

EVALUATION OF A CANOPY AIR CURTAIN FOR REDUCING DIESEL PARTICULATE MATTER CONCENTRATIONS

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ABSTRACT

Diesel exhaust is considered a carcinogen to humans by the International Agency for Research on Cancer (IARC). Miners are one of the highest exposed occupations, and those who work outside of cabs, such as blasters, surveyors, and roof bolters, can be the highest exposed working groups. One potential control technology to help reduce these exposures is to use a canopy air curtain (CAC). The CAC delivers clean filtered air over the operator's breathing zone. It has been designed for reducing exposures to respirable dust for roof bolters and shuttle car operators. This study, conducted by researchers from the National Institute for Occupational Safety and Health (NIOSH), modified the CAC design to enable the technology to capture diesel particulate matter (DPM) instead of dust and tested the efficiency of the CAC to reduce DPM concentrations underneath the CAC. With a 3-inch lip, the CAC reduced DPM exposures by over 90% at its center and about 80% in the left and right front of the canopy, demonstrating the effectiveness of the redesigned CAC. Therefore, the CAC may provide protection to blasters and other types of mine workers working under a canopy.

INTRODUCTION

Exposure to diesel exhaust has been linked to various adverse health outcomes (Vermeulen et al. 2014, Attfield et al. 2012, Silverman et al. 2012, Ping and Guang 2017). In 2012, the International Agency for Research on Cancer (IARC) categorized diesel engine exhaust as a carcinogen to humans (Group 1) (IARC 2012). Exposure to DPM is especially concerning for underground miners. Since underground miners work alongside diesel equipment in a confined environment, they can be exposed to some of the highest levels of diesel exhaust in the country (EPA 2002, MSHA 2001, 2006, Pronk et al. 2009). Therefore, 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 $\mu\text{g}/\text{m}^3$ total carbon (TC) (MSHA 2001, MSHA 2006, 2008). This compliance limit is based upon feasibility with the goal being to reduce a carcinogen, in this case DPM, to the lowest levels possible.

Since this rule went into effect, DPM exposures have been reduced, but they are still above levels of other occupations (Pronk et al. 2009, Noll et al. 2015). Looking at MSHA compliance data between 2009–2014, approximately 20%–25% of personal samples are out of compliance each year. Further investigation shows that 46% of the out-of-compliance samples are from blasters, load haul dump (LHD) drivers, and scalers, with blasters being one of the highest exposed professions in mining. The average DPM exposures for blasters is about 156 $\mu\text{g}/\text{m}^3$ TC with exposures at times above 500 $\mu\text{g}/\text{m}^3$ TC. These professions usually work outside of cabs and, many times, downstream of diesel equipment. Mines can have a difficult time ventilating the areas where these miners commonly work because they are often dead-end entries. Some mines are using administrative controls to have the blasters work upstream of diesel vehicles or on a different shift than co-workers who operate diesel vehicles to avoid the exposures to DPM (Noll et al. 2015). However, these types of solutions are not always feasible or practical. It can be equally as difficult to control the DPM exposures of scalers and bolters who work outside of

cabs and LHD operators who work in dead-end entries with a diesel vehicle.

Many of these workers spend a substantial amount of their time under a canopy. Therefore, one potential control technology to help reduce their exposures may be using the canopy air curtain (CAC). As demonstrated in Figure 1, the CAC is designed to fit underneath a canopy and to deliver clean air over the operator's breathing zone. A fan draws in air through a filter to capture the dust and then supplies clean air beneath the canopy where a miner is working. The development of the CAC dates back to the 1970s starting with the initial development of the CAC by the Donaldson Company, Inc. under contract from the U.S. Bureau of Mines (Krisco 1975). This CAC was originally developed for continuous miner operators when continuous mining machines had cabs. The need for a CAC on the continuous miner was eliminated when the cab was removed from the machine design. However, CAC development progressed to include designs for a roof bolting machine to protect roof bolters from respirable coal mine dust (Goodman and Organiscak 2002, Listak and Beck 2012, Reed et al. 2017). The original NIOSH design of the CAC provided even airflow across the entire canopy, and laboratory testing demonstrated the ability of the CAC to reduce respirable dust concentrations by about 67%–75% in ventilation ranging from 10–120 fpm (Listak and Beck 2012).

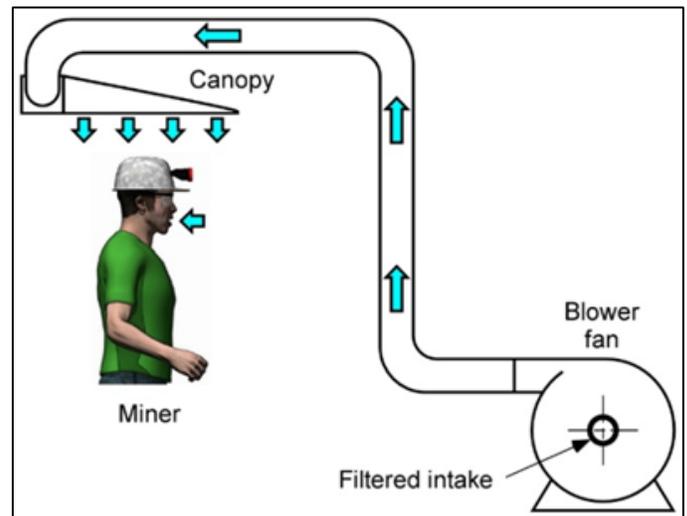


Figure 1. Schematic of the operation of the canopy air curtain.

J.H. Fletcher and Co. incorporated the CAC into their roof bolters but revised the design to have the airflow just around the perimeter of the canopy using slotted openings. Laboratory testing revealed this design only reduced the respirable dust concentrations by 17%–24% (Reed et al., 2017). In order to increase its effectiveness, Fletcher redesigned the air canopy to provide airflow over the entire canopy, but the perimeter airflow had a higher flow rate. Laboratory testing showed this change increased the reduction of respirable dust from 17%–24% to about 50% (Reed et al. 2017). There were still some differences

between the original NIOSH design and the new Fletcher roof-bolter design, for the original NIOSH design had smaller diameter holes and provided uniform air velocity across the canopy. The next type of CAC was designed for shuttle cars and incorporated many of the design parameters from the original NIOSH-designed CAC, such as uniform airflow across the canopy. Some initial testing in the NIOSH laboratory demonstrated reductions in respirable coal dust between 74%–83% in a ventilation airflow of 120 fpm (Reed et al. 2018).

Given the success of the CAC to reduce dust exposures, this technology may be modified to provide protection of some miners to DPM as well. However, there are some extra challenges when trying to reduce DPM instead of dust. The particles of DPM are smaller (submicron and nanometer) than dust particles (greater than 1 micron) and act more like a gas. Therefore, one of the first adjustments is for the filtration system to have the ability to capture submicron particles. A MERV 13 filter is currently used in the CAC for shuttle cars, but this filter is only designed to capture 50%–75% of submicron particles. This capture efficiency is too low. Therefore, the initial tests will be performed with higher-rated filters.

Efficiency is not the only characteristic to evaluate when determining the best filter for the CAC, for the filter with the best collection efficiency may not provide the best protection. A higher-rated filter media can increase backpressure resulting in decreased airflow or an increase in leaks around the filter, reducing the amount of protection from DPM to the miner. 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. MERV 16 filters are designed to reduce this size of particles by over 95% and have been shown to be effective for use in enclosed cabs (Noll et al. 2014, Noll et al. 2011, Cecala et al. 2016).

A CAC was designed and constructed to fit an ANFO loader and to capture DPM. It was based upon the design of the one for the shuttle car. Two identical 3-foot by 3-foot CAC systems were fabricated out of plastic using 3D printing technology based upon the shuttle car design where there is uniform airflow across the plenum (Figure 2). Combining these two pieces would cover the whole canopy for a Fletcher ANFO loader. A MERV 16 filtration system was implemented to capture the DPM, and a blower with a capacity of 1,800-cfm airflow was used to overcome the backpressure due to the CAC size, filtration, and tubing to provide the same airflow as the shuttle car CAC onto the miner.

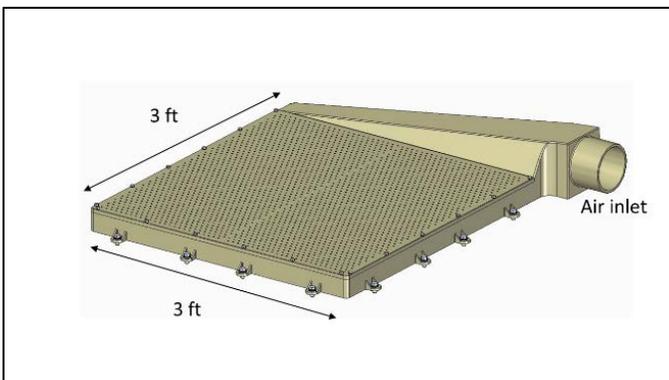


Figure 2. The canopy air curtain designed for the ANFO loader.

The CAC was tested for reducing DPM concentrations in the Experimental Mine at NIOSH Pittsburgh. This study concentrated on evaluating how well providing clean air over a mine worker would reduce DPM exposures. The study did not evaluate the efficiency of the filtration technology, just the concept of the ability of the CAC to provide protection against DPM. Therefore, for the purpose of this study, the air for the CAC was drawn from a DPM-free environment. If providing clean air over the miner resulted in substantial reductions in DPM exposures, then the filtration system would be evaluated and optimized.

METHODS

DPM Laboratory in Experimental Mine

At the NIOSH Pittsburgh site, a coal mine, which was a working mine over 100 years ago, is used as a laboratory setting for performing tests to evaluate the CAC for DPM protection. In this Experimental Mine, a section as shown in Figure 3 was set up to provide DPM into the test section. The entry is about 13 feet across, 7 feet high, and 40 feet long. Tubing is extended from the face of the entry outby to the first cross-cut where a 4,000-cfm fan draws air from the entry. Fresh air enters through a 2-feet by 4-feet opening window of a stopping that isolates the test section from the rest of the mine. DPM is injected using an Onan diesel generator [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, meets 2012 Tier 4 emissions for U.S. EPA and California nonroad CI engines) (Cummings, Gibsonia, PA) (Figure 4). Fresh air and diesel are introduced at the stopping inside the test section, and a fan is used for mixing. 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 cross-cut. The mine's ventilation system removes the DPM out of the mine.

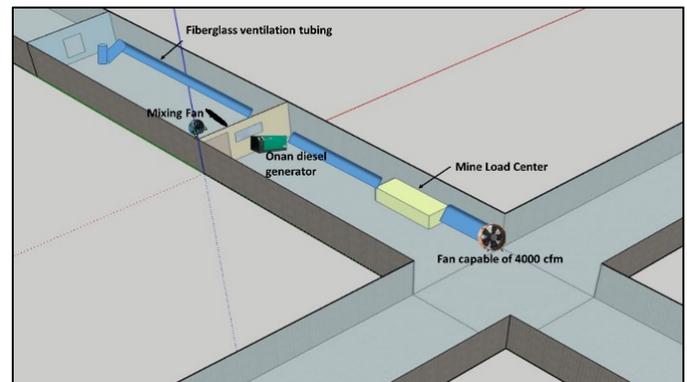


Figure 3. Schematic of diesel laboratory in the Experimental Mine at NIOSH Pittsburgh.



Figure 4. The filtration unit to the CAC was upstream of the diesel source and outside of the entry. Tubing was attached to the filtration and blower into the entry and onto the CAC inside the entry.

Sampling Methodology

SKC DPM cassettes with MSA Elf pumps were used to collect elemental carbon (EC) samples for NIOSH method 5040 (NIOSH 2016, Birch 2003). These cassettes are used in mining for compliance sampling and contain an impactor to segregate dust from diesel and quartz fiber filters to collect the particulate (Noll et al. 2005). After

collecting the DPM, the quartz fiber filters are sent to a laboratory to be analyzed for EC and total carbon (TC) via NIOSH method 5040.

FLIR Airtec monitors (FLIR, Stillwater, OK) were used to provide near-real-time EC data (Noll et al. 2013). This instrument was developed as a result of extensive research conducted at NIOSH (Pittsburgh, PA) and allows for near-real-time monitoring of EC concentrations and exposures via laser extinction. A diaphragm pump draws ambient air at a set flow rate that enables a preselector to perform size selection at a 1- μm size cut-point. Conductive tubing connects the preselector to a Teflon filter to allow EC to embed on the filter without adhering to the tubing walls. The 37-mm Teflon filter is 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.

The flow rate for samplers was set at 1.7 lpm. Flow rate was calibrated using a Gilibrator (Gilian Instrument Corp., West Caldwell, NJ) as described by Bugarski, et al. (2012).

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).

A high-sensitivity (HS) cassette with a quartz filter was also used to collect NIOSH method 5040 samples in the CAC tests. This cassette has a LOD about 5 times lower than the SKC DPM cassette (Noll et al. 2020). In addition, an Airtec monitor was selected to use an HS cassette to detect the lower DPM concentrations present in the center of the CAC. The HS cassette uses the top two sections of a SureSeal three-piece cassette (SKC, Inc., Eighty Four, PA) with a modified bottom section. The modified bottom section is designed to fit a 37-mm filter but directs the DPM onto just a 0.5-cm² section of the filter. This concentrates the DPM and allows the measurement of lower concentrations with the standard flow rate.

Test Procedure – Baseline

The first set of experiments were to indicate how uniform DPM was throughout the testing area. A CAC was placed into the entry as shown in Figure 5. It was centrally located in the test section. Tubing was attached to the CAC and extended out of the entry and attached to the blower filtration system (MERV 16 filter used) upstream of the source of DPM. This allowed DPM-free air to be drawn through the tubing from a blower to the CAC. The CAC setup and location were held consistent throughout all testing for baseline and efficiency tests.

Three SKC DPM cassettes with MSA ELF pumps and one Airtec instrument were placed in a basket outside of the canopy air curtain. Underneath the canopy, one SKC DPM cassette as well as one Airtec monitor were located in the center. They were located 15 inches below the CAC to simulate the breathing zone of a male at average height. If the CAC was installed directly onto the canopy of a Fletcher ANFO loader, the top of the CAC would be 79 inches from the bottom of the basket. The average height of a male is 70 inches and the breathing zone is approximately 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 CAC.

DPM was introduced into the chamber from the Onan diesel generator (Cummins Inc., Gibsonia, PA). Sixty-four percent load was applied to the engine by a Simplex Swift-E plus 15kW portable load bank (Simplex, Springfield, IL). At this loading, the EC-to-TC ratio simulates the composition observed in underground mines (Noll et al. 2015). After 2–3 hours, the DPM was turned off. After the chamber was exhausted, the samplers were turned off. This was repeated three times.

The quartz filter samplers were analyzed for elemental carbon (EC) using NIOSH method 5040 at NIOSH Pittsburgh. The average of the three samples outside of the CAC were calculated as well as the average for the samples under the CAC. The % reduction due to the

location of the samplers (under the CAC compared to outside) was calculated for each test. The average reduction of the three tests was calculated as well as the 95% confidence limit as described by Skoog and West 1986.



Figure 5. Photo of the CAC inside the entry showing the sampling baskets.

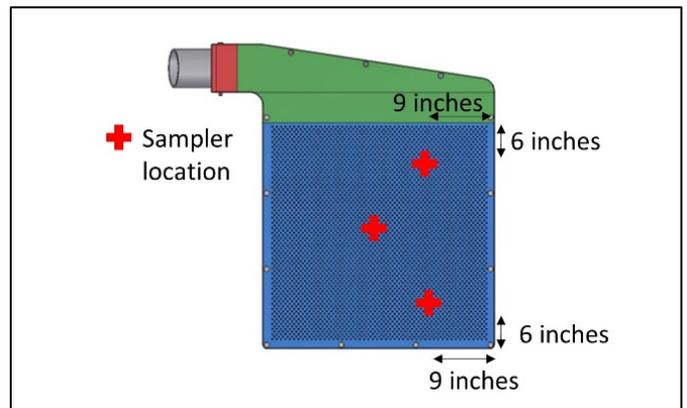


Figure 6. Sampler locations underneath the canopy plenum (not to scale).

Test Procedure – DPM Evaluation

The next set of experiments was to evaluate the efficiency of the CAC to reduce DPM concentrations.

With the CAC located as previously mentioned, three SKC DPM cassettes and one Airtec instrument were placed in a basket outside of the canopy air curtain. Underneath the canopy, one SKC DPM cassette as well as one Airtec monitor were located in the center. They were located 15 inches below the CAC to simulate the breathing zone of a male at average height. If the CAC was installed directly onto the canopy of a Fletcher ANFO loader, the top of the CAC would be 79 inches from the bottom of the basket. The average height of a male is 70 inches and the breathing zone is approximately 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 CAC.

In the center of the CAC, the high-sensitivity (HS) cassette with a quartz filter was also used to collect NIOSH method 5040 samples. In addition, the Airtec monitor also used an HS cassette to detect the lower DPM concentrations present in the center of the CAC. DPM was introduced into the chamber from the Onan diesel generator (Cummins, Gibsonia, PA) as previously mentioned. After 2–3 hours, the DPM was turned off. After the chamber was exhausted, the samplers were turned off. The Airtec was downloaded and the filters

were analyzed using NIOSH method 5040. The whole test with new filters was repeated six times.

Then, to try to direct more airflow in the location of the miner, brattice cloth was placed around the CAC allowing a 3-inch lip to extend below the CAC. A strap and duct tape were used to temporarily hold and seal the lip for this testing. The test was repeated another six times with the lip.

In order to determine if the reductions in DPM would change if the worker is located more towards the front of the CAC, the sampling locations were changed. The DPM cassette and the Airtec monitor with HS cassette were placed 9 inches from the front of the CAC and 15 inches below on the left and 6 inches from the right side. Another SKC DPM cassette and Airtec monitor were placed 9 inches from the front of the CAC and 15 inches below on the left but 6 inches from the left side (Figure 6). The three outside samplers were again placed in the basket outside of the CAC. Then, the DPM experiment was repeated three times, first with no lip on the CAC and then with a 3-inch lip on the CAC.

Another experiment was performed, except this time the SKC DPM cassette and Airtec monitor were placed 6 inches from the front of the CAC and 6 inches from the right. Another set was placed 6 inches from the front and 6 inches from the left. A test was performed, once with no lip on the CAC and once with the 3-inch lip.

RESULTS AND DISCUSSION

Baseline

What could be considered a statistically significant reduction in DPM under the CAC when measuring in the NIOSH laboratory in the Experimental Mine? In other words, what reductions could just be from sampling in the section of the chamber under the CAC compared to the location outside of the CAC. With the CAC off, the average reduction in EC when comparing samples collected outside of the CAC to those under the CAC was $11.81 \pm 9.76\%$. With 95% confidence, the reduction due to just the location of the sample will be between 2-22%. The 95% confidence range is from only three sets which coincides with a t value of 4.3. More tests may reduce this range.

Reductions in DPM

As seen in Table 1, the reductions of EC, hence DPM, in the center of the CAC ranged from 81%–91% with an average of $86 \pm 4\%$ (the $\pm 4\%$ represents the 95% confidence interval). Figure 7 provides a good visual aspect of the reductions and concentrations of DPM from a typical test. The outside concentration was between 200–300 $\mu\text{g}/\text{m}^3$ EC that is in the range of concentrations that can be present in underground mines (Noll et al. 2015). The point at which the EC starts to drop off corresponds to the time the diesel generator was shut down for the test. The inside CAC concentrations are all less than 50 $\mu\text{g}/\text{m}^3$ EC, with the average closer to 35 $\mu\text{g}/\text{m}^3$ EC. These inside concentrations are less than half of the personal exposure limit (PEL).

Table 1. % Reductions in DPM for the CAC.

Position: center of CAC 15 inches below CAC	
no lip	3 inch lip
81	95
82	96
85	90
87	98
89	95
91	94
Average and 95% confidence range	
$86 \pm 4\%$	$95 \pm 3\%$

What if the worker is not under the center but more towards the front as could be expected when blasters are loading the face? As seen in Tables 2 and 3, DPM was reduced by over 80% when 9 inches from the front edge and 15 inches from the top. As mentioned earlier, 15 inches was chosen since this would be the location of the breathing zone of a worker at the average height of a man if the CAC was mounted to the canopy of a Fletcher ANFO loader.

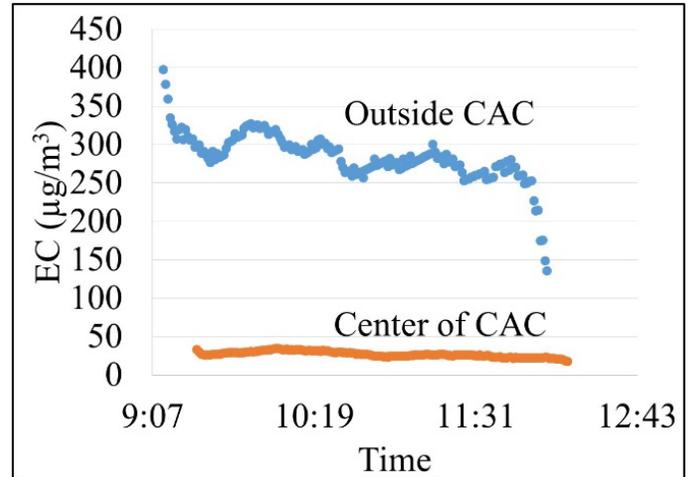


Figure 7. Real-time graph of the DPM outside of the CAC and then underneath at the center of the CAC with no lip.

Table 2. % Reductions in DPM for the CAC.

Position: 9 inches from front, 6 inches from right 15 inches below CAC	
no lip	3 inch lip
88	95
80	90
94	90
Average and 95% confidence range	
$87 \pm 17\%$	$92 \pm 7\%$

Table 3. % Reductions in DPM for the CAC.

Position: 9 inches from front, 6 inches from left 15 inches below CAC	
no lip	3 inch lip
86	86
80	89
80	96
Average and 95% confidence range	
$82 \pm 9\%$	$90 \pm 13\%$

When the measuring the DPM 6 inches from the front and either 6 inches from the left or the right, the reduction in DPM was at 80%. As seen in Figure 8, the concentration of EC around 200–300 $\mu\text{g}/\text{m}^3$ outside coincided with concentrations of EC below 50 $\mu\text{g}/\text{m}^3$. Again, DPM concentrations are well below the personal exposure limit (PEL). As the miner works more towards the edge, the DPM concentrations under the CAC are expected to increase.

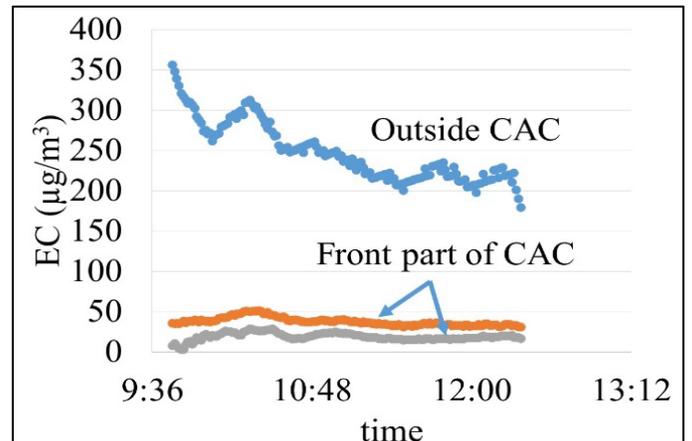


Figure 8. Real-time EC concentration outside and under front part of CAC with no lip.

In order to attempt to improve the reductions of DPM by directing more of the air towards the worker, a 3-inch lip was placed around the CAC. As seen in Table 1, this modification resulted in the reduction of DPM in the center of the CAC to increase from 86% to 95% when 15 inches below the CAC. As seen in Figure 9, at concentrations of 200–300 $\mu\text{g}/\text{m}^3$ EC outside, the concentrations of EC at the center are about 10–15 $\mu\text{g}/\text{m}^3$ EC; again, well below the PEL.

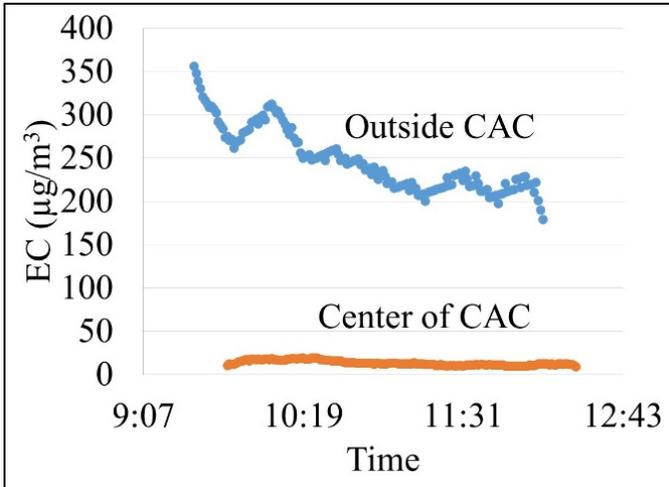


Figure 9. Real-time EC concentration outside and under center of CAC with 3-inch lip.

As seen in Tables 2 and 3, the percent reductions 9 inches from the front of the CAC with the lip were mostly near 90%, while the reductions without the lip were mostly in the 80% range, with reaching 90% at times. For most experiments, the lip seemed to produce higher percent reductions than when the lip was absent, but the 95% confidence intervals between the data from underneath the CAC with no lip and the data from underneath the CAC with the 3-inch lip overlapped each other, demonstrating no statistical difference between the average reductions at this location whether the lip was used or not. However, only three tests were performed which may not be a sufficient number of tests for analysis. Conducting more tests may reduce the variability, which in turn may reduce the 95% confidence interval.

At 6 inches from the front, the lip provided little to no improvement in DPM reductions compared to the results for the 9-inch distance from the front. When 6 inches from the front and 6 inches from the left, an 81% reduction in DPM was measured with the CAC with the lip. When 6 inches from the front and 6 inches from the right, 84% reductions were observed. These reductions are very similar to the 80% reductions observed without the lip.

CONCLUSION

The CAC has demonstrated that it can provide an atmosphere in the miner's breathing zone well below the PEL in concentrations observed in underground mines. The atmosphere underneath the CAC can be up to 95% lower in DPM concentrations than the mine atmosphere. The amount of DPM in the air under the CAC will depend upon the location horizontally and vertically relative to the center of the CAC. The reductions decreased from 95% in the center to 80% approximately 12 inches towards the front of the CAC with the 3-inch lip. A 3-inch lip around the CAC provided some improvements to the reductions of DPM at certain locations under the CAC. A longer lip may even provide some further benefit.

This shows promise for reducing exposures to blasters and roof bolters. The actual reductions to blasters will depend on how much time they spend under the CAC and where they are positioned under the CAC. If they spend a lot of time leaning over the edge, out of the protection zone of the CAC, then their DPM exposures will be higher than if they can design their work habits to be underneath the CAC

most of the time. Therefore, field work is necessary to determine actual expected reductions with work habits taken into account.

The effects of the filtration system also need further evaluation. The reductions reported in this study only represent a scenario in which DPM free air is used as the source for the CAC. The filtration section of the CAC was outside of the chamber or entry way where the diesel exhaust was inserted because the first part of our evaluations of the CAC was to determine if providing clean air over a miner could reduce DPM concentrations. The variable of the efficiency of the filtration unit was not to be considered at this time.

Since the data does seem to show that providing clean air upon a miner can substantially reduce DPM exposures, one of the next steps is to evaluate the effectiveness of the filtration unit. Because the filtration unit may not collect all DPM, the DPM reductions reported in this study may be lower when the whole system including filtration unit is considered.

LIMITATIONS

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

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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