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ORIGINAL ARTICLE

A Laboratory Investigation of Underside Shield Sprays to Improve Dust Control of Longwall Water Spray Systems

S. S. Klima[1] · W. R. Reed[1] · J. S. Driscoll[1] · A. L. Mazzella[1]

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Abstract
Researchers at the National Institute for Occupational Safety and Health (NIOSH) performed laboratory testing to improve longwall dust control by examining the use of underside shield sprays in conjunction with the longwall directional spray system. In a field survey of longwall operations, NIOSH researchers observed dust clouds created by the fracturing and spalling of coal immediately upwind of the headgate drum that migrated into the walkway, exposing mining personnel to respirable coal dust. The goal of this research was to create an effective traveling water curtain to prevent this dust from reaching the personnel walkway by redirecting it toward the longwall face. The location, orientation, and pressure of the water sprays were the primary testing parameters examined for minimizing dust exposure in the walkway. Laboratory testing indicates that the use of underside shield sprays on the longwall face may be beneficial toward reducing respirable dust exposure for mining personnel.

Keywords Coal mining · Health and safety · Longwall mining · Respirable dust control · Underside shield sprays · Water spray systems

1 Introduction

Overexposure to respirable coal dust can lead to coal workers' pneumoconiosis (CWP), commonly known as black lung. CWP is a preventable occupational lung disease that is caused by the inhalation of respirable coal dust in underground coal mines. A person with CWP will develop issues in their lungs over time, which can lead to respiratory failure and premature death [1, 2]. In August 2016, the US Mine Safety and Health Administration's (MSHA's) new respirable dust standard (CFR 70.100) went into effect, which decreased the concentration limits allowed for respirable coal mine dust from 2.0 mg/m^3 over an 8-h shift to 1.5 mg/m^3 over the full actual working shift [3]. This maximum allowable exposure for mine personnel can be a challenge to maintain without proper underground engineering controls.

While longwall mining can be an efficient method for coal extraction in underground mines, longwall personnel can face exposure to respirable coal mine dust from a variety of sources. These dust generation sources include the intake entry, stage loader, shearer, and shield advance [4]. The longwall shearer was shown to be the highest contributor, comprising anywhere from 43 to 50% of the respirable dust generated on the longwall face [2, 4]. NIOSH researchers have observed that the fracturing and spalling of coal just upwind of the shearer headgate drum creates a cloud of dust that can migrate into the personnel walkway.

To mitigate respirable dust overexposures, CFR 75.325 states that the required ventilation on a longwall face is to be a minimum of 14.2 m^3/s (30,000 ft^3/min) [3]. This requirement is to ensure proper respirable dust control on the longwall. In addition to meeting face ventilation requirements, longwall mines are required to use water sprays to further improve dust control. Typically, a longwall will have water spray systems that include drum-mounted water sprays, splitter arm sprays, a shearer-clearer system, and tailgate manifolds in operation during mining [5–7]. While these systems can help to reduce respirable dust exposures, further improvement may be necessary.

Underside shield sprays were observed in 2011 [4]. These sprays are mounted on the underside of the longwall shields and directed toward the face. The benefit of using underside shield sprays is that they can create a moving water curtain along the longwall face to prevent contaminated air caused by

✉ S. S. Klima
sklima@cdc.gov

[1] CDC NIOSH, Pittsburgh, PA, USA

the shearer from reaching the mining personnel walkway. These sprays can be programmed to automatically activate and deactivate based on the location of the shearer. However, there was no consistency in the use of these sprays; the alignment and sequencing of the underside shield sprays varied considerably among longwall operations [4]. There are potential drawbacks if the sequencing or alignment of these sprays is not correct. This can lead to negative interactions with the splitter arm sprays by allowing a cloud of dust and mist to enter the personnel walkway. It is important to properly determine how these sprays will work within a longwall's overall dust control plan.

The goal of this research was to evaluate the underside shield sprays to prevent the formation of a dust cloud, created due to coal spalling from the longwall face ahead of the shearer, from reaching the longwall personnel walkway. Proper installation and alignment of underside shield sprays would expand the overall effective zone of the shearer's directional spray system in reducing mining personnel dust exposures. These sprays, located on the headgate drum side of the shearer, were evaluated to provide guidance for the best operating parameters for reducing mining personnel dust exposures.

2 Methodology

Researchers performed laboratory testing in the NIOSH Pittsburgh Mining Research Division's longwall gallery (Fig. 1). It is a full-scale laboratory that simulates a longwall operation. This lab has been successfully used to develop respirable dust control interventions and is described in previous literature [7–9]. A recent update revised the dimensions of the simulated shearer to upgrade it from a Joy 4LS model to a Joy 7LS model (Komatsu Mining Corp.) The main shearer body is 7.65 m (25.1 ft) long, 1.60 m (5.25 ft) wide, and 1.17 m (3.83 ft) high. Each ranging arm is 2.72 m (8.92 ft) long, 0.61 m (2 ft) wide, and 0.51 m (1.67 ft) high. The overall length of the simulated longwall shearer is 13.1 m (42.9 ft) from the center axis of the headgate cutter drum to the center axis of the tailgate cutter drum. The drums are 1.52-m (5 ft) diameter.

The underside shield sprays tested in this study were located upwind of the splitter arm sprays for the headgate shearer. The three splitter arm sprays were spaced evenly along its 3.40-m (11.2 ft) length (from shearer body to end of splitter arm). The underside shield sprays were located 0.86 m (2.83 ft) in front of the splitter arm sprays. Figure 2 shows the layout of the underside shield sprays with respect to the headgate shearer. While the figure shows two sets of underside shield sprays at different distances from the face, only one set was examined at a time. This was done to determine if one set of underside shield sprays at a given distance from the face would provide sufficient protection from respirable dust. Operating more than one set of sprays at a time would significantly increase water consumption. The sprays were moved depending upon test parameters. Several operating parameters were examined to determine the most effective approach in minimizing mining personnel dust exposures along the longwall. The first parameter examined was the pressure of the underside shield sprays. This was done to determine if higher water pressures had a positive impact on minimizing dust exposures. The three water pressures examined were 690 kPa (100 psi), 1034 kPa (150 psi), and 1379 kPa (200 psi). The spray nozzles used in the underside shield sprays were Spraying Systems VeeJet H 3/8 U 65/15 flat pattern sprays (Spraying Systems Co.).

In order to create an effective traveling water curtain, the underside shield sprays need to be properly aligned with respect to the overall longwall directional spray system. Three different water spray locations were tested at distances of 1.37 m (4.5 ft), 1.52 m (5.0 ft), and 1.68 m (5.5 ft) measured from the mining face. These distances proved to be the most

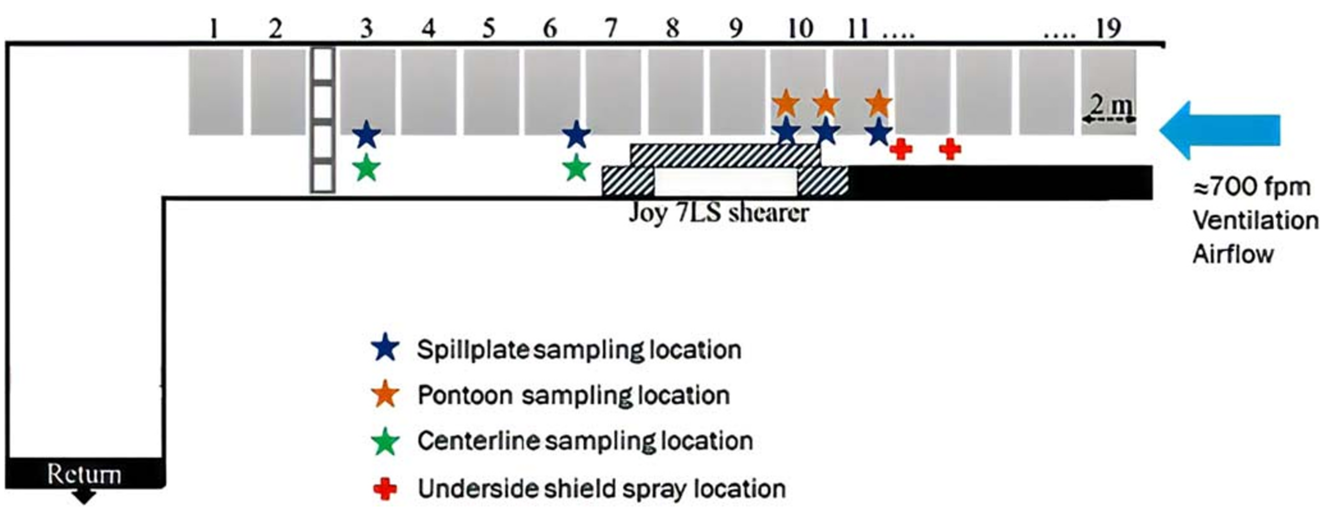

Fig. 1 Longwall gallery setup showing the underside shield spray locations and the ten dust sampling locations

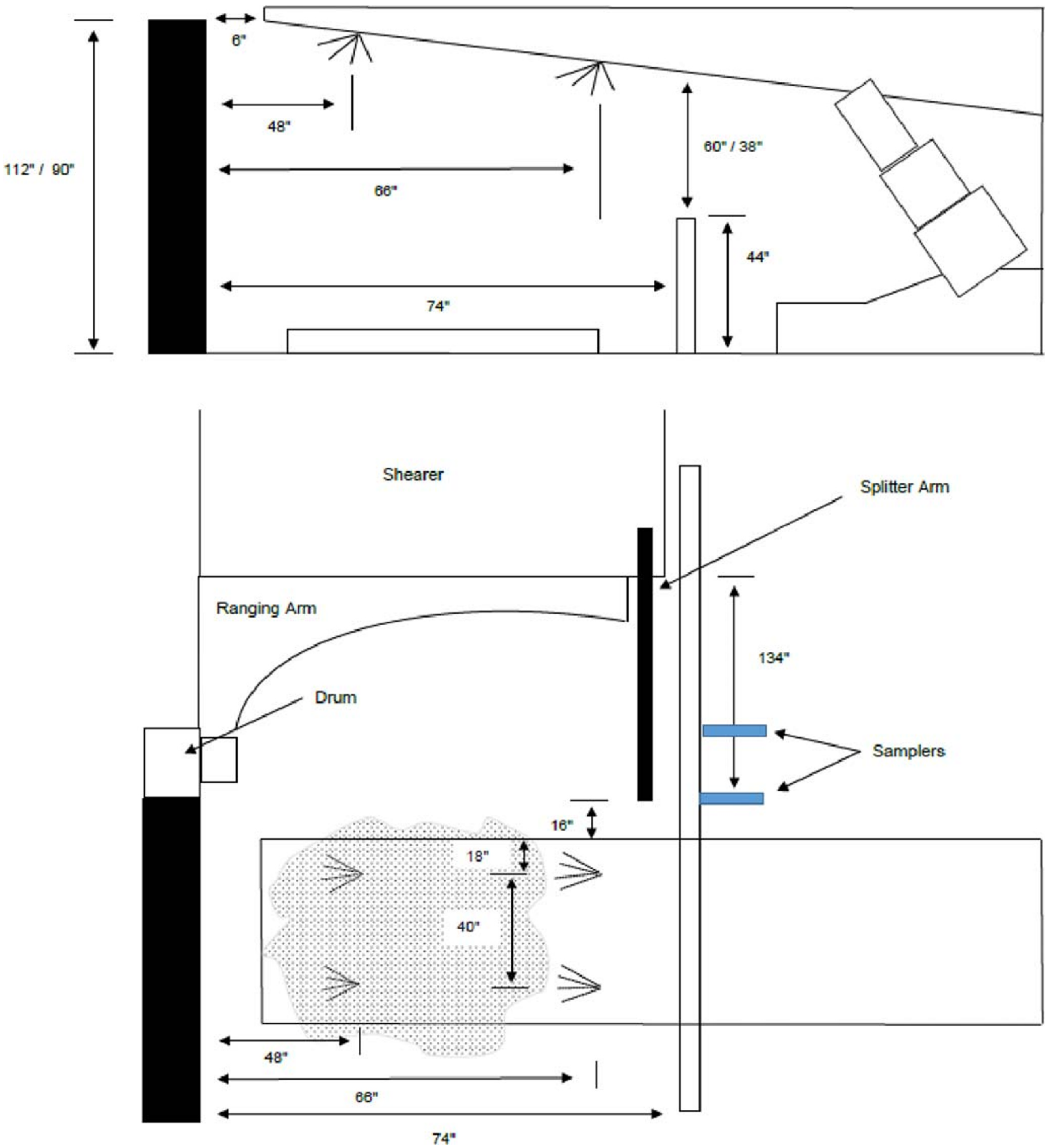

Fig. 2 Layout of underside shield sprays with respect to the longwall shearer (diagram not to scale). Note: only 1.37-m (4.5 ft) and 1.68-m (5.5 ft) underside spray locations are shown. 1.52-m (5.0 ft) testing location not shown

effective during preliminary testing. Sprays located too close to the mining face did not provide good protection from dust entering the personnel walkway. Sprays that were located further from the face resulted in water entering the walkway where mining personnel would be positioned.

Similar to determining the location of the water sprays, it was important to determine the most effective orientation of the sprays at these locations. The water spray distance and orientation could be greatly dependent on each other. Three water spray orientations were examined for this testing at 45,

Fig. 3 NIOSH longwall gallery showing the dust injection system located near the shearer drum, with splitter arm and underside shield sprays in operation without dust injection

60, and 75°, measured from the mining roof. Using too small of an orientation angle would allow dust to pass under the spray pattern into the walkway, as well as not meeting the recommended spray angle for the model 65/15 sprays at the tested pressures. Using an orientation approaching 90° would not direct the dust into the mining face as desired.

It was important to maintain a relatively constant face ventilation in the longwall gallery during this testing for consistency between each test. Face ventilation was measured before and after each test by performing a vane anemometer traverse just upwind of the sampling area. The targeted face ventilation of each test was 3.56 m/s (700 ft/min), but this varied between tests due to environmental and laboratory factors. The measured face ventilations ranged from 3.21 m/s (631 ft/min) to 3.98 m/s (783 ft/min), meaning the ventilation was always within 12% of the targeted value.

Dust was injected into the longwall gallery by an automatic dust feeder and through use of two blowers with attached tubing. The feeder (Schenck AccuRate) and blowers (American Fan AF-10) were all located outside of the longwall gallery with their attached tubes running through the longwall face. Figure 3 shows the outlets of the tubes placed near the shearer cutting drum. This was done to best simulate the dust cloud created by the fracturing and spalling of coal just upwind of the cutting drum. One blower tube contained dust injected from the dust feeder, with the second blower tube acting as a booster to push the dust cloud away from the cutting drum toward the personnel walkway, as has been observed in field studies of longwall operations. Dust feed rate, location, and blower pressure levels remained constant throughout testing.

Each individual test followed the same testing sequence, which is shown in Table 1. The testing sequence was broken up into seven 15-min blocks for data collection, with a 3-min stabilization period following each block to allow changing conditions to stabilize. The first block of each test began with a baseline dust-only condition, with zero sprays in operation while dust was being injected into the longwall gallery. For the next block, the splitter arm sprays were turned on with dust still being injected into the gallery. The splitter arm sprays used were Spraying Systems BD3 hollow cone sprays (Spraying Systems Co.) operated at 1034 kPa (150 psi) for each test. The next three blocks added the operation of the underside shield sprays at the three pressures being examined: 690 kPa (100 psi), 1034 kPa (150 psi), and 1379 kPa (200 psi). The final two blocks repeated the first two blocks but in reverse order. This was done to further gain baseline data as well as ensuring each test maintained a similar dust feed rate from start to finish.

Table 1 Complete testing sequence for each test, where each block included a 3-min stabilization period followed by a 15-min test for capturing data

Block #	Testing conditions
1	Dust only
2	Dust + splitter arm sprays
3	Dust + splitter arm sprays + underside sprays at 690 kPA (100 psi)
4	Dust + splitter arm sprays + underside sprays at 1034 kPA (150 psi)
5	Dust + splitter arm sprays + underside sprays at 1379 kPA (200 psi)
6	Dust + splitter arm sprays
7	Dust only

Table 2 Testing matrix for underside shield sprays compared at 690 kPa (100 psi), 1034 kPa (150 psi), and 1379 kPa (200 psi) pressures. X = test condition evaluated a minimum of three times, NA = testing not performed due to ineffectiveness of that combination

	Spray distance		
Spray angle	1.37 m (4.5 ft)	1.52 m (5.0 ft)	1.68 m (5.5 ft)
45°	NA	X	X
60°	X	X	X
75°	X	X	NA

X test condition evaluated, *NA* test condition not evaluated

Each test compared different underside shield spray angles and distances. A minimum of three tests per combination was performed. Some conditions were repeated more than three times due to equipment or data collection error. Preliminary shakedown testing was conducted to identify all ineffective spray distance and angle combinations. The smallest distance of 1.37 m (4.5 ft) was ineffective with the smallest spray angle of 45°. The same ineffectiveness was seen with the furthest distance of 1.68 m (5.5 ft) and the steepest spray angle of 75°. These combinations were discontinued from testing. The testing matrix is shown in Table 2. Since each testing sequence included operation at the three different underside shield spray pressures, these parameters are not shown in the testing matrix.

Dust concentration data was collected at five primary locations in the longwall gallery, shown in Fig. 1, with two sampling units at each location. A total of ten PDM-3600s (Thermo Fisher Scientific) were used to collect real-time dust exposure data at these locations. The first three sampling locations were in succession along the personnel walkway. These were located upwind of the splitter arm sprays (but still downwind of the underside shield sprays), at the centerline of the shearer drum, and at the ranging arm motor. Each of these locations featured a PDM placed above the spill plate and another placed above the shield pontoon or in the walkway. PDMs were placed at a height that was approximated to be the average breathing height of mining personnel standing in the walkway. The spill plate is the typical location of the mining personnel, as it has been observed that this is typically where the mine workers are standing and being exposed to dust from the longwall face. Two more sampling locations were located downwind of these locations, along the shearer body and at the tailgate. The PDMs at these locations were placed at the spill plate and at the centerline between the spill plate and longwall mining face.

3 Results

Each test contained blocks of data collection with dust-only injection into the gallery and no splitter arm or underside shield sprays in operation. This was done to gain baseline dust concentration data, which varied between tests (< 1.0 to 15 mg/m^3). These variations can occur due to slight changes in face ventilation and air properties. The face ventilation varied up to 12% from the targeted 3.56 m/s (700 ft/min) value between tests. The baseline dust numbers were also dependent on the sampling location. To remove the effect of the variations in baseline concentrations, the baseline data was used to normalize dust concentration data at each sampling location based upon the baseline dust concentration for that location. Equation 1 shows this calculation.

$$\text{Ratio} = \left[\frac{\text{Parameter concentration}}{\text{Dust baseline concentration}}\right] \quad (1)$$

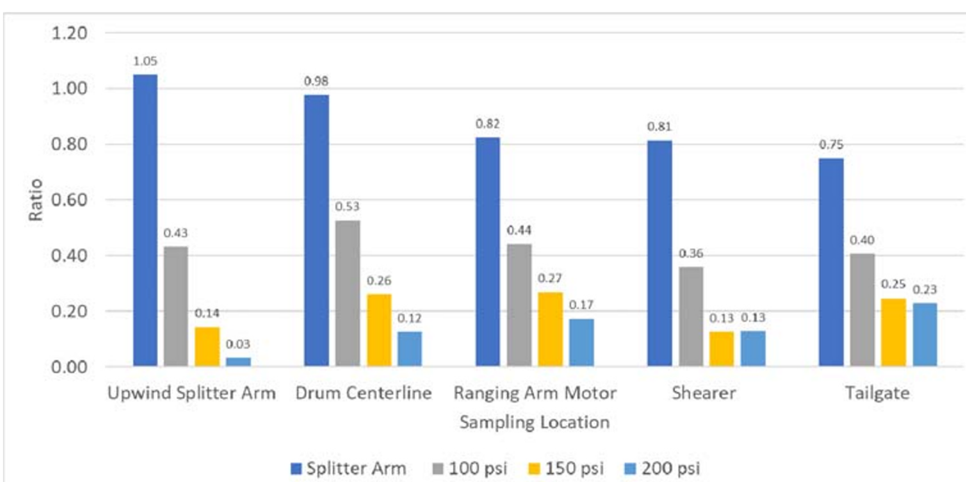

Fig. 4 Spill plate concentration ratios with 45° spray angle at 1.52 m (5.0 ft) from the face

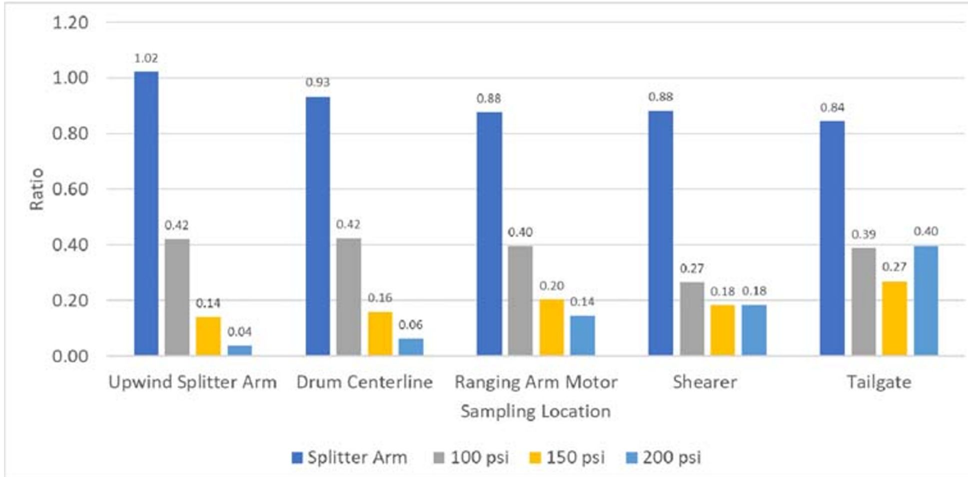

Fig. 5 Spill plate concentration ratios with 45° spray angle at 1.68 m (5.5 ft) from the face

where

Parameter concentration = dust concentration (mg/m^3) during measurement at the splitter arm, 690 kPa (100 psi), 1034 kPa (150 psi), or 1379 kPa (200 psi) parameter.

Dust baseline concentration = dust concentration (mg/m^3) during dust baseline measurement.

This resulted in a ratio that can be used to compare the three different underside shield spray pressures tested to the splitter arm block and the baseline dust block (1.0 ratio). When the ratio was < 1.0, a reduction in respirable dust concentration occurred. When the ratio was > 1.0, an increase in respirable dust concentration occurred. ANOVA analysis was conducted at a 95% confidence level at all sampling locations to determine the statistical significance of the different testing parameters.

Figures 4, 5, 6, 7, 8, 9, and 10 show the dust concentration ratios at the spill plate sampling locations. The pontoon location is not shown in these figures. Figures 4 and 5 show tests at a 45° spray angle at distances of 1.52 m (5.0 ft) and 1.68 m (5.5 ft), respectively. Figures 6, 7, and 8 show tests at a 60° spray angle at distances of 1.37 m (4.5 ft), 1.52 m (5.0 ft), and 1.68 m (5.5 ft), respectively. Figures 9 and 10 show tests at a 75° spray angle at distances of 1.37 m (4.5 ft) and 1.52 m (5.0 ft), respectively. Each of these figures shows that the splitter arm sprays, when operated without the underside shield sprays, did not reduce respirable dust concentrations compared with when the underside sprays were in use in conjunction with the splitter arm sprays. In many cases, use of the splitter arm sprays increased dust concentrations (ratio > 1.0) upwind of the splitter arm and at the drum centerline sampling locations. This shows that, when exclusively using the splitter arm sprays, the dust concentrations in the walkway are generally not improved around the shearer. There were some dust reductions (ratio < 1.0) observed at the downwind sampling locations when just using the splitter arm sprays.

The use of underside shield sprays in conjunction with the splitter arm sprays always resulted in a reduction of respirable dust. Increasing the water pressure on the underside shield sprays generally resulted in better reductions in respirable dust at the splitter arm, drum centerline, and ranging arm motor locations at the spill plate. Table 3 shows the dust concentration ratios at their corresponding locations for the pontoon.

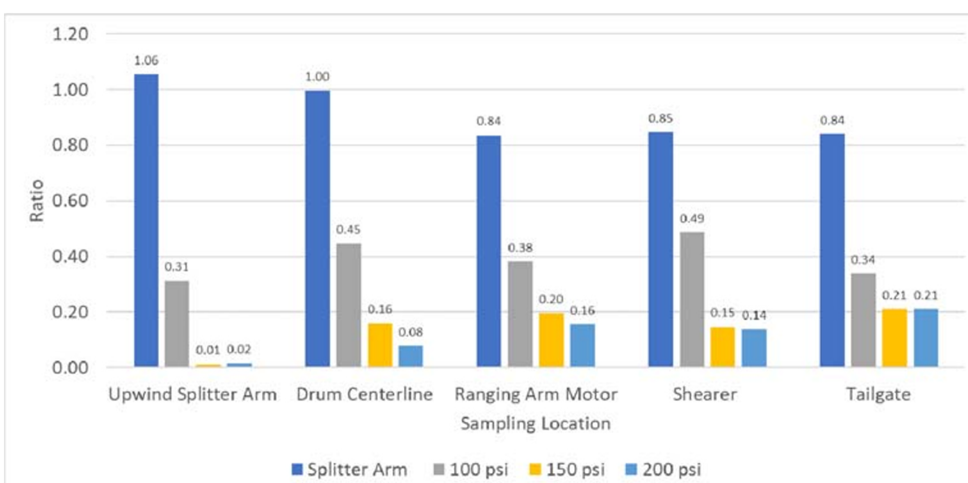

Fig. 6 Spill plate concentration ratios with 60° spray angle at 1.37 m (4.5 ft) from the face

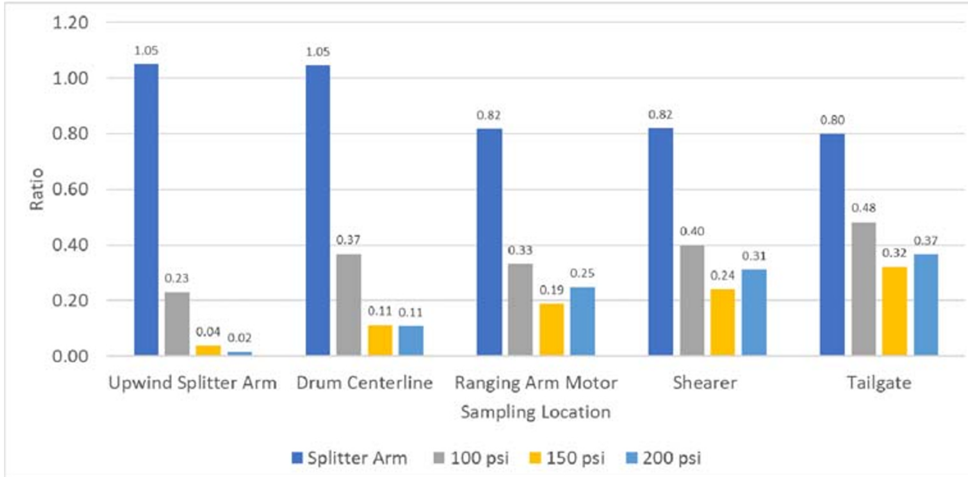

Fig. 7 Spill plate concentration ratios with 60° spray angle at 1.52 m (5.0 ft) from the face

The pontoon sampling location showed a similar pattern of reductions to the spill plate location, except that the ratios tended to increase at the downwind locations of the drum centerline and ranging arm motor locations, which were further downwind of the splitter arm. At the shearer and tailgate locations for the splitter arm, the reductions from increasing water pressure were diverse; reductions generally occurred from 690 kPa (100 psi) to 1034 kPa (150 psi), but not necessarily from 1034 kPa (150 psi) to 1379 kPa (200 psi). Shearer and tailgate locations at the pontoon were not sampled.

Table 4 shows results from the ANOVA analysis at the spill plate sampling locations at a 95% confidence level. This statistical analysis was performed at three sampling locations: upwind of the splitter arm, drum centerline, and ranging arm motor. The shearer and tailgate sampling locations were not analyzed here as mine personnel are not expected to be standing at these locations during longwall operation. An analysis was done to determine if angle, distance, and pressure had a statistical significance with the use of underside shield sprays for dust reductions. Water pressure had a statistical significance at each of the three spill plate locations. Angle and distance had statistical significance at the drum centerline and ranging arm motor spill plate locations. At the upwind of splitter arm and drum centerline sampling locations, statistically significant dust reductions were seen at 75° and 1.37 m (4.5 ft). This steep spray angle, working in conjunction with a shorter distance from the face, was able to significantly decrease dust levels at these two sampling locations. The reductions at these locations are shown in Fig. 9. At the ranging arm motor, significant dust reductions were seen at angles of 60 and 75°, with distances of 1.52 m (5.0 ft) and 1.68 m (5.5 ft). These angles and spray distances appeared to have a better effect on dust reductions moving downwind of the shearer cutting drum at the spill plate sampling locations.

Table 5 shows results from the ANOVA analysis at the pontoon sampling locations at a 95% confidence level. Like the spill plate, this analysis was done at the three sampling locations near the shearer cutting drum. Water pressure had a statistical significance at the drum centerline location. Angle and distance were statistically significant at the drum centerline and ranging arm motor locations. At the drum centerline, a statistical significance in dust reduction was seen at 75° and

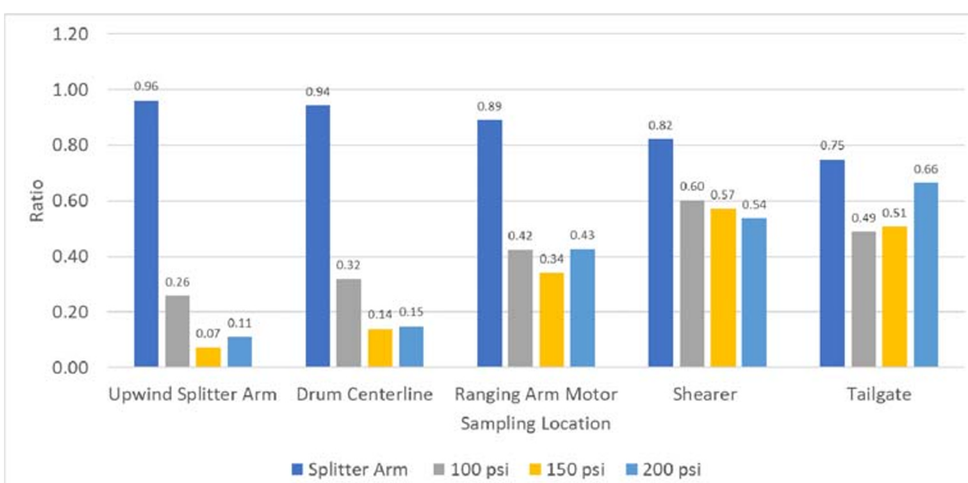

Fig. 8 Spill plate concentration ratios with 60° spray angle at 1.68 m (5.5 ft) from the face

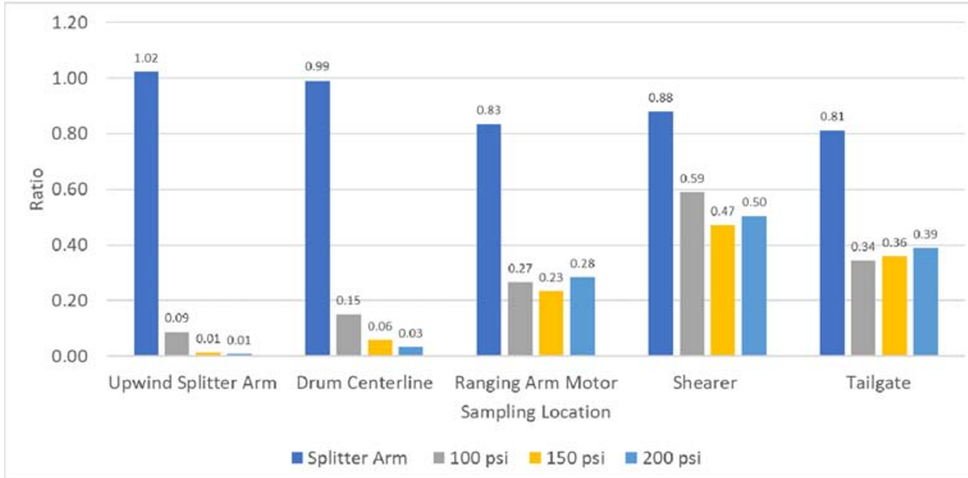

Fig. 9 Spill plate concentration ratios with 75° spray angle at 1.37 m (4.5 ft) from the face

1.37 m (4.5 ft), like the spill plate location. Also, like the spill plate results, a statistical significance was seen at the ranging arm motor pontoon location at angles of 60 and 75°, although only at 1.52 m (5.0 ft). Overall, the pontoon data followed a similar trend as the spill plate data except for the upwind of splitter arm location, where statistical significance was only seen at the spill plate for water pressure. Additionally, the 45° spray angle never produced statistically significant dust reductions at either the spill plate or pontoon locations.

4 Conclusions

NIOSH researchers investigated the impact of underside shield sprays on longwall dust control in a laboratory setting. The testing indicates that underside shield sprays can decrease respirable dust exposure for mining personnel working along the longwall face. Proper alignment and positioning of the underside sprays are important to most effectively reduce exposure to respirable dust. The location of where the mining personnel is positioned is also important to ensure they are best protected from respirable dust exposure. Laboratory testing showed that there is no optimal set of parameters for the underside shield sprays applicable for all locations, as these parameters were dependent upon the sampling location. Analysis did show that the 45° angle underside shield spray, although producing substantial dust reductions, was not the best angle to use when compared with the 60° and 75° angles.

Testing showed that the use of the splitter arm sprays without using the underside shield sprays provided little to no additional reduction in dust concentrations when compared with the dust-only baseline tests. It did appear that the splitter arm sprays worked well in conjunction with the underside sprays in preventing dust from entering the personnel walkway. According to these results, mining personnel would be best protected at the upwind splitter arm and drum centerline locations. Dust is more likely to enter the walkway further downwind toward the tailgate. While these are the best locations for mining personnel to be positioned, the use of underside shield sprays in conjunction with the splitter arm sprays always resulted in reduction of respirable dust at all sampling locations.

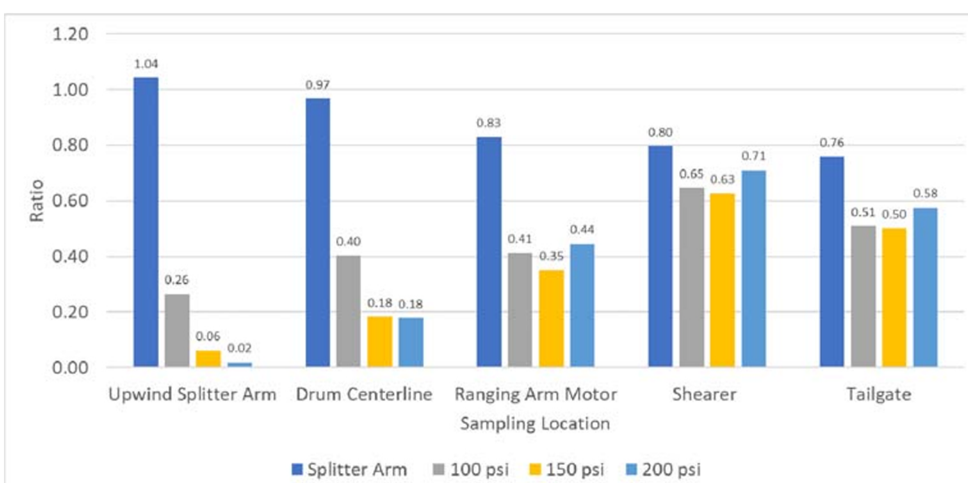

Fig. 10 Spill plate concentration ratios with 75° spray angle at 1.52 m (5.0 ft) from the face

Table 3 Calculated ratios for the different sampling locations at the pontoon

Spray angle	Distance (m)	Underside spray water pressure (kPa)	Upwind splitter arm	Drum centerline	Ranging arm motor
75°	1.37	Off	1.08	1.01	0.86
75°	1.37	690	0.03	0.11	0.17
75°	1.37	1034	0.17	0.02	0.14
75°	1.37	1379	0.04	0.01	0.13
75°	1.52	Off	1.08	1.00	0.83
75°	1.52	690	0.10	0.32	0.43
75°	1.52	1034	0.01	0.09	0.35
75°	1.52	1379	0.11	0.07	0.38
60°	1.37	Off	1.03	1.01	0.84
60°	1.37	690	0.20	0.33	0.30
60°	1.37	1034	0.02	0.07	0.11
60°	1.37	1379	0.04	0.03	0.05
60°	1.52	Off	1.09	1.03	0.89
60°	1.52	690	0.12	0.25	0.28
60°	1.52	1034	0.00	0.03	0.13
60°	1.52	1379	0.03	0.03	0.23
60°	1.68	Off	0.98	0.95	0.83
60°	1.68	690	0.11	0.26	0.37
60°	1.68	1034	0.02	0.07	0.36
60°	1.68	1379	0.10	0.11	0.47
45°	1.52	Off	1.90	1.00	0.82
45°	1.52	690	0.34	0.41	0.39
45°	1.52	1034	0.07	0.18	0.19
45°	1.52	1379	0.02	0.07	0.09
45°	1.68	Off	0.89	1.00	0.87
45°	1.68	690	0.37	0.36	0.31
45°	1.68	1034	0.09	0.14	0.14
45°	1.68	1379	0.01	0.04	0.07

The best parameters for minimizing respirable dust concentrations in this study at the upwind splitter arm and drum centerline locations are using a 75° spray angle at the 1.37-m (4.5 ft) distance. This combination of parameters provides a steeper wall of water close to the mining face, which is best able to protect the sampling locations that were closest to the headgate side of the gallery. The highest spray pressure of 1379 kPa (200 psi) also provided the best protection, showing that using a higher water pressure did not seem to have a negative interaction with the splitter arm sprays. For better protection downwind moving toward the tailgate, a 60° spray angle was more beneficial to use.

Table 4 *P* values from ANOVA analysis at the spill plate sampling locations (P value < 0.05 is statistically significant at a 95% confidence level)

	Upwind of splitter arm	Drum centerline	Ranging arm motor
Angle and distance	0.192	0.001	6.4×10^{-5}
Water pressure	8.8×10^{-17}	1.5×10^{-15}	0.006
45°	0.596	0.446	0.855
60°	0.912	0.707	0.031
75°	0.002	8.29×10^{-5}	0.024
1.37 m (4.5 ft)	0.001	0.001	0.954
1.52 m (5.0 ft)	0.197	0.586	0.018
1.68 m (5.5 ft)	0.388	0.492	0.048

Table 5 *P* values from ANOVA analysis at the pontoon sampling locations (*P* value < 0.05 is statistically significant at a 95% confidence level)

	Upwind of splitter arm	Drum centerline	Ranging arm motor
Angle and distance	0.805	0.023	5.0×10^{-5}
Water pressure	0.546	1.6×10^{-15}	0.055
45°	0.703	0.657	0.913
60°	0.692	0.975	0.020
75°	0.464	0.007	3.62×10^{-4}
1.37 m (4.5 ft)	0.490	0.008	0.656
1.52 m (5.0 ft)	0.521	0.501	0.025
1.68 m (5.5 ft)	0.466	0.411	0.078

This testing did not use a shearer-clearer spray system. Future testing is planned to implement this spray system in conjunction with the underside shield sprays using the parameters that were found to be the most successful during this study. This future testing will determine if there are any negative effects between the two spray systems or whether they will work well in conjunction with one another. Additional future testing of underside shield sprays would ideally take place in an underground coal mine setting in order to confirm the positive results of this laboratory study. This will determine if the sprays can work effectively without affecting the ability of mine personnel to perform their tasks in a safe and productive manner.

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Compliance with Ethical Standards

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

Conflict of Interest The authors declare that they have no conflict of interest.

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