with the lower face-air velocity, at least for the conditions tested at the NIOSH longwall gallery. This is in spite of the fact that the scrubber capacity is 24% of the face air quantity at 700 fpm (3.56 m/s) compared with 34% of the quantity at 500 fpm (2.54 m/s). (See Table 4.4 for quantities.)

With splitter arm sprays ON, dust reduction in the return is also highest with the inlet extension included, the scrubber at maximum capacity, and face-air velocity at 700 fpm (3.56 m/s). However, performance is only marginally better than that with the splitter arm water sprays OFF, at 62.5% compared with 56.4%. The effect of the scrubber to reduce dust concentrations in the walkway is not as clear. The best performance (97.4% reduction in dust concentration) is with the inlet extension removed, 100% scrubber capacity, and face-air velocity 500 fpm (2.54 m/s). The lowest performance is an 85.5% reduction in dust concentration.

Table 5.15. Summary of scrubber performance with splitter arm sprays OFF

General Location	Dust Monitoring Stations	Treatments for best performance	Maximum Predicted Dust Reduction	Comments
Return	13-16	Inlet extension included 100% scrubber capacity Face air velocity 700 fpm	56.4%	Scrubber capacity is largest effect
Walkway	1, 2, 3, 8	Inlet extension included 100% scrubber capacity Face air velocity 700 fpm	74.2%	Scrubber capacity is largest effect
Face Area	7, 12	Inlet extension included 100% scrubber capacity Face air velocity 700 fpm	65.1%	
Shearer Body above scrubber module	4-6	Inlet extension included 100% scrubber capacity Face air velocity 700 fpm	60.6%	
Shearer Body above tailgate module	9-11	Inlet extension included 100% scrubber capacity	80.6%	No face-air-velocity main effect

Table 5.16. Summary of scrubber performance with splitter arm sprays ON

General Location	Dust Monitoring Stations	Treatments for best performance	Maximum Predicted Dust Reduction	Comments
Return	13-16	Inlet extension included 100% scrubber capacity Face air velocity 700 fpm	62.5%	Scrubber capacity is largest effect No face-air-velocity main effect
Walkway	1, 2, 3, 8	Inlet extension removed 100% scrubber capacity Face air velocity 500 fpm	97.4%	- Correlation coefficient of 0.60 - Intercept of 91.5% - Dust reduction ranges from 85.5% to 97.4% - These results indicate that the splitter arm sprays prevent a significant portion of dust from entering the walkway regardless of the treatments

5.8 Summary of Accomplishments

A full-size mockup of a longwall shearer with an integrated 50-hp flooded-bed dust scrubber was designed and constructed at the University of Kentucky and subsequently transported to NIOSH's Pittsburgh Research Laboratory (PRL) and installed in the PRL longwall gallery. Fifty tests, 10 baseline tests without the scrubber and 40 tests with the scrubber operational, were conducted (by NIOSH personnel) using ThermoFisher Scientific Personal Dust Monitors (PDM 3600 and PDM 3700) to evaluate the performance of the flooded-bed dust scrubber.

The results of the tests indicate that a shearer with an integrated dust scrubber has the potential to be effective at reducing airborne respirable dust concentrations. By analyzing the dust reduction in the return airway, the tests indicate that up to 56% of the respirable dust released near the headgate drum could be captured and cleaned without the assistance of splitter arm water sprays and up to 62% with splitter arm water sprays. The most significant effect is the scrubber capacity.

Results also show that the scrubber can help to reduce dust concentrations in the longwall walkway along the shearer body, where mine personnel are likely to be located. Without the assistance of splitter arm water sprays, the scrubber reduced dust concentrations in the walkway by up to 74%. The most significant factor is the scrubber capacity, followed by the inlet extension. With the assistance of splitter arm sprays, the dust reduction was well over 90%, under the conditions tested.

It must be noted that these results are under controlled laboratory conditions, and not actual mining conditions, e.g., intake dust levels were not being generated, run-of-mine coal was not being cut and loaded, and dust from shield advance was not being liberated.

6.0 Dissemination Efforts and Highlights

A major dissemination highlight is that arrangements have been made with NIOSH to keep the shearer mockup in its longwall dust gallery. The University of Kentucky does not have the facilities for continued testing. Leaving the shearer mockup at the dust gallery will allow NIOSH personnel to continue testing the scrubber and to investigate possible improvements to the present design. Thus, collaborations will occur and information will continue to be disseminated through research presentations and publications.

Additionally, the following are presentations related to the project and papers published:

Professional Presentations:

- Kumar, Ashish Ranjan. 2014. "Application of flooded-bed dust scrubber to a longwall shearer operating in a thin US coal seam." SME Bi-Annual Meeting, Central Appalachian Section, Lexington, KY.
- Novak, T., "Application of Flooded-Bed Scrubber to a Longwall Shearer," Joint Meeting of the West Virginia Mining Institute and the Central Appalachian Section of SME, July 2015.
- Kumar, Ashish, Wedding, W. and Novak, T., "Analysis and Evaluation of the Application of a Flooded-Bed Dust Scrubber to a Longwall Shearer Operating in a US Coal Seam Using Computational Fluid Dynamics," SME Annual Conference and Exposition, Denver, CO, February 15-18, 2015.

- Wedding, W.C. “Longwall Dust Control,” Kentucky Professional Engineers in Mining Seminar, Lexington, KY, September 11, 2015.
- Wedding, W.C. “Research Efforts at the University of Kentucky into Coal Dust Mitigation,” West Virginia Coal Mining Meeting, White Sulphur Springs, WV, (October 22-23, 2015).
- Sottile, J., “Flooded-Bed Dust Scrubber for Coal Mine Longwall Shearer,” CDC/NIOSH Central Appalachian Regional Education and Research Center, September 16, 2016.
- Wedding, W.C. “Longwall Dust Control,” Kentucky Professional Engineers in Mining Seminar, Lexington, KY, August 26, 2016.

Conference Papers:

- Wedding, William Chad, Thomas Novak, Sampurna Arya, and Ashish Kumar. 2015. "CFD modeling of a flooded-bed scrubber concept for a longwall shearer operating in a U.S. coal seam." 15th North American Mine Ventilation Symposium. Blacksburg, Virginia.
- Kumar, Ashish, Wedding, Jolly, A., Arya, S.., and Novak, T., “Modeling Capture Efficiency for a Flooded Bed Dust Scrubber Incorporated into a Longwall Shearer using a Small Scale Physical Model and CFD”, Proceedings of the 2016 SME Annual Conference, February 21-24. Phoenix, AZ, SME.

Invited Article:

- Novak, Thomas, and Wedding, W.C., 2015, “Scrubbed Clean”. World Coal, London, UK, January, 23-26.

Papers Accepted for Publication:

- Ashish Kumar, Sampurna Arya, William Chad Wedding, and Thomas Novak. 2017. “Examination of Capture Efficacies of a Shearer Mounted Flooded Bed Dust Scrubber Using Experiments and Computational Fluid Dynamics (CFD) Modeling on a Reduced Scaled Model”. 16th North American Mine Ventilation Symposium. Denver. Colorado. [Accepted]
- Sampurna Arya, William Chad Wedding, Thomas Novak, Ashish Kumar, and Adam Levy. 2017. “Pressure Drop Measurement across Flooded-Bed Scrubber Screen and Demister in a Laboratory Setup for its Use in a Longwall Shearer”. 16th North American Mine Ventilation Symposium. Denver, Colorado. [Accepted]

Paper in progress:

- Sampurna Arya, William Chad Wedding, Thomas Novak, Ashish Kumar, and Adam Levy "CFD Validation of Air Quantity Surveys in the Longwall Test Gallery at the NIOSH Pittsburgh Research Laboratory"

7.0 Conclusions and Impact Assessment

The overall research objective of this project is the reduction of *respirable dust* and *float dust* in longwall mining systems through the application of flooded-bed dust scrubbers. Using scrubbers to capture and remove dust, addresses two focus areas of the Alpha Foundation – health and safety. Longwall mining, which accounts for more than one-half of the coal produced by underground mines in the U.S., exhibits greater difficulty in maintaining compliance with federally mandated dust regulations, as compared with continuous mining. Moreover, the newly enacted dust rule has exacerbated these difficulties for longwall mine operators.

Researchers at the University of Kentucky worked with a longwall equipment manufacturer, a longwall operator, and other experts to design and fabricate a full-size mockup of a longwall shearer with an integrated 50-hp flooded-bed dust scrubber. The shearer mockup was transported to the NIOSH Pittsburgh Research Laboratory and installed in the Longwall Dust Gallery. This gallery replicates a portion of an actual longwall face with 19 shields, and dust-generating mechanisms for simulating respirable dust produced by a shearer cutting coal. Forty tests, plus 10 base case tests, were conducted using Personal Dust Monitors to measure dust concentrations.

The study indicates that a shearer-mounted scrubber could be very effective at reducing airborne respirable dust. Test results show that up to 56% of the respirable dust released near the headgate drum was captured and cleaned, without the assistance of splitter arm sprays helping to direct dust away from the walkway. The most significant factor is scrubber capacity.

Results show that the scrubber could also help reduce dust concentrations in the longwall walkway. Without the assistance of splitter arm water sprays, the scrubber reduced dust concentration in the walkway by up to 74%. The most significant factor is the scrubber capacity.

While there is still room for improvement in the overall design of the scrubber system, much was learned from the project, and the results demonstrated that the scrubber is capable of significant dust-reduction improvements in longwall mining. However, even with encouraging results, the impact on the health and safety of miners will only occur if the design is implemented into an actual longwall shearer. Information from this project will continue to be disseminated to longwall mine operators, particularly those who are having difficulties meeting the requirements of the new dust regulations. With difficult economic times for the coal industry, the investigators may need to take a long-term outlook and continue to work with longwall equipment manufacturers and mine operators to pursue the goal of developing a functional prototype.

8.0 Recommendations for Future Work

This project has demonstrated the viability of a shearer-mounted dust scrubber for reducing respirable dust at longwall sections. The design can certainly be refined and future research should focus on improving the design of the scrubber and the development of a prototype that could be evaluated in an operating coal mine.

8.1 Additional Data Analysis and CFD Modeling to Optimize Capture Efficiency

The experimental testing was completed in mid-November, 2016; test results were available beginning in December. Although the analysis of results has shown the viability of a shearer-mounted dust scrubber, there is a wealth of information in the results for future study. One task would be to use the results to validate a CFD model with the goal of optimizing the design of a scrubber for capture efficiency. Subsequently, additional testing could be performed.

8.2 Scrubber and Demister Design

Because flooded-bed dust scrubbers have been used successfully on continuous miners for decades, the emphasis of this project was on capture efficiency rather than on the design of the scrubber for cleaning efficiency. However, results of the experiments suggest that the required flow rates for a shearer-mounted scrubber need to be approximately double that of the present-day continuous-miner scrubbers. Therefore, there is the need to develop a mesh and demister for the flow rates used in our experiments, i.e., at least 13,700 cfm.

8.3 Design for the Mine Environment

Although the scrubber was designed considering the mining environment, a stronger emphasis needs to be placed on modifying the design so that it would be capable of handling the larger coal/rock particles that are present on longwall faces. Additional research needs to be done on the inlet location and design to keep large particles from overloading or damaging the scrubber.

8.4 Design of Tailgate Scrubber

This project considered only the dust generated at the headgate-end of the shearer. Assuming that the headgate scrubber is successfully developed, a tailgate scrubber should next be considered. This is a much more difficult task than the development of a headgate scrubber.

8.5 Design of a New Type of Scrubber

The major disadvantage of a flooded-bed scrubber is that the screen gets clogged with particles larger than those of respirable dust and must be replaced or cleaned on a regular schedule. The research team at the University of Kentucky is presently working on the development of a vorticone scrubber for mining applications. This scrubber does not use a screen and has been effectively used in the automotive industry for capturing paint particles, which are comparable in size to respirable coal-dust particles. If successful, this scrubber would have a major benefit to the coal-mining industry since it is essentially maintenance free.

9.0 References

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10.0 Appendices

10.1 Appendix A - Summary of Experimental Test Results

10.2 Appendix B – Method for Determining Average Dust Reduction

10.3 Appendix C – Regression Model Parameters for each Monitoring Location – Splitter Arm Sprays OFF

10.1 Appendix A - Summary of Experimental Test Results

Table A.1. Inlet extension removed, scrubber at 50% capacity, 500 fpm (2.54 m/s) face-air velocity

	Test#				**Scrubber Filter - The Hub + 252"**					**Tailgate - The Hub + 474"**					**Return**			
Date	start time		**Splitter**	**Inlet**	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Top left	Bottom left	Top right	Bottom right
test levels	dust	**Operating condition**	*0506*	*2070*	*2056*	*0507*	*1881*	*0030*	*1495/ 008*	*009A*	*0001*	*0021*	*0054*	*009B*	*0751*	*0814/ 1380*	*1380/ 056*	*1355*
10/4/16	**26**	Dust	25.28	30.25	27.76	20.74	16.76	15.94	16.05	10.21	15.27	17.36	18.71	20.72	9.07	4.88	8.46	7.37
501 fpm	1:00	Fan	22.24	26.13	14.01	18.75	16.75	14.88	11.83	3.43	6.46	11.31	14.25	18.58	8.13	5.16	7.01	9.17
Inlet	2.71	Scrubber	22.91	27.41	16.58	17.95	11.80	15.22	11.91	4.01	7.67	11.61	14.94	19.14	7.17	4.10	6.15	7.31
50%		Splitter	2.47	2.30	0.60	4.07	12.44	18.11	19.46	0.49	1.44	3.95	7.96	16.31	5.66	3.46	4.94	5.98
		Dust	26.49	27.43	26.28	21.56	17.01	16.17	16.01	9.81	14.69	16.56	18.26	21.26	9.26	5.10	8.38	7.68
10/13/16	**36**	Dust	24.40	35.88	23.43	19.98	20.29	16.63	16.93	8.32	9.70	17.28	19.18	18.87	10.94	8.52	4.93	7.55
488 fpm	1:00	Fan	21.20	35.14	11.56	21.94	17.03	15.39	13.49	3.35	4.26	10.99	15.85	18.12	9.09	7.29	5.14	10.22
Inlet	2.66	Scrubber	21.44	34.64	14.67	21.39	16.64	14.45	12.99	4.01	5.12	12.62	16.64	18.05	7.38	5.21	3.96	6.64
50%		Splitter	2.99	3.98	0.58	3.13	12.04	18.63	24.59	0.29	0.72	2.73	7.17	15.53	6.09	4.87	3.36	6.35
		Dust	25.78	34.50	24.19	20.02	18.26	16.99	16.94	9.48	10.30	18.16	19.30	19.15	11.09	7.59	5.22	7.75
10/14/16	**38**	Dust	23.60	29.66	19.50	17.85	13.46	15.75	14.91	9.21	14.92	17.09	18.33	16.10	9.02	7.63	5.00	4.89
496 fpm	10:00	Fan	18.98	30.09	10.65	19.21	12.33	14.84	12.15	2.66	6.26	11.71	15.86	15.95	8.31	8.12	4.84	7.76
Inlet	2.57	Scrubber	17.75	30.51	10.88	18.44	11.87	13.85	11.53	2.98	6.86	12.21	15.98	15.65	6.76	6.11	3.84	5.55
50%		Splitter	2.02	2.69	0.65	2.72	9.26	18.90	23.66	0.38	0.85	3.12	6.89	13.20	5.67	5.39	3.32	5.33
		Dust	21.26	31.27	18.97	18.67	13.20	14.73	15.31	8.33	14.60	17.70	19.37	16.41	9.17	7.92	5.68	5.83
10/19/16	**45**	Dust	20.12	39.00	28.05	19.16	17.46	16.14	13.72	7.52	14.08	16.87	16.76	17.23	9.13	8.59	5.67	5.85
498 fpm	10:00	Fan	17.34	35.89	10.81	22.01	18.78	15.22	11.99	2.73	5.74	10.56	13.48	16.90	7.25	7.84	4.84	7.17
Inlet	2.9	Scrubber	16.99	35.71	12.41	21.81	18.58	15.45	12.17	3.12	6.08	11.04	13.61	16.93	6.19	6.23	4.39	5.56
50%		Splitter	2.29	3.39	0.42	2.16	11.13	17.83	23.61	0.45	1.46	2.46	5.60	15.79	5.57	5.45	3.94	4.89
		Dust	21.02	34.53	26.44	18.12	19.55	16.49	13.75	6.98	12.55	16.35	15.48	16.52	8.84	8.34	5.39	5.61
11/1/16	**61**	Dust	23.02	44.69	26.09	23.38	16.57	12.04	16.97	8.58	14.99	17.73	17.77	19.84	7.57	7.16	4.82	6.52
510 fpm	10:00	Fan	17.92	42.35	17.27	25.20	21.50	10.56	16.90	3.01	7.17	12.17	15.89	20.48	6.97	7.78	4.67	7.14
Inlet	2.3	Scrubber	19.81	40.66	18.24	23.16	20.89	10.45	17.62	3.96	7.87	12.43	14.68	19.51	5.94	6.21	3.90	5.91
50%		Splitter	1.10	3.72	5.39	3.00	12.81	22.06	22.43	0.39	1.08	2.86	7.69	17.84	4.98	5.63	3.49	5.57
		Dust	27.15	40.67	28.37	24.81	18.78	13.87	19.76	9.06	15.69	18.56	19.32	22.10	8.25	7.99	5.32	6.98

Table A.2. Inlet extension added, scrubber at 50% capacity, 500 fpm (2.54 m/s) face-air velocity

					Scrubber Filter - The Hub +252"					**Tailgate - The Hub + 474"**					**Return**			
Date test levels	**Test#** start time dust	**Operating condition**	**Splitter** *0506*	**Inlet** *2070*	Walkway *2056*	Mid-walkway *0507*	Mid-shearer *1881*	Mid-face *0030*	Face *1495/008*	Walkway *009A*	Mid-walkway *0001*	Mid-shearer *0021*	Mid-face *0054*	Face *009B*	Top left *0751*	Bottom left *0814/1380*	Top right *1380/056*	Bottom right *1355*
9/19/16	**2**	Dust	25.55	45.01	22.90	23.96	22.94	13.52	11.34	8.77	8.71		17.24	18.59	9.24	6.58	4.67	6.08
492 fpm	1:00	Fan	21.16	35.40	14.66	14.75	16.84	12.28	9.99	3.12	4.05		10.53	14.75	8.87	6.98	4.60	8.73
Extension	2.87	Scrubber	22.46	35.94	8.21	15.08	17.21	12.02	9.10	3.43	4.24		11.07	14.04	6.80	5.15	3.63	5.77
50%		Splitter	7.20	11.56	0.00	7.82	17.24	21.57	14.68	1.03	1.68		8.59	17.13	5.77	4.42	3.33	5.05
		Dust	26.50	43.64	22.93	21.80	20.09	13.21	11.33	8.09	7.84		15.88	17.82	9.00	6.20	4.19	5.80
9/20/16	**3**	Dust	20.30	36.81	19.49	24.12	17.42	10.18	7.26	7.00	12.68	16.93	20.76	16.39	6.54	6.34	5.30	3.78
502 fpm	8:00	Fan	12.21	26.67	8.68	12.94	12.29	7.87	4.98	1.87	4.68	7.88	11.43	11.94	5.26	5.52	4.81	4.14
Extension	2.46	Scrubber	16.70	33.11	11.42	15.90	15.77	10.34	7.53	2.62	6.21	10.08	14.25	14.62	5.24	4.99	4.56	3.89
50%		Splitter	5.89	10.57	1.98	7.99	17.79	23.30	11.85	0.93	2.54	5.86	12.33	16.99	4.81	4.61	4.27	3.72
		Dust	24.38	41.01	21.78	24.75	14.05	12.73	9.34	7.97	13.76	17.64	22.66	18.60	7.86	7.07	5.60	4.13
9/21/16	**8**	Dust	32.84	43.29	27.25	25.40	25.58	16.77	12.76	11.04	14.42	17.82	21.87	19.61	8.35	7.04	7.56	5.95
493 fpm	1:00	Fan	20.89	29.76	13.92	17.27	24.80	14.77	11.38	3.37	5.86	9.41	12.84	15.06	8.18	7.52	6.80	7.51
Extension	2.79	Scrubber	21.92	30.56	14.87	17.82	17.05	14.79	11.20	3.84	6.35	9.76	12.97	15.15	6.44	5.60	5.19	5.41
50%		Splitter	3.45	3.80	8.13	4.87	11.27	19.24	24.58	0.72	1.89	4.19	7.67	14.73	5.10	4.63	4.36	4.90
		Dust	32.49	40.10	23.81	23.11	22.54	16.61	12.06	10.28	13.20	16.10	19.50	18.47	7.83	6.67	6.94	5.50
10/17/16	**41**	Dust	25.42	40.44	24.83	19.31	19.64	13.55	12.90	8.48	13.38	16.92	19.64	16.90	8.91	7.36	4.13	6.65
480 fpm	1:00	Fan	19.37	34.37	13.95	18.34	17.69	12.10	10.28	2.88	5.58	9.84	14.96	15.71	7.88	7.23	5.33	6.10
Extension	2.01	Scrubber	18.40	33.74	14.52	17.21	17.33	11.68	9.94	3.28	5.96	10.26	14.65	15.22	6.00	5.21	3.75	4.53
50%		Splitter	2.42	3.07	0.87	3.91	12.71	18.24	19.90	0.41	1.28	3.66	8.50	13.71	4.76	4.46	3.60	3.80
		Dust	30.72	45.73	27.49	20.00	20.18	14.72	14.28	9.19	13.84	17.39	20.51	18.38	9.66	8.13	4.69	7.26
10/18/16	**43**	Dust	33.87	54.53	26.03	21.46	26.43	16.42	14.00	12.45	14.86	19.22	21.56	17.98	9.09	6.77	7.23	5.17
493 fpm	10:00	Fan	24.61	40.58	12.92	18.12	22.10	14.68	11.78	4.51	6.20	10.74	15.07	15.48	7.60	7.00	6.30	6.24
Extension	2.69	Scrubber	26.24	43.23	14.98	19.02	23.02	14.64	11.94	4.57	7.05	12.99	16.04	16.53	6.59	5.63	5.18	4.87
50%		Splitter	4.52	5.55	1.53	6.96	21.42	23.50	27.10	1.98	2.00	5.50	12.20	18.58	5.46	4.85	4.78	4.41
		Dust	31.80	47.69	25.31	20.63	23.12	17.41	14.23	12.51	14.80	18.65	21.11	18.19	9.18	6.89	7.46	5.13

Table A.3. Inlet extension removed, scrubber at 100% capacity, 500 fpm (2.54 m/s) face-air velocity

Date test levels	Test# start time dust	Operating condition	Splitter	Inlet	Scrubber Filter - The Hub + 252"					Tailgate - The Hub + 474"					Return			
					Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Top left	Bottom left	Top right	Bottom right
			0506	*2070*	*2056*	*0507*	*1881*	*0030*	*1495/ 008*	*009A*	*0001*	*0021*	*0054*	*009B*	*0751*	*0814/ 1380*	*1380/ 056*	*1355*
9/26/16	**11**	Dust	23.09	19.09	21.93	20.45	21.67	14.53	13.09	9.27	13.22	15.04	18.26	13.34	7.79	7.12	7.51	4.46
495 fpm	1:00	Fan	13.39	19.06	2.53	10.80	22.25	16.37	16.13	0.34	0.74	2.21	5.63	8.91	7.50	7.49	6.76	6.58
Inlet	2.67	Scrubber	17.83	20.42	3.12	11.84	23.75	17.48	16.80	0.62	1.09	3.23	6.75	9.91	4.22	4.04	4.12	3.62
100%		Splitter	2.66	1.11	0.24	0.56	2.43	10.89	17.51	0.24	0.52	1.00	2.52	4.83	3.43	3.39	3.19	3.09
		Dust	24.90	20.24	23.08	19.75	21.39	14.69	13.41	9.59	13.53	15.10	18.03	13.73	7.88	7.46	8.03	5.27
10/4/16	**24**	Dust	16.06	31.17	22.08	18.49	13.35	11.56	11.91	6.88	12.46	15.08	16.94	15.77	7.11	6.10	5.45	5.68
506 fpm	8:00	Fan	9.89	26.82	2.05	11.10	16.62	15.55	11.46	0.50	0.99	3.48	7.46	13.23	7.25	6.10	6.14	7.18
Inlet	2.59	Scrubber	12.10	28.82	2.64	12.79	17.48	15.36	11.77	0.49	1.40	4.37	8.60	15.42	3.80	3.13	3.33	3.64
100%		Splitter	1.09	0.98	-0.25	0.52	5.90	12.63	16.30	0.27	0.40	1.45	3.60	15.26	3.18	2.53	2.93	2.45
		Dust	21.04	31.87	25.10	19.61	11.39	14.56	na	8.05	13.65	16.51	18.62	13.24	7.95	6.10	6.53	5.96
10/18/16	**42**	Dust	22.42	35.81	22.86	17.96	15.92	13.08	12.12	8.65	13.79	10.82	17.00	14.65	7.22	5.51	4.73	4.09
494 fpm	8:00	Fan	14.18	33.81	2.78	12.71	20.93	16.56	14.59	0.95	0.87	4.50	7.66	11.10	7.28	6.30	5.35	5.77
Inlet	2.56	Scrubber	15.59	37.41	3.41	14.79	23.61	18.46	16.67	1.35	1.18	3.94	8.94	12.50	4.69	3.73	3.46	3.48
100%		Splitter	2.80	2.69	0.23	0.68	5.92	11.34	22.56	0.54	0.43	1.35	3.25	7.41	4.10	3.33	3.05	3.18
		Dust	28.03	41.33	28.48	20.90	20.81	17.53	15.21	11.47	15.88	18.11	20.19	17.97	9.10	6.63	7.02	4.94
10/20/16	**46**	Dust	23.17	39.60	31.23	21.91	11.48	15.56	12.84	7.83	14.93	19.43	19.97	17.98	7.98	8.49	4.82	4.64
493 fpm	10:00	Fan	11.57	32.69	2.89	12.58	37.54	15.45	14.98	0.39	0.92	3.17	7.49	11.07	6.83	7.39	4.80	5.88
Inlet	2.4	Scrubber	12.27	33.71	3.60	14.20	23.59	15.63	15.56	0.54	1.08	3.54	8.30	12.07	4.17	4.50	2.87	3.51
100%		Splitter	1.47	1.74	0.22	0.35	4.28	9.08	16.27	0.21	0.54	0.99	2.38	5.50	3.19	3.58	2.15	2.77
		Dust	21.45	34.66	29.45	19.69	18.72	14.92	12.05	7.52	14.53	17.76	19.43	16.34	7.51	7.92	4.86	4.45
11/3/16	**64**	Dust	18.98	41.32	26.18	23.93	26.52	16.28	15.62	8.89	15.38	15.99	23.89	22.17	9.91	9.08	10.23	9.21
519 fpm	10:00	Fan	11.17	35.62	3.22	15.40	25.58	18.52	18.24	0.12	1.05	5.78	10.11	13.96	8.74	8.73	8.78	8.64
Inlet	2.95	Scrubber	9.78	36.06	4.15	19.20	25.03	16.97	17.50	0.57	1.31	5.25	11.18	15.00	4.80	5.05	4.91	5.05
100%		Splitter	1.41	1.84	0.12	0.58	6.84	15.32	24.18	0.28	0.22	1.12	3.23	8.01	3.97	4.06	4.34	4.05
		Dust	17.65	42.02	28.68	22.35	25.00	16.10	16.79	9.54	15.96	17.16	23.43	21.76	9.87	9.55	10.32	9.48

Table A.4. Inlet extension removed, scrubber at 50% capacity, 700 fpm (3.55 m/s) face-air velocity

Date test levels	**Test#** start time dust	**Operating condition**	**Splitter** 0506	**Inlet** 2070	**Scrubber Filter - The Hub + 252"** Walkway 2056	Mid-walkway 0507	Mid-shearer 1881	Mid-face 0030	Face 1495/ 008	**Tailgate - The Hub + 474"** Walkway 009A	Mid-walkway 0001	Mid-shearer 0021	Mid-face 0054	Face 009B	**Return** Top left 0751	Bottom left 0814/ 1380	Top right 1380/ 056	Bottom right 1355
9/28/16	**15**	Dust	0.48	14.23	3.53	12.72	13.52	6.16	8.40	1.57	3.53	8.29	11.47	8.59	4.86	3.56	5.35	4.95
756 fpm	8:00	Fan	0.26	9.34	1.22	12.01	10.43	5.22	7.14	0.23	1.68	4.73	9.32	7.75	4.39	3.98	5.26	5.40
Inlet	2.08	Scrubber	0.43	10.20	1.45	12.97	11.40	5.16	7.10	0.59	1.84	5.32	10.08	8.18	3.75	3.15	4.35	4.20
50%		Splitter	0.12	0.81	0.18	6.42	17.85	14.07	4.89	0.13	0.68	3.59	10.93	13.11	3.68	3.08	4.29	4.07
		Dust	0.49	15.27	4.11	13.07	13.63	8.53	9.53	1.67	4.20	9.14	12.77	9.67	5.10	4.19	5.52	5.83
10/20/16	**40**	Dust	0.69	22.21	4.01	16.76	16.12	6.54	8.82	1.21	3.65	11.40	14.03	9.09	3.80	4.07	4.22	3.55
722 fpm	8:00	Fan	0.86	12.51	1.64	13.10	13.39	6.13	7.86	0.42	1.81	6.47	11.43	8.56	4.20	4.16	4.30	3.87
Inlet	2.4	Scrubber	0.95	15.00	1.88	14.78	14.86	6.15	8.28	0.62	1.85	7.24	12.59	9.05	3.54	3.66	3.56	3.24
50%		Splitter	0.12	1.27	0.01	4.49	16.97	18.02	6.96	0.16	0.52	3.94	11.11	14.29	3.61	3.80	3.67	3.27
		Dust	1.40	32.80	7.36	21.13	18.49	7.04	10.67	2.04	5.89	15.15	18.10	12.14	5.33	5.58	5.92	4.61
10/21/16	**47**	Dust	1.56	32.87	9.00	19.56	21.97	7.24	10.05	2.24	6.21	13.67	17.82	11.89	5.40	5.53	6.10	4.64
668 fpm	1:00	Fan	1.58	20.99	3.64	16.03	17.00	5.72	7.70	0.80	2.66	7.23	13.43	10.55	5.05	5.69	5.43	4.55
Inlet	2.26	Scrubber	1.43	20.82	3.61	15.84	16.92	5.82	7.57	0.90	2.76	7.45	13.42	10.53	3.93	4.11	4.12	3.56
50%		Splitter	0.62	2.63	0.24	3.80	17.91	16.74	11.09	0.15	0.73	2.97	9.75	14.34	3.88	4.11	4.08	3.66
		Dust	1.54	31.55	8.50	18.61	21.68	6.80	9.05	1.97	5.61	13.23	17.75	11.87	5.36	5.59	6.19	4.65
10/25/16	**50**	Dust	1.83	34.36	2.07	19.94	20.10	8.95	9.45	9.68	6.82	14.31	18.28	12.14	4.93	4.98	4.54	6.31
753 fpm	8:00	Fan	1.77	21.85	0.80	17.17	17.18	6.05	8.12	4.31	2.83	8.92	14.79	12.06	4.92	5.19	4.18	6.34
Inlet	2.61	Scrubber	1.71	23.90	0.88	17.77	16.81	5.60	6.74	4.50	3.15	9.64	14.85	11.63	3.95	3.79	3.43	4.68
50%		Splitter	1.16	1.73	0.23	5.79	16.17	18.29	8.87	0.64	0.79	4.71	11.51	15.07	3.92	3.77	3.27	4.84
		Dust	1.90	36.00	2.47	18.78	18.36	8.24	9.44	10.39	7.05	15.08	17.33	11.33	5.12	5.21	4.69	6.41
10/26/16	**52**	Dust	2.36	29.44	8.96	18.88	18.93	7.98	10.76	2.31	6.88	13.91	16.99	11.53	4.95	5.50	6.33	5.59
730 fpm	8:00	Fan	2.32	18.74	3.86	17.75	16.63	5.90	7.87	1.08	3.30	10.31	15.34	11.58	4.97	6.02	5.97	5.35
Inlet	2.43	Scrubber	2.55	20.75	4.35	18.71	16.65	5.77	7.84	1.25	3.72	10.90	15.89	11.59	4.18	4.54	4.91	4.72
50%		Splitter	1.07	2.14	0.52	8.05	15.68	18.62	8.73	0.29	1.08	5.99	14.52	16.57	4.06	4.30	4.97	4.68
		Dust	2.06	31.92	9.69	18.27	19.37	8.08	9.43	2.73	6.71	14.77	17.44	11.84	5.24	5.59	6.32	5.98

Table A.5. Inlet extension added, scrubber at 100% capacity, 500 fpm (2.54 m/s) face-air velocity

					Scrubber Filter - The Hub + 252"					Tailgate - The Hub + 474"					Return			
Date test levels	**Test#** start time dust	**Operating condition**	**Splitter** *0506*	**Inlet** *2070*	Walkway *2056*	Mid-walkway *0507*	Mid-shearer *1881*	Mid-face *0030*	Face *1495/008*	Walkway *009A*	Mid-walkway *0001*	Mid-shearer *0021*	Mid-face *0054*	Face *009B*	Top left *0751*	Bottom left *0814/1380*	Top right *1380/056*	Bottom right *1355*
9/20/16	**4**	Dust	23.60	42.39	18.52	26.71	21.55	12.62	9.14	8.73	14.13	18.59	23.80	19.06	7.90	7.31	6.76	4.33
503 fpm	10:00	Fan	7.67	15.12	1.26	7.52	11.99	11.85	8.72	0.26	0.63	1.87	4.38	6.80	7.12	6.71	6.03	5.65
Extension	2.3	Scrubber	7.96	15.53	1.93	7.94	11.51	11.54	8.98	0.41	0.61	1.94	4.81	6.67	3.38	3.07	2.93	2.72
100%		Splitter	1.49	1.60	0.00	0.43	3.49	10.52	12.90	0.16	0.60	1.04	2.02	3.96	2.95	2.75	2.51	2.46
		Dust	24.98	39.15	19.33	18.11	19.37	13.77	9.59	7.95	12.19	15.43	20.87	17.79	7.33	6.70	6.71	3.90
10/5/16	**28**	Dust	30.16	34.84	26.80	22.40	25.05	12.42	10.69	8.43	14.81	17.76	19.01	16.39	7.14	6.83	4.19	5.98
	8:00	Fan	10.71	21.64	2.85	12.70	20.59	9.28	6.78	0.56	1.20	4.06	8.16	9.94	7.37	7.66	4.91	7.87
Extension		Scrubber	12.36	25.08	3.67	14.64	22.21	10.14	7.68	0.51	1.62	4.76	9.25	11.04	3.44	3.76	2.45	3.90
100%		Splitter	1.70	1.22	0.14	0.63	7.82	13.68	13.17	0.25	0.50	1.86	4.00	7.11	2.86	3.05	1.96	3.21
		Dust	32.10	42.83	31.70	24.10	29.24	14.61	12.35	11.59	17.30	20.06	21.35	19.01	7.61	7.99	5.01	6.49
10/13/16	**35**	Dust	32.78	55.64	24.04	20.76	21.98	15.43	15.16	7.74	9.82	18.10	19.89	18.36	10.29	7.58	4.13	6.78
490 fpm	10:00	Fan	11.35	24.76	1.60	8.94	14.90	12.55	10.88	0.41	0.74	2.53	5.67	8.40	8.59	6.76	4.47	8.65
Extension	2.79	Scrubber	12.48	29.58	2.15	11.11	16.83	13.97	11.96	0.45	0.75	3.71	6.89	10.09	4.52	3.49	2.27	4.47
100%		Splitter	1.94	1.99	0.14	0.78	5.14	9.85	15.36	-0.25	0.47	1.26	2.57	5.31	3.53	2.73	1.78	3.52
		Dust	37.30	56.31	23.85	21.61	23.01	15.77	15.69	8.62	10.07	na	20.60	19.42	10.36	7.13	4.45	6.96
10/19/16	**44**	Dust	26.12	41.73	24.51	18.80	19.55	13.06	9.53	6.70	12.57	17.39	16.40	15.22	9.87	8.07	5.41	5.32
502 fpm	8:35	Fan	10.06	19.71	1.76	9.12	32.11	12.26	10.07	0.20	0.91	2.64	5.00	8.81	7.98	8.03	4.78	7.30
Extension	2.43	Scrubber	9.59	19.00	2.10	9.09	17.25	11.42	9.82	0.47	0.82	2.65	4.84	8.65	3.79	3.77	2.27	3.11
100%		Splitter	1.35	1.33	0.01	0.31	4.64	10.59	15.02	0.07	0.74	0.90	2.02	4.90	3.36	3.25	2.08	2.77
		Dust	28.61	46.61	26.84	19.05	25.06	14.67	11.34	7.38	12.68	17.34	17.27	17.42	8.53	8.43	5.58	5.67
10/24/16	**48**	Dust	22.35	34.96	18.66	18.41	17.93	10.50	8.75	6.23	11.02	17.16	17.57	13.25	6.49	6.22	5.26	6.37
513 fpm	10:00	Fan	8.93	14.26	1.89	8.79	14.95	11.23	7.26	0.46	1.26	3.84	6.96	8.77	7.78	6.77	5.56	6.41
Extension	2.54	Scrubber	8.74	13.92	1.98	11.05	14.99	9.82	7.34	0.42	1.21	4.28	8.07	9.49	4.05	3.75	3.01	3.34
100%		Splitter	1.65	1.59	0.17	0.86	5.66	13.03	14.00	0.22	0.53	1.87	3.78	6.68	3.33	2.97	2.45	2.60
		Dust	27.15	41.07	21.96	20.63	19.33	11.95	10.84	7.05	13.12	18.44	20.91	15.92	7.59	7.41	6.18	7.04

Table A.6. Inlet extension added, scrubber at 50% capacity, 700 fpm (3.55 m/s) face-air velocity

	Test#				**Scrubber Filter - The Hub + 252"**					**Tailgate - The Hub + 474"**					**Return**			
Date	start time		**Splitter**	**Inlet**	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Top left	Bottom left	Top right	Bottom right
test levels	dust	**Operating condition**	*0506*	*2070*	*2056*	*0507*	*1881*	*0030*	*1495/ 008*	*009A*	*0001*	*0021*	*0054*	*009B*	*0751*	*0814/ 1380*	*1380/ 056*	*1355*
9/21/16	**7**	Dust	1.67	7.18	7.14	14.81	9.63	7.11	11.13	2.56	4.78	10.04	11.69	8.68	4.29	3.96	5.50	4.83
743 fpm	10:00	Fan	0.91	2.89	1.79	9.31	5.46	4.48	9.20	0.67	1.68	4.49	6.86	5.72	3.87	4.09	4.94	4.56
Extension	2.3	Scrubber	1.20	3.44	2.40	10.99	6.17	4.97	10.11	0.82	2.26	5.42	7.97	6.41	3.14	3.04	3.71	3.61
50%		Splitter	0.31	0.63	0.30	3.44	9.94	9.79	5.77	0.24	0.58	2.64	6.89	9.02	2.66	2.78	3.24	3.19
		Dust	2.13	7.51	8.50	17.18	10.80	7.53	12.22	3.03	5.98	11.93	13.13	9.81	4.74	4.27	6.29	5.65
9/29/16	**18**	Dust	1.27	5.07	6.78	13.58	9.91	7.80	11.44	1.67	4.09	8.78	11.10	8.94	5.41	4.30	4.11	3.98
769 fpm	8:00	Fan	1.07	2.62	1.98	8.55	6.58	4.74	10.28	0.48	1.42	4.18	6.68	5.85	5.01	4.91	3.89	3.88
Extension	2.33	Scrubber	1.34	2.73	2.40	9.11	6.78	4.72	9.56	0.60	1.65	4.65	7.09	5.98	3.54	3.17	2.85	2.72
50%		Splitter	0.28	0.58	0.16	3.88	9.73	8.62	4.81	0.15	0.48	2.79	7.14	8.24	3.13	2.73	2.52	2.49
		Dust	1.57	5.51	7.16	12.99	10.07	7.67	11.72	2.09	4.28	9.25	11.35	8.93	5.73	4.82	4.24	3.76
10/4/16	**25**	Dust	1.22	12.11	10.61	14.41	9.35	8.83	12.10	3.27	6.44	10.97	11.72	10.93	4.68	3.03	6.48	5.83
708 fpm	10:00	Fan	1.16	5.08	3.88	12.70	6.63	5.99	9.55	1.02	2.93	6.62	8.91	8.44	4.76	3.48	6.21	4.75
Extension	2.55	Scrubber	1.31	5.81	4.03	12.57	6.94	5.67	9.38	1.25	2.97	6.93	8.87	8.41	3.44	2.29	4.34	3.38
50%		Splitter	0.13	0.75	0.61	5.68	12.03	10.95	6.03	0.22	0.74	3.43	8.41	11.12	2.93	2.08	3.76	2.88
		Dust	1.59	15.21	12.03	15.49	10.84	7.99	12.57	3.80	7.27	12.55	12.69	12.06	5.24	3.34	7.15	4.94
10/26/16	**54**	Dust	2.92	11.84	11.40	16.10	11.87	8.93	10.57	2.92	6.89	12.08	13.81	9.64	4.96	5.66	6.61	6.31
712 fpm	1:00	Fan	2.08	5.27	3.31	12.71	9.37	4.69	8.22	0.87	2.30	5.70	8.61	6.50	4.68	5.91	5.83	6.32
Extension	2.74	Scrubber	2.20	5.76	3.88	11.56	8.00	4.95	8.72	1.00	2.76	6.64	9.61	6.98	3.39	3.86	4.11	4.21
50%		Splitter	1.04	1.63	0.40	5.11	13.13	13.23	8.54	0.38	0.94	3.95	9.68	11.98	3.26	3.76	4.15	4.27
		Dust	4.94	19.24	13.26	16.50	12.17	7.30	11.23	3.52	7.82	13.33	14.25	9.56	5.32	5.94	6.84	6.60
10/31/16	**58**	Dust	2.51	11.41	8.27	15.17	11.34	9.71	11.33	2.66	6.13	8.53	13.10	9.12	5.05	5.33	4.47	4.31
730 fpm	10:00	Fan	1.43	4.97	2.35	10.46	7.71	3.68	9.44	0.78	2.31	5.24	8.60	6.72	4.88	5.76	4.38	4.52
Extension	2.76	Scrubber	1.16	4.68	2.47	11.33	8.48	9.86	10.70	0.53	2.56	5.80	9.49	7.24	3.49	3.82	3.15	3.08
50%		Splitter	0.20	1.22	0.22	5.20	13.30	13.08	6.51	0.14	0.76	-0.72	8.83	10.76	3.09	3.43	2.84	2.94
		Dust	1.25	11.65	9.42	15.24	12.72	6.15	12.43	2.57	6.26	10.32	11.92	9.55	5.67	5.74	5.10	4.51

Table A.7. Inlet extension removed, scrubber at 100% capacity, 700 fpm (3.55 m/s) face-air velocity

	Test#				**Scrubber Filter - The Hub + 252"**					**Tailgate - The Hub + 474"**					**Return**			
Date	start time		**Splitter**	**Inlet**	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Top left	Bottom left	Top right	Bottom right
test levels	dust	**Operating condition**	*0506*	*2070*	*2056*	*0507*	*1881*	*0030*	*1495/ 008*	*009A*	*0001*	*0021*	*0054*	*009B*	*0751*	*0814/ 1380*	*1380/ 056*	*1355*
9/26/16	**10**	Dust	1.41	12.94	5.23	15.13	17.68	4.48	9.99	2.14	4.93	10.50	13.90	7.78	4.79	4.55	6.75	3.63
714 fpm	10:00	Fan	1.11	4.36	0.47	6.65	12.00	13.19	4.71	0.17	0.47	2.04	4.97	4.12	4.85	4.37	5.75	3.69
Inlet	2.14	Scrubber	1.37	4.00	0.57	6.99	12.47	4.96	4.53	0.16	0.41	1.97	5.02	4.24	2.33	2.21	3.07	2.13
100%		Splitter	0.47	0.53	0.11	1.14	9.55	12.04	7.88	0.04	0.15	0.99	3.23	6.00	2.33	2.20	3.07	2.12
		Dust	1.15	12.12	4.92	15.11	17.65	6.85	10.22	2.00	4.82	10.44	14.09	8.38	4.74	4.56	6.98	3.73
9/29/16	**20**	Dust	1.18	3.38	6.97	15.96	15.73	9.50	10.07	1.36	4.07	10.27	14.74	10.76	6.36	4.70	4.70	3.69
720 fpm	1:00	Fan	1.04	2.24	0.74	6.60	9.97	5.72	4.70	0.07	0.32	1.64	4.78	5.49	5.58	5.04	4.84	3.78
Inlet	2.13	Scrubber	1.08	2.36	0.70	7.32	13.22	5.91	5.18	0.13	0.42	2.01	5.33	5.80	3.08	2.31	2.45	2.19
100%		Splitter	0.33	0.53	0.11	1.11	7.07	13.63	8.26	-0.01	0.19	0.84	3.61	7.61	3.09	2.55	2.45	2.14
		Dust	1.59	4.33	8.09	18.23	17.86	9.04	10.99	2.13	4.68	12.10	16.79	12.44	7.08	5.46	5.07	3.89
10/7/16	**32**	Dust	1.41	0.43	7.38	15.45	13.24	7.33	12.64	2.50	5.76	11.00	12.17	9.76	6.22	3.63	5.52	4.62
742 fpm	8:00	Fan	1.00	0.38	0.92	10.65	8.97	5.02	6.28	0.27	0.85	3.52	6.63	6.27	5.94	4.44	5.80	6.46
Inlet	2.73	Scrubber	1.13	0.52	1.26	12.99	10.73	5.68	6.94	0.26	1.06	4.27	8.20	7.72	3.21	2.31	3.08	2.97
100%		Splitter	0.41	0.20	0.09	2.39	12.12	14.05	7.60	0.14	0.20	1.41	5.40	10.20	3.16	2.22	3.17	2.75
		Dust	2.00	0.71	10.09	19.72	14.18	6.72	14.58	3.43	7.36	12.86	15.28	11.78	6.93	4.16	6.97	5.65
10/14/16	**37**	Dust	2.08	28.13	6.69	15.17	13.06	6.70	9.94	2.19	5.96	11.27	14.13	10.04	4.44	4.23	5.15	5.23
750 fpm	8:00	Fan	2.28	12.09	1.32	9.60	8.60	4.53	4.79	0.25	0.83	2.55	6.86	6.71	5.68	5.12	4.88	5.51
Inlet	2.2	Scrubber	2.07	11.86	1.34	9.43	8.54	4.61	4.80	0.29	0.76	3.63	7.12	7.02	3.11	2.66	2.64	2.86
100%		Splitter	0.70	1.03	0.14	1.86	8.07	14.13	12.26	0.10	0.17	1.45	4.06	9.40	3.01	2.61	2.65	2.75
		Dust	2.00	28.40	6.04	15.70	12.53	6.47	12.38	2.42	5.61	12.36	15.35	10.61	5.74	5.17	5.94	5.67
11/3/16	**63**	Dust	1.29	39.17	8.11	22.32	21.06	9.55	12.25	3.45	8.57	18.39	19.30	13.62	5.82	4.97	7.07	6.88
735 fpm	8:00	Fan	1.05	13.49	0.76	11.51	13.66	4.83	5.96	0.18	1.03	5.33	9.49	9.33	5.44	4.75	6.44	6.51
Inlet	3.07	Scrubber	0.93	14.72	0.84	13.24	15.06	5.46	6.58	0.21	1.27	5.63	10.40	10.27	2.96	2.48	3.49	3.31
100%		Splitter	0.27	0.87	0.02	1.26	12.27	14.80	10.14	0.23	0.34	2.23	5.12	10.90	2.85	2.31	3.57	3.12
		Dust	1.47	40.20	8.35	22.25	23.13	8.01	14.07	3.05	8.00	15.24	20.23	13.93	6.85	5.43	7.92	7.50

Table A.8. Inlet extension added, scrubber at 100% capacity, 700 fpm (3.55 m/s) face-air velocity

	Test#				**Scrubber Filter - The Hub + 252"**					**Tailgate - The Hub + 474"**					**Return**			
Date	start time		**Splitter**	**Inlet**	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Walkway	Mid-walkway	Mid-shearer	Mid-face	Face	Top left	Bottom left	Top right	Bottom right
test levels	dust	**Operating condition**	*0506*	*2070*	*2056*	*0507*	*1881*	*0030*	*1495/ 008*	*009A*	*0001*	*0021*	*0054*	*009B*	*0751*	*0814/ 1380*	*1380/ 056*	*1355*
9/20/16	**5**	Dust	1.77	7.05	7.42	16.10	9.01	7.82	11.48	2.18	5.63	10.51	12.85	9.61	4.83	4.75	6.76	3.92
746 fpm	1:00	Fan	1.22	3.13	0.73	5.09	3.93	2.88	3.96	0.18	0.44	1.51	3.50	3.55	5.84	4.83	6.41	4.57
Extension	2.28	Scrubber	0.81	2.58	0.70	4.97	2.37	2.96	4.31	0.09	0.32	1.41	3.25	3.11	2.34	2.07	2.69	1.96
100%		Splitter	-0.40	0.76	0.10	0.77	7.25	4.97	3.01	0.10	0.14	0.84	2.23	3.11	1.91	1.72	2.30	1.71
		Dust	2.27	8.61	8.81	17.55	9.97	7.67	12.04	2.62	6.33	11.71	14.18	10.59	4.98	4.97	7.15	4.14
9/26/16	**9**	Dust	1.38	4.13	6.48	14.18	10.84	8.70	11.92	2.78	5.95	10.11	11.25	6.46	4.17	4.58	5.83	3.72
750 fpm	8:00	Fan	0.41	1.03	0.44	4.73	4.81	2.97	3.79	0.09	0.20	1.43	3.13	2.14	4.79	4.39	5.43	3.86
Extension	2.39	Scrubber	0.61	1.14	0.43	4.67	4.71	3.09	3.99	0.04	0.37	1.51	3.06	2.03	1.64	1.71	2.13	1.52
100%		Splitter	0.16	0.23	0.10	0.93	5.29	2.98	2.03	0.03	0.15	0.69	2.22	2.57	1.26	1.43	1.82	1.38
		Dust	1.82	5.08	5.70	13.16	10.80	6.75	9.76	2.44	4.71	9.11	10.83	5.84	3.82	4.20	5.76	3.32
10/25/16	**51**	Dust	1.82	11.60	2.04	15.01	13.07	7.04	11.92	9.53	5.19	10.48	11.88	9.86	4.67	5.23	4.29	6.25
723 fpm	1:00	Fan	1.11	2.33	0.15	4.31	4.67	3.73	5.31	1.34	0.37	1.73	2.90	2.50	5.42	5.61	4.47	6.41
Extension	2.65	Scrubber	1.30	2.92	0.09	5.26	5.21	3.94	5.35	1.04	0.35	2.06	3.59	3.19	2.28	2.33	1.95	3.07
100%		Splitter	0.51	0.57	0.07	1.19	7.29	8.88	4.60	-0.23	0.17	1.14	3.43	4.60	2.16	2.23	1.76	3.05
		Dust	1.15	14.48	2.64	17.21	13.60	7.08	13.57	11.77	6.92	13.41	13.90	10.85	5.29	5.87	4.91	7.23
10/27/16	**55**	Dust	3.20	11.88	9.55	14.70	9.79	8.18	10.80	3.12	5.84	8.88	13.48	9.87	4.47	4.03	4.88	5.25
703 fpm	8:00	Fan	2.68	4.48	1.01	5.01	5.51	2.90	4.55	0.20	0.61	1.87	4.57	4.38	5.40	4.38	5.40	6.01
Extension	2.52	Scrubber	3.00	5.91	1.40	5.66	6.34	2.95	4.46	0.61	0.92	2.37	5.65	5.00	2.36	1.95	2.22	2.46
100%		Splitter	1.07	1.21	0.20	0.98	6.38	9.12	4.33	0.24	0.31	1.02	3.71	5.64	2.17	1.66	2.15	2.19
		Dust	4.78	20.11	14.20	15.43	10.98	7.16	10.74	3.66	7.46	11.58	14.62	10.03	5.07	4.30	5.83	5.94
10/31/16	**59**	Dust	2.76	18.05	11.02	16.85	13.83	7.27	11.60	3.76	6.80	11.22	15.35	9.61	5.92	5.95	5.23	4.54
719 fpm	1:00	Fan	1.86	4.68	0.73	5.97	5.75	na	4.92	0.29	0.61	1.87	4.54	3.83	6.53	6.18	4.93	5.03
Extension	2.09	Scrubber	1.61	5.45	1.15	6.79	6.11	4.88	4.80	0.23	0.86	2.64	4.82	3.95	2.68	2.63	2.24	2.18
100%		Splitter	0.23	0.95	0.02	1.29	8.73	8.78	4.23	0.21	0.22	0.97	3.08	5.36	2.61	2.38	2.00	2.05
		Dust	2.41	21.38	13.23	21.29	16.06	7.31	12.83	3.83	8.18	13.94	16.74	10.83	6.43	6.75	5.70	5.12

10.2 Appendix B – Method for Determining Average Dust Reduction

The following steps were performed to calculate average dust reduction in the walkway:

Step 1: Average dust concentration at each PDM location (PDM 1, 2, 3, and 8) was calculated by averaging the dust only operating condition concentrations at the beginning and end of a test (step 1 and step 5 of the operating condition).

$$C_{Avg} = \left(\frac{C_{01} + C_{02}}{2}\right)$$

Where,
C_{01} = Dust concentration at the beginning (step 1 of the operating condition) of a test
C_{02} = Dust concentration at the end (step 5 of the operating condition) of a test
C_{Avg} = Average dust concentration

Step 2: Percentage dust reduction at each PDM location was calculated using the following formula:

$$DR_{PDMi} = \left(1.00 - \left[\frac{C_s}{(C_{Avg})}\right]\right)(100\%)$$

Where,
C_S = Dust concentration at a PDM with scrubber fan and scrubber sprays ON (step 3 of the operating condition)
DR_{PDMi} = Percentage Dust concentration at a PDM *i* (where *i* refers to PDM 1, 2, 3, and 8)

Step 3: The percentage dust reduction at each PDM location were averaged to calculate average dust reduction in the walkway.

$$Average\ dust\ reduction\ in\ the\ walkway = \left(\frac{DR_{PDM1} + DR_{PDM2} + DR_{PDM3} + DR_{PDM8}}{4}\right)$$

Note that the same general procedure was used for determining average dust reduction values for the face area (locations 7 and 12) and locations above the shearer body (locations 4-6 and locations 9-11).

10.3 Appendix C – Regression Model Parameters for each Monitoring Location – Splitter Arm Sprays OFF

Table C.1. Regression model parameter estimates for Location 1

$R^2 = 0.66$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	28.864	2.141	13.48	<.0001
A	9.964	2.141	4.65	<.0001
B	10.593	2.141	4.95	<.0001
C	-7.315	2.141	-3.42	0.0017
AB	2.457	2.141	1.15	0.2595
AC	1.349	2.141	0.63	0.5332
BC	-4.417	2.141	-2.06	0.0473
ABC	-2.052	2.141	-0.96	0.345

Table C.2. Regression model parameter estimates for Location 2

$R^2 = 0.85$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	36.423	1.664	21.89	<.0001
A	13.534	1.664	8.14	<.0001
B	7.967	1.664	4.79	<.0001
C	16.080	1.664	9.67	<.0001
AB	4.084	1.664	2.46	0.0197
AC	-2.366	1.664	-1.42	0.1646
BC	-1.214	1.664	-0.73	0.4707
ABC	-3.452	1.664	-2.07	0.0461

Table C.3. Regression model parameter estimates for Location 3

$R^2 = 0.94$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	71.623	0.842	85.09	<.0001
A	2.699	0.842	3.21	0.003
B	17.284	0.842	20.53	<.0001
C	5.138	0.842	6.1	<.0001
AB	-0.627	0.842	-0.74	0.462
AC	0.475	0.842	0.56	0.5767
BC	-4.736	0.842	-5.63	<.0001
ABC	0.024	0.842	0.03	0.9771

Table C.4. Regression model parameter estimates for Location 4

$R^2 = 0.84$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	30.727	1.570	19.58	<.0001
A	10.570	1.570	6.73	<.0001
B	16.182	1.570	10.31	<.0001
C	5.583	1.570	3.56	0.0012
AB	0.019	1.570	0.01	0.9903
AC	-0.507	1.570	-0.32	0.7486
BC	2.211	1.570	1.41	0.1687
ABC	1.309	1.570	0.83	0.4105

Table C.5. Regression model parameter estimates for Location 5

$R^2 = 0.79$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	19.322	2.050	9.43	<.0001
A	13.408	2.050	6.54	<.0001
B	1.861	2.050	0.91	0.3708
C	14.283	2.050	6.97	<.0001
AB	7.386	2.050	3.6	0.0011
AC	-1.369	2.050	-0.67	0.5091
BC	7.327	2.050	3.57	0.0011
ABC	-4.122	2.050	-2.01	0.0528

Table C.6. Regression model parameter estimates for Location 6

$R^2 = 0.69$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	19.046	2.000	9.52	<.0001
A	6.905	2.000	3.45	0.0016
B	1.417	2.000	0.71	0.4837
C	12.656	2.000	6.33	<.0001
AB	6.503	2.000	3.25	0.0027
AC	-0.703	2.000	-0.35	0.7275
BC	6.519	2.000	3.26	0.0027
ABC	-0.216	2.000	-0.11	0.9146

Table C.7. Regression model parameter estimates for Location 7

$R^2 = 0.90$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	23.434	1.281	18.3	<.0001
A	4.591	1.281	3.58	0.0011
B	5.367	1.281	4.19	0.0002
C	14.475	1.281	11.3	<.0001
AB	6.091	1.281	4.76	<.0001
AC	-3.625	1.281	-2.83	0.008
BC	13.311	1.281	10.39	<.0001
ABC	-2.848	1.281	-2.22	0.0334

Table C.8. Regression model parameter estimates for Location 8

$R^2 = 0.94$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	77.450	0.667	116.16	<.0001
A	2.509	0.667	3.76	0.0007
B	15.026	0.667	22.54	<.0001
C	0.485	0.667	0.73	0.4724
AB	-1.750	0.667	-2.63	0.0132
AC	0.870	0.667	1.3	0.2013
BC	-1.181	0.667	-1.77	0.0861
ABC	-1.233	0.667	-1.85	0.0737

Table C.9. Regression model parameter estimates for Location 9

$R^2 = 0.97$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	72.369	0.519	139.54	<.0001
A	1.581	0.519	3.05	0.0046
B	18.268	0.519	35.22	<.0001
C	0.503	0.519	0.97	0.3391
AB	-0.428	0.519	-0.82	0.4155
AC	0.871	0.519	1.68	0.1027
BC	-1.739	0.519	-3.35	0.0021
ABC	-0.102	0.519	-0.2	0.8452

Table C.10. Regression model parameter estimates for Location 10

$R^2 = 0.93$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	57.841	0.957	60.44	<.0001
A	3.903	0.957	4.08	0.0003
B	19.660	0.957	20.54	<.0001
C	1.515	0.957	1.58	0.1235
AB	-0.015	0.957	-0.02	0.9877
AC	0.393	0.957	0.41	0.6841
BC	-1.672	0.957	-1.75	0.0905
ABC	0.427	0.957	0.45	0.6585

Table C.11. Regression model parameter estimates for Location 11

$R^2 = 0.91$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	42.718	1.099	38.88	<.0001
A	6.799	1.099	6.19	<.0001
B	18.520	1.099	16.86	<.0001
C	0.421	1.099	0.38	0.7041
AB	-0.234	1.099	-0.21	0.833
AC	0.641	1.099	0.58	0.5637
BC	0.319	1.099	0.29	0.7734
ABC	0.839	1.099	0.76	0.4507

Table C.12. Regression model parameter estimates for Location 12

$R^2 = 0.84$				
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	27.994	1.445	19.38	<.0001
A	10.448	1.445	7.23	<.0001
B	13.750	1.445	9.52	<.0001
C	5.924	1.445	4.1	0.0003
AB	2.445	1.445	1.69	0.1003
AC	1.326	1.445	0.92	0.3657
BC	2.308	1.445	1.6	0.12
ABC	-0.900	1.445	-0.62	0.5376

11.0 Acknowledgements/Disclaimer

11.1 Acknowledgement

The Investigators wish to acknowledge and thank the following:

- The following graduate students who devoted many hours and contributed so much to the success of this project:
  - Sampurna Arya, Ph.D. student
  - Ashish Kumar, Ph.D. student
  - Adam Levy, M.S. student
  - Brad Coleman, Ph.D. student
  - Kayla Mayfield, Ph.D. student
- Ed Thompson, Laboratory Supervisor, for his technical, practical, and organizational skills that he so effectively used in helping, guiding, and working along with the graduate students.
- Personnel at NIOSH – Office of Mine Safety and Health Research, in Pittsburgh, Pennsylvania, particularly Jim Rider and Jay Colinet, for making available the Longwall Dust Gallery, and its associated equipment and instrumentation, as well as for taking dust measurements. The shearer mounted scrubber could not be tested without the use of NIOSH facilities and personnel.
- Personnel from Joy Global, Inc., particularly Joe Defibaugh, and personnel from Alliance Coal, LLC, for supplying drawings, information, visits, and guidance.
- The Alpha Foundation for the Improvement of Mine Safety and Health for funding this project.

11.2 Disclaimer