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Canopy Air Curtain to Reduce Diesel Particulate Matter Exposure for Underground Blasters

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INTRODUCTION

Diesel-powered equipment is widely used in the underground mining industry and their popularity results from properties including efficiency, versatility, reliability, and durability. In the U.S. approximately 7,700 diesel engines were used in 177 underground metal and nonmetal mines as of 2005 [MSHA 2005], and these numbers have likely increased since that time. Diesel engines have been shown to be a major contributor to submicron carbonaceous, respirable, and total particulate mass in the air of underground metal mines [Zielinska et al. 2002, McDonald et al. 2003], and their extensive use results in approximately 13,000 underground metal/nonmetal (M/NM) miners (MSHA 2005) in the U.S. being potentially exposed to aerosols and gases emitted by diesel engines (MSHA 2001, MSHA 2006).

Exposure to diesel exhaust has been linked to adverse health outcomes including cancer, cardiovascular, and respiratory diseases (Attfield et al. 2012, Silverman et al. 2012), and in 2012 diesel exhaust was categorized by the International Agency for Research on Cancer (IARC) as a Group 1 human carcinogen (IARC 2012). Exposure to diesel particulate matter (DPM) is especially concerning for underground miners since underground mine environments have been shown to have some of the highest levels of diesel exhaust in the

U.S. (EPA 2002, MSHA 2001, MSHA 2006, Pronk et al. 2009). Due to the potential for elevated DPM concentrations in mines, the Mine Safety and Health Administration (MSHA) promulgated a rule to limit exposures of metal/nonmetal underground miners to DPM to an eight-hour time-weighted average (TWA) of 160 μg/m^3 total carbon (TC) (MSHA 2001, MSHA 2006, MSHA 2008).

Since this rule went into effect, DPM exposures have been reduced, but are still elevated when compared to other occupations (Pronk et al. 2009, Noll et al. 2015). MSHA compliance data between 2005 to the present show that underground blasters represent 21% of all DPM overexposures in M/NM mines and are one of the highest exposed professions in mining often resulting from low ventilation in the area where blasters are working. Because mines have difficulty controlling DPM in these low ventilation areas, additional control technologies may be needed to reduce exposures. Administrative controls, where miners work on off schedules or upstream of diesel vehicles to avoid the exposures to DPM (Noll et al. 2015) is one possibility, but these types of solutions are not always feasible or practical.

A canopy air curtain is another potential control technology to help reduce exposures of blasters to DPM. Listak and Beck (2012) showed that this control technology reduced respirable dust concentration under a roof bolter's canopy by 67%–75% and recommended air velocities greater than 0.5 m/s for dust reductions of greater than 50%. Additional work showed that a canopy air curtain could be designed for a shuttle car, and some initial testing by the National Institute for Occupational Safety and Health (NIOSH) showed reductions of respirable mine dust between 66% to 70%. As seen in Figure 1, the canopy air curtain delivers clean air over the operator's breathing zone. A fan draws in air through a filter to capture the dust

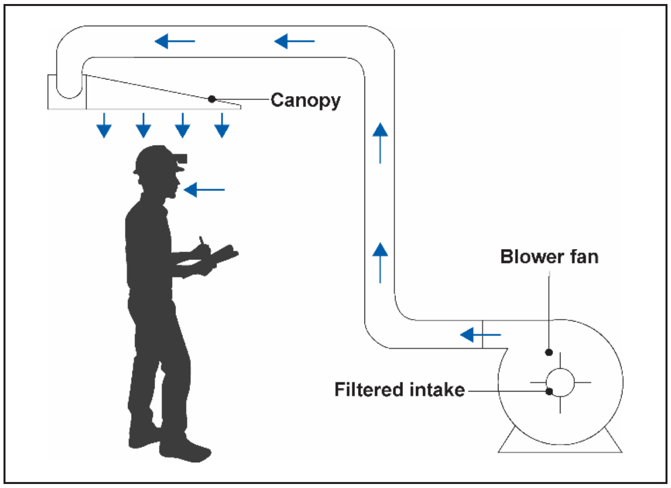

Figure 1. Schematic of canopy air curtain

Figure 2. ANFO loader with basket (the DCAC would be inserted over the basket)

and then supplies clean air beneath the canopy where a miner is working.

The use of the canopy air curtain to reduce exposures to diesel particulate matter was first discussed by Noll et al. (2020). In this study the diesel canopy air curtain (DCAC) reduced the DPM concentrations under the canopy by up to 90%. For this research the DCAC was designed to attach to the basket cover of an ammonium nitrate fuel oil (ANFO) loader (Figure 2) and provide clean air blowing over the miners as they work in the basket. The initial tests used clean air drawn from the mine's intake and did not try to filter the DPM from the air. Filtering DPM has extra challenges when compared to filtering mine dust particles. The particles of DPM are smaller (submicron and nanometer) than dust particles (greater than 1 micron); therefore, the filtration system must be adjusted to capture submicron particles. A MERV 13 filter was used in previous canopy air curtain research on mine dust control, but this filter is only designed to capture 50%–75% of submicron particles, and this capture efficiency is too low for removing DPM, so a higher efficiency filter is needed.

Higher efficiency filters increase the pressure across the filter media which results in decreased airflow or leaks around the filter and reduces the effectiveness of the control for protecting miners from DPM. The optimal filter needs to capture DPM particles at a high efficiency while still allowing the needed airflows to prevent contaminated air from entering the miner's breathing zone. Listak and Beck (2012) recommended velocities greater than 0.5 m/s for dust reductions of greater than 50%. However, airflows too high have been shown to reduce miners' thermal comfort; Roghanchi et al. (2016) suggest the optimal velocity for thermal comfort is between 1–2 m/s. Thus, airflow over the miner should be limited to the range of 0.5 to 2.0 m/s.

This current study presents the results from research evaluating the reduction of DPM concentrations, under the DCAC, when using a higher efficiency filter (MERV 16) to remove DPM from the DCAC airstream.

METHODS

DPM Laboratory in Experimental Mine

Evaluation of the DCAC occurred in the Experimental Mine at the NIOSH Pittsburgh Mining Research Laboratory. Figure 3 is a schematic of the diesel laboratory in the Experimental Mine. The test entry measures approximately 13 feet across, 7 feet high, and 40 feet long. Ventilation flow was maintained through the test entry using a 4,000-cfm fan with the intake located at the back of the test entry and being exhausted into the first crosscut for removal in the mine's return. DPM was injected into the test entry using a diesel generator—Onan model number 12.5HDKCB-11506E with power output 12,500 watts max. @ 120/240 volts, 1 phase, 52 amps, 1800 rpm Genset (3-cylinder in-line water cooled indirect injection 4-stroke, which meets 2012 Tier 4 emissions for U.S. EPA and California nonroad CI engines (Cummings, Gibsonia, PA). For all tests, the Genset load was set to 72% (9,000 watts). A mixing fan, located 6 feet directly in front of the diesel exhaust pipe, is used to mix the fresh air and diesel exhaust. DPM continuously fills the entry, and the ventilation through the test section is approximately 30 ft/min, flowing from the stopping to the face of the entry and then out via the vent tubing into the first crosscut.

The DCAC (Noll 2020) was centrally located in the test entry in the Experimental Mine as shown in Figure 3. Briefly, each plenum, fabricated using durable flame-retardant plastic, measured 3-ft by 3-ft (0.91-m by 0.91-m) with a series of boreholes at uniform spacing (Figure 4) and designed to create airflow of 1.16 m/sec at each borehole

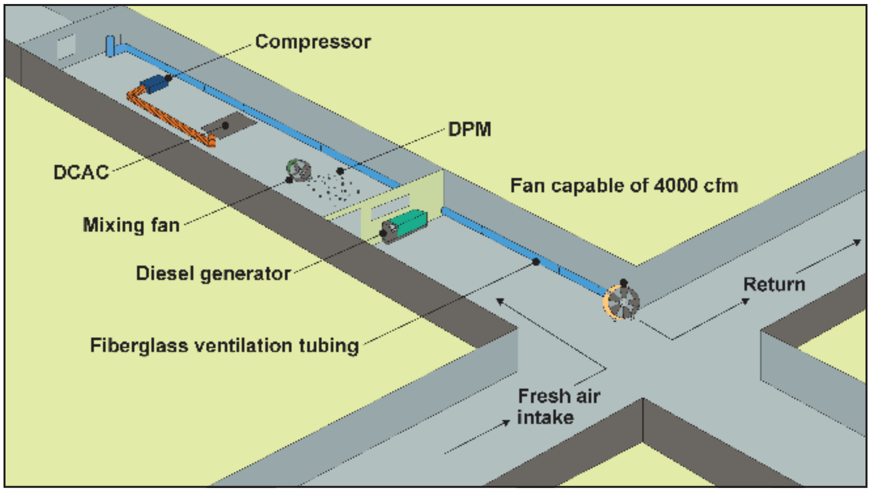

Figure 3. Schematic of the diesel laboratory in the Experimental Mine at NIOSH Pittsburgh

when connected to a compressor rated at 1,800 standard cubic feet per minute (scfm). The compressor passed air through a V-bank filter setup with a MERV 16 filter and was connected to the DCAC with approximately 40 ft of 6-in (15.24-cm) tubing. Airflow (scfm) to the DCAC from the compressor was measured continuously during DCAC operation using a Veltron II transmitter connected to an ACCU-flo Flow Station (Air Monitor, Santa Rosa, CA). Both the blower and associated filter bank were located at the back of the test entry, as shown in Figure 3. The DCAC setup and location were held consistent throughout all testing.

Temperature and relative humidity in the test section were measured continuously during the test using a Vaisala HM70 HUMICAP® (Vantaa, Finland).

DCAC Air Velocity Profile

To determine the air velocity profile of the DCAC and measure DPM concentration, a metal grid, measuring approximately 3 ft × 3 ft , was hung 15 inches below and parallel with the plenum. The 15-inch distance was used to simulate the distance of the miner's breathing zone below the ANFO loader roof, as seen in Figure 2. If the DCAC was installed directly onto the canopy of an average ANFO loader, the top of the DCAC would be approximately 79 inches from the bottom of the basket. The average height of a male is 70 inches, and the breathing zone is 6 inches below the top of the head (Grasgruber et al. 2016, CDC 2016). Therefore, the breathing zone of an average height male would be about 15 inches from the DCAC. The measurement grid contained 3-inch (7.62-cm) squares numbering 9 to a side. Each square was uniquely identified by numbers from front to back from 1 to 9 (Y-axis) and then

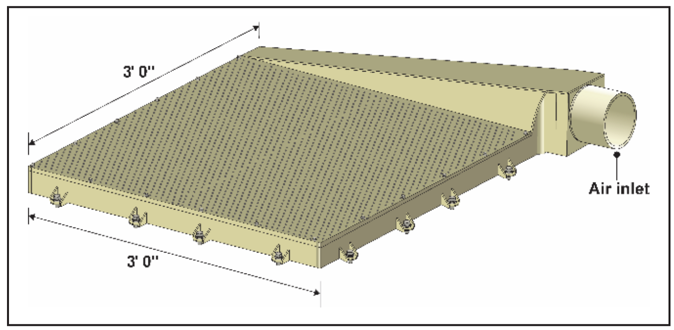

Figure 4. The canopy air curtain designed for the ANFO loader

from left to right by letters ranging from A to I (X-axis), for a total of 81 sampling points. With the DCAC operating, the velocity in the center of each square was measured using a vane anemometer (Davis Instruments, Baltimore, MD) for a period of one minute, after a 30-second stabilization period at each point. This testing scenario was completed in duplicate, and the averaged results are presented.

Sampling Methodology

SKC DPM cassettes (Eighty-Four, PA) with Zefon Elf pumps were used to collect elemental carbon (EC) samples for NIOSH Method 5040 analysis (NIOSH 2016, Birch 2003). These cassettes are used in mining for compliance sampling and include an impactor, with a 1-µm size cut-point, to remove the mine dust from diesel particulate matter, which is then collected on a quartz fiber filter (Noll et al. 2005). After collecting the DPM, the quartz fiber filters were analyzed at the Pittsburgh laboratory for EC and total carbon (TC) via NIOSH Method 5040. The flow rate for samplers was set at 1.7 lpm. Flow rate was calibrated using a Gilibrator (Sensidyne., St. Petersburg, FL) as described by Bugarski et al. (2012).

FLIR Airtec monitors (Teledyne FLIR, Stillwater, OK) were used to provide near-real-time EC data (Noll et al. 2013). This instrument, which was developed at NIOSH (Pittsburgh, PA) measures near-real-time EC concentrations. A diaphragm pump draws EC-laden air, at a set flow rate of 1.7 lpm, through an impactor with a 1-µm size cut-point where the EC is collected onto a 37-mm Teflon filter, housed in a three-piece standard cassette to achieve uniform distribution of EC on the filter. A laser penetrates through a portion of the sample simultaneous with the collection of DPM, and the absorption of the laser's energy is measured and converted to µg of EC collected on the filter using a calibration curve. The instrument collects a reading every minute and provides the average concentration over the past 5–15 min (5–15 min rolling averages), depending on DPM concentration.

EC was used as a surrogate to determine the uniform distribution of DPM. Since EC is a major component of DPM, it has been shown to provide a consistent representation of DPM in underground mines and is used as a surrogate for DPM by NIOSH and MSHA. EC can also be measured at lower concentrations than total carbon measurements and is not prone to interferences (Noll et al. 2006, 2015, 2019).

DPM Reduction Efficiency with Direct Reading Instruments

A metal grid, measuring approximately 3ft × 3ft, was hung 15 inches below and parallel with the DCAC plenum (Figure 5), as discussed in the air velocity profile section. DPM measurements were collected using both an Aerodynamic Particle Sizer (APS, model 3201, TSI Inc., particle size range 0.5–20 µm) and a NanoScan (model 3910, TSI Inc., particle size range 11.5–365 nm) at 25 (5×5) sampling points evenly spaced on the sampling grid.

Test Procedure

Three SKC DPM cassettes with MSA ELF pumps and one Airtec instrument were placed in a basket 2 feet directly in front of the canopy air curtain (C_{Mine}). Three SKC DPM cassettes as well and one Airtec monitor were also placed in a basket located under the DCAC, 15 inches below (to simulate the breathing zone of a male at average height) and in the direct center (C_{DCAC}) as shown in Figure 5. One Airtec monitor was also placed next to the V-bank filter housing located in the rear of the test section. This data was used to calculate DPM loading onto the filter potentially resulting in decreased DCAC flow.

DPM was introduced into the chamber from the Onan diesel generator (Cummins Inc., Gibsonia, PA). A seventy-two percent (72%) load was applied to the generator by a Simplex Swift-e plus 15-kW portable load bank (Simplex, Springfield, IL). At this loading, the EC-to-TC ratio approximates the composition observed in underground mines (Noll et al. 2015). The generator was run for 45 minutes to stabilize the DPM concentration within the test section. DPM stabilization was measured, during this 45-minute period, using both the Airtec and the real-time instruments.

After the 45-minute stabilization period, the DCAC flow was initiated. The DPM cassette pumps were started after an additional 10-minute stabilization period and sampled for 120 minutes, after which they were stopped.

The quartz filter samplers were analyzed for elemental carbon (EC) using NIOSH Method 5040 at NIOSH Pittsburgh. EC is used as a surrogate for DPM for MSHA sampling. The average of the three samples outside of and under the DCAC were calculated. The percent (%) DPM reduction due to the DCAC (E_{DPM}, %) was calculated for each test using equation (1):

$$E_{DPM}(\%) = \left(1 - \frac{C_{DCAC}}{C_{Mine}}\right) \times 100 \qquad (1)$$

The percent reductions for each test were averaged, and a standard deviation was calculated.

The , (%) was calculated for the Airtec instrument data by averaging the rolling averages over the time the DCAC was running for both the instruments located under and outside of the DCAC, then applying equation (1).

The DPM number concentration of the Experimental Mine, not under the DCAC , was first measured with the APS and NanoScan and was immediately followed by a measurement of the DPM concentration beneath the DCAC at one of the 25 sampling points. Air sampling for both APS and NanoScan was conducted simultaneously for one minute by using a Y-shaped stainless-steel tube and conductive tubing that was for splitting the airflow to the APS and NanoScan. A total of 25 aerosol concentrations of the Experimental Mine and 25 DPM concentrations for each sampling point beneath DCAC were measured with three repetitions. The DPM reduction efficiency (, %) of the DCAC was determined by the following equation (2):

$$E_{DPM}(\%) = \left(1 - \frac{C_{DCAC}}{C_{Mine}}\right) \times 100 \qquad (2)$$

Figure 5. Photo of the DCAC inside the test entry showing the sampling baskets, real-time instruments and measurement grid

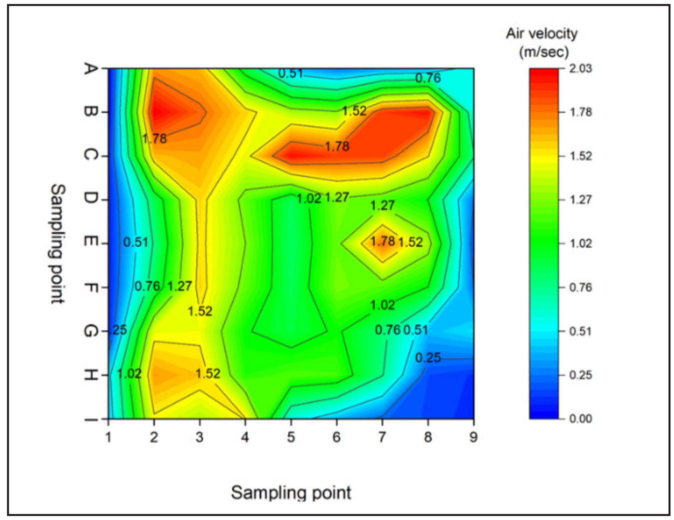

Figure 6. DCAC Air Velocity Profile measured 15 inches below DCAC surface

RESULTS AND DISCUSSION

DCAC Air Velocity Profile

Previous research on canopy air curtains showed that velocities greater than 0.5 m/s are necessary for greater than 50% reduction in dust concentration, but air velocities over 2.0 m/s may create worker discomfort (Listak and Beck 2012, Roghanchi et al. 2016). Using these criteria, the DCAC was designed to create flow rates from 0.5 to 2.0 m/sec. Figure 6 is an air velocity profile measured at 15 inches below the DCAC, as discussed in the Methods section. This figure shows that, although the flow rate across the DCAC is not uniform, it does generally meet the 0.5 to 2.0 m/s specifications, as discussed in the Methods section.

DCAC Flow Rate

The air volume entering the DCAC system did not significantly decrease during our testing. Over the 394 minutes the DCAC was operating, the accumulation of DPM on the MERV 16 filter resulted in a 4.8% reduction in air volume moving through the system. One concern with using the DCAC was that the MERV 16 filter would quickly clog with DPM and reduce the flow rate to the DCAC, resulting in reduced miner protection. Additional tests are necessary for the optimization of filter type to both reduce DPM exposure and filter replacement.

Reduction in DPM (as EC)

Table 1 presents the reduction in DPM (as EC) measured under the direct center of the DCAC for each of the tests.

As shown in Table 1, measurements with the SKC DPM cassette ranged between 84% and 89% with an average of 87% and ranged between 80% and 85% with an average of 83% using the Airtec monitors. Figure 7 presents a chart showing the averaged Airtec monitor data over the three tests. As shown, the initial stabilization period results in very similar DPM concentrations, with a significant decrease once the DCAC is started. DPM exposure for underground blasters have been recorded above 500 μg/m^3. With the greater than 83% protection provided by the DCAC, miners' exposure would be reduced from 500 μg/m^3 without the control to 85 μg/m^3 using the DCAC, which is below the MSHA permissible exposure limit (PEL) for DPM.

Table 1. Percent reduction in DPM (as EC) measured under the direct center of the DCAC.

Test Date	Percent DPM (as EC) reduction with DPM cassettes	Percent DPM (as EC) reduction with Airtec monitor
8/10/2023	84	83
8/17/2023	88	80
8/22/2023	89	85
Average	**87**	**83**
Std dev	**2.6**	**2.5**

Reduction in Particle Number Concentrations

Figure 8 presents a contour plot showing average particle number reduction over the three tests using the NanoScan across the operating DCAC, and Figure 9 presents a contour plot showing average particle number reduction over the three tests using the APS across the operating DCAC.

The DPM percent reduction, as measured by both the APS and NanoScan, ranges from approximately 88% in the center to less than 10% on the edges. However, a large area under the DCAC provides protection of greater than 50%.

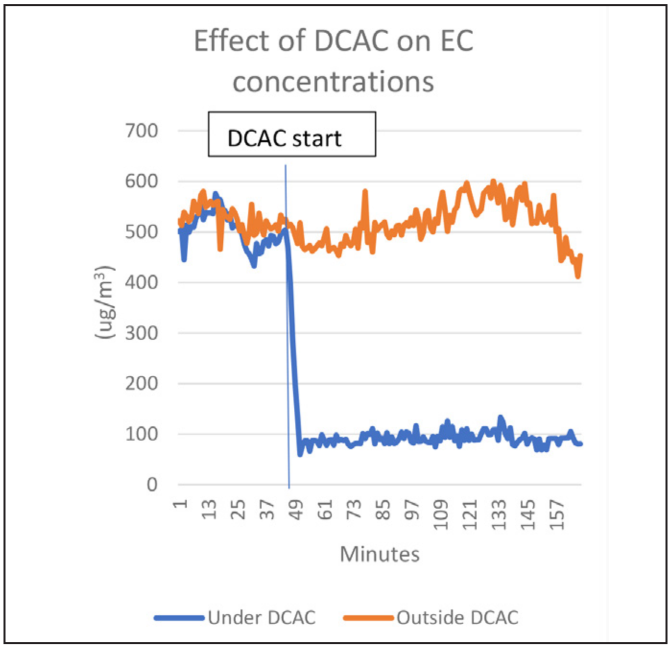

Figure 7. Averaged Airtec data collected in the center of the DCAC

This is an important factor since underground blasters will be moving around under the canopy as they are loading the face.

For each instrument used to measure DPM in these experiments, the results were similar with all showing percent reductions above 80% in the center of the DCAC. Thus, when using the DCAC and conservatively assuming an 80% reduction, an underground blaster could work in DPM concentrations as high as 800 µg/m^3 and still not exceed the PEL of 160 µg/m^3.

Additional research in working mines is necessary to confirm the reductions measured in this laboratory study and to better understand the miners' movements while completing their tasks. For instance, in an ANFO loader operating in an underground mine, two plenums would need to be attached side by side on the canopy of the ANFO loader to cover the whole area of the ANFO platform/basket. Each plenum would use its own blower (rated at 1,800 cfm) and operate independently. Because the reduction in exposure is dependent on the area under the DCAC where the miner is positioned, field-based measurement results may differ from these lab-based results. However, the results reported here show the potential of this control technology for significantly reducing exposure of underground blasters to DPM.

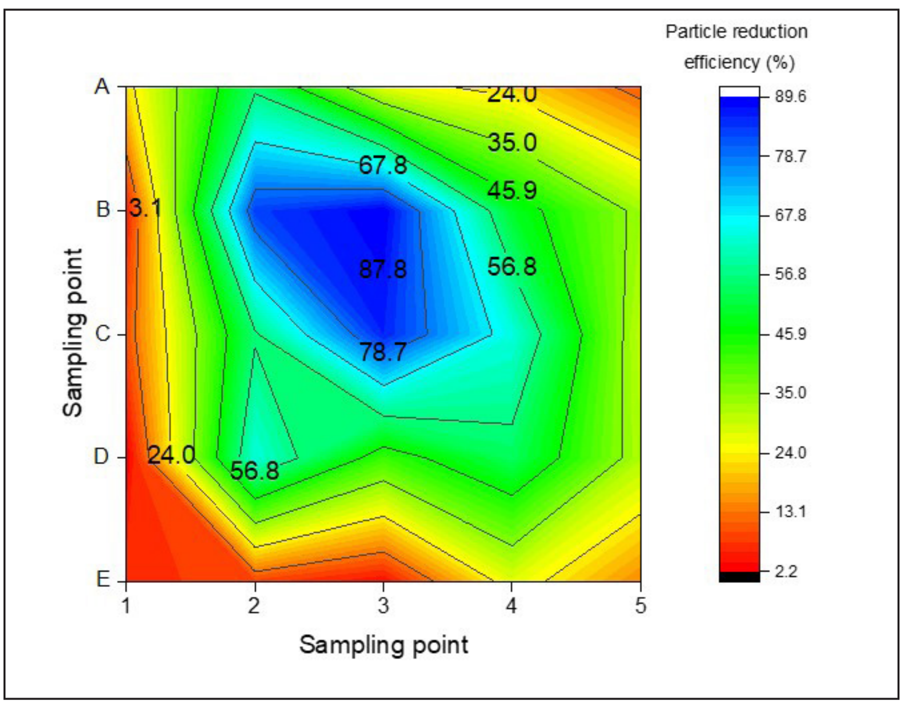

Figure 8. Heatmap showing average particle number reduction over the three tests using the NanoScan across the operating DCAC

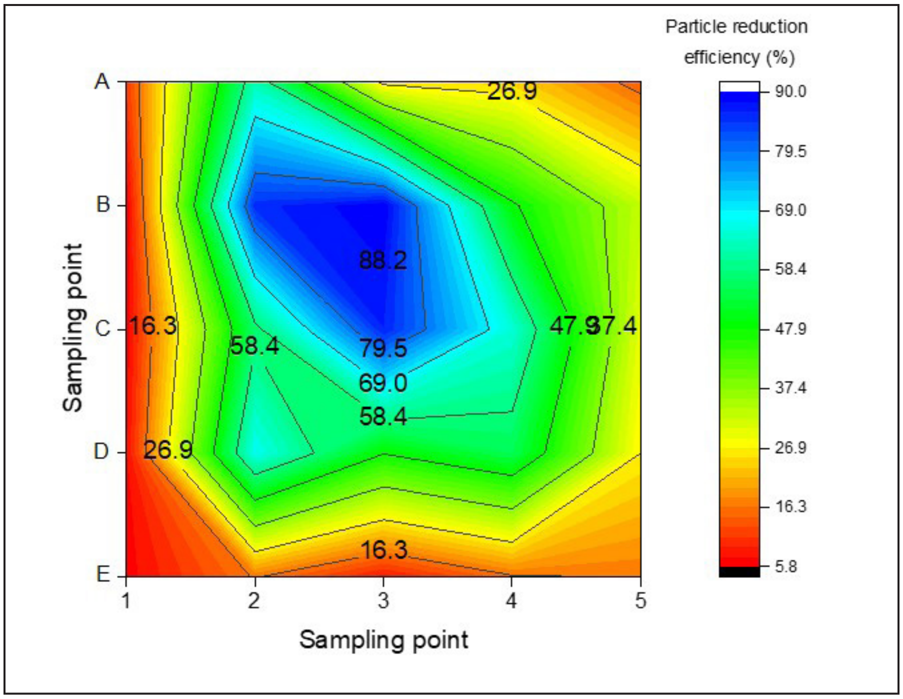

Figure 9. Heatmap showing average particle number reduction over the three tests using the APS across the operating DCAC

CONCLUSIONS

In this study, the DCAC was shown to reduce diesel particulate matter (DPM) concentrations by over 80% when measured 15 inches under the center of the DCAC. Although previous work documented the ability of blowing DPM-free air over a miner to reduce DPM concentrations, this study was the first to test the DCAC's reduction ability when using a filter to remove DPM prior to blowing over the miner. The filter used in this test was a MERV 16 and filtered the high concentrations of DPM for 394 minutes with only a 4.8% reduction in air volume moving through the system. These results show the promise of this equipment for reducing the exposure of underground blasters to DPM while working in areas of elevated DPM concentrations and low ventilation conditions. The low ventilation scenarios used in this study are typical for underground blasters that regularly work in areas with ventilation below 100 fpm. Although this work shows significant reductions using the DCAC, actual reductions for underground blasters will depend on the amount of time blasters remain under the DCAC while working. Additional field work in operating mines is necessary to confirm the results of this study and to determine expected reductions considering real-life work habits of underground blasters.

LIMITATIONS

The amount of data collected for mapping the reductions for other locations besides the center is limited, and additional data would be beneficial. This study did not determine how work habits, such as leaning away from the DCAC, may affect the overall DPM exposures. This study also did not determine the effects of ventilation on the DCAC. Other studies have demonstrated that ventilation can affect the efficiency of the DCAC. However, for the miners who would most likely use this DCAC, the ventilation is usually not high in their work zones.

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DISCLAIMER

The findings and conclusions in this report are those of the authors 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.

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