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Improving protection against respirable dust at an underground crusher booth

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Abstract

The U.S. National Institute for Occupational Safety and Health completed a 15-month study at an underground limestone mine crusher booth that evaluated three research parameters: (1) the effectiveness of a filtration and pressurization system for improving the air quality inside the operator booth, (2) the relative effectiveness of $\eta > 99$ and $\eta > 95$ experimental prototype filters in the system, and (3) the performance of three different cab pressure monitoring devices. The protection factor was quantified monthly using particle counters in the respirable dust range of 0.3 to 1 μm particle size, and gravimetric dust samples were gathered at the beginning and end of the overall study. Under static (closed-door) conditions, the filtration unit offered a gravimetric calculated protection factor between 10 and 31, depending on the filter type and loading condition. The monthly particle counting analysis shows that the $\eta > 95$ filter offers a protection factor nearly five times that of the $\eta > 99$ filter, where $n = 15$ samples. The booth pressure monitors were tested and proved to be a valid indicator of system performance over time.

Introduction

Designed and installed correctly, enclosed cabs, operator booths and control rooms offer mine workers protection from noise and physical hazards, such as flying rock and debris, as well as a more comfortable environment in regards to temperature and humidity (Organiscak et al., 2016). While it is easy to quantify the operation of a cab's air-conditioning unit by measuring the temperature, or observe whether the cab offers protection from flying debris, it is somewhat more difficult to quantify its performance in reducing respirable dust hazards.

The U.S. National Institute for Occupational Safety and Health (NIOSH) has been conducting applied research to improve the air quality inside the enclosed cabs of mobile equipment, resulting in the mathematical modeling of enclosed cab filtration systems (Organiscak and Cecala, 2008). The same principles that govern the performance of filtration systems on mobile equipment are applicable to stationary enclosures such as operator booths and control rooms (Noll, Cecala and Hummer, 2015). While stationary

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enclosures are similar to mobile cabs, the work area can be significantly larger. Workers in booths and control rooms also tend to stay within the enclosure for a greater percentage of the day as opposed to workers on mobile equipment who enter and exit frequently.

Enclosures must also ensure that workers have a healthy supply of fresh air to avoid elevated levels of carbon dioxide (CO_2), which are known to cause headache and dizziness, impairing cognitive function. The American Society of Agricultural and Biological Engineers (ASABE, 2013) recommends a minimum airflow for enclosed cabs of at least 42.5 m^3/h (25 cfm) per person to ensure acceptable levels of CO_2.

An effective filtration system must be designed, installed and maintained to ensure workers' protection against respirable particulates over the course of their shift. This design is a function of the key operating parameters, such as intake and recirculation airflow quantities, filter efficiencies and the leaks around filters (Cecala et al., 2014). Pressure monitors offer an inexpensive and effective way to track the performance of a booth's filtration and pressurization system. By referencing the pressure immediately after a new filter installation, as well as when in-take air volume drops below 42.5 m^3/h (25 cfm) per person, operators can accurately estimate the filter's remaining life and better plan maintenance tasks. In addition to long-term duration pressure changes that correspond to routine filter loading, the signal can also be useful for detecting possible problems (Cecala, Organiscak and Noll, 2012). For example, a sudden decrease in enclosure pressure may indicate that a door is stuck open, a tear has developed in a seal, or there is blockage in the ductwork. Continuous pressure monitors can be logged as part of an overall maintenance program, and alerts at either the operator or health and safety staff level can be used to facilitate maintenance and improve cab protection.

NIOSH partnered with a mine that had relocated its primary crusher operation and control booth from the surface to an underground site. In an effort to determine the effectiveness of this commercially installed booth, the air quality was evaluated. The original booth did not have a dedicated filtration system — only a ductless heating and cooling system and a roof-mounted fan, which brought air in through a diffuser plenum. Sensing that the fan was pulling dust inside the booth, the crusher operators at this mine typically kept the fan off whenever possible. Simultaneous particle counting inside and outside the booth confirmed their intuition: the air quality inside the booth was significantly worse, with 2.9 times higher submicrometer dust concentrations (Table 1) with the fan operating. Without effective filtration, the fan simply pulled dust-laden air and diesel particulate matter in from the outside.

To address these circumstances at the cooperating mine, the objective of this field study was to quantify, improve and monitor the air quality inside an underground crusher booth. Specifically, NIOSH researchers designed the following research tasks to meet these objectives:

- Quantify the protection factor offered by the installation of an after-market pressurization and filtration system.

- Compare the effectiveness of two filters: one with higher efficiency and restriction, and the other with lower efficiency and restriction.
- Compare the outputs of three manufacturers' pressure monitors against a known standard monitor.

Test conditions

The booth installed by the mine had interior dimensions of 295 × 244 × 180 cm (116 × 96 × 71 in.), yielding a volume of approximately 13.0 m^3 (459 cu ft). Occupants of the booth are subject to a variety of dust sources, including mining activities upstream (blasting, scaling and haulage) and, notably, the dumping pit, where 60-t (66-st) diesel-powered haul trucks dump mined ore. The collected samples' composition was not directly quantified, except for silica. However, the samples are expected to contain limestone and some diesel particulate matter.

In an effort to improve the booth's protection against respirable dust, NIOSH installed a filtration and pressurization system: the FPS 955 by Clean Air Filter (CAF, Defiance, IA). The system includes a single 110-V axial cooling fan capable of producing 255 m^3/h (150 cfm) with dual inlets, allowing both intake and recirculation air to pass through a single filter. NIOSH requested that the custom filters manufactured for this study be produced using mechanical filtering media, as opposed to electrostatic, because they are more efficient over time as they become loaded with contaminants. The filters were purposely designed to achieve, respectively, both ultra high ($\eta > 99$, abbreviated as F99) and high ($\eta > 95$, abbreviated as F95) efficiency ratings. Due to the cost and time associated with filter certification, the filters were not tested to either minimum efficiency reporting value (MERV) or high-efficiency particulate air (HEPA) criteria, but the F95 filter approximates a MERV 16 classification while the F99 filter is closer to the HEPA designation. While both filters were constructed from high-efficiency glass media, an additional layer of fabric plus charcoal was added to the F99 filter. Both filters measured approximately 273 mm (10.75 in.) in outer diameter, 86 mm (3.4 in.) in inner diameter and 406 mm (16 in.) in length.

With the filtration and pressurization system installed on the side of the crusher booth, intake air enters through the rain hood on the top of the pressurizer/filter unit, mixes with the recirculation air, passes through the filter and fan, and then moves through a 102-mm (4-in.)-diameter polyvinyl chloride (PVC) pipe into the top of the booth (Fig. 1). This combination of intake and recirculation air then passes through a rectangular plenum before entering the booth interior through a round ventilation grate. The roof plenum acts to reduce the entrance velocity and thus the noise created with the volume of intake air. The interior air is recirculated, being drawn back to the single intake pressurizer/filter unit through a 76-mm (3-in.)-diameter PVC pipe whose inlet is near the floor in the back of the control room.

Parameterization of booth protection

The key performance metric used during the study is the protection factor (PF), which is the ratio of outside to inside concentrations and is inversely proportional to both the filtration efficiency and penetration. This value can be determined with either gravimetric samples or real-time optical particle counting instruments. With field sampling, the time allotted for sample collection may be quite limited. In these cases, there is not sufficient time to acquire significant mass through gravimetric sampling, and particle counting is the preferred method (Cecala et al., 2005). PFs are presented using gravi-metric techniques (Table 2) when more time was allotted during the pre- and post-installation work, while particle counting results are presented for the shorter-duration monthly visits.

Sampling and analysis methods

To establish the initial protection offered by the booth as well as the change brought about by the installation of the external pressurization and filtration unit, respirable dust sampling packages were used. Each sampling package consisted of three Escort Elf personal sampling pumps operated at 1.7 L/min (Zefon International, Ocala, FL), three Dorr-Oliver respirable dust cyclones (Zefon International, Ocala, FL), three 37-mm dust cassettes (SKC Inc, Eighty Four, PA) and one Thermo Scientific pDR-1000AN instantaneous dust monitor (Thermo-Fischer Scientific, Waltham, MA). After testing, the instantaneous data were corrected so that the mean concentration matched the gravimetric average on that sampling rack. Four sampling locations were used: two inside and two outside the booth.

After the pressurization and filtration unit was operational for three months, NIOSH conducted particle count sampling using a TSI 3330 optical particle sizer (TSI Inc., Shoreview, MN) approximately every month for 15 months to track the performance of the system in terms of PF as the filters loaded with dust. In order to eliminate instrument bias, two tests were conducted for each monthly session, whereby instrument 1 was inside and instrument 2 was outside on the first test, and then the units were swapped for the second test. The cab pressure was continuously monitored using a Dwyer DM-2000 digital manometer (Dwyer Instruments, Michigan City, IN) and logged using an Onset UX120–006M 16-bit analog data logger (Onset Computer Corp., Bourne, MA). The intake and recirculation volumetric flow rates and centerline duct flows were also measured using a TSI 9565 hot-wire anemometer (TSI Inc., Shoreview, MN). A minimum of three measurements were taken to establish the mean airflow. Filters were replaced when intake airflow approached 42.5 m^3/h (25 cfm), the minimum intake airflow recommended per person. Over the course of 454 days or roughly 15 months of sampling, 16 individual visits were made, and in that time the filter was replaced twice, resulting in three filter test sets. The F99 filter was used for the first 121 days, then the F95 filter was installed and used for 252 days, after which a new F95 filter was installed for the final 81 days. No changes were made to the booth throughout the duration of the 15-month study other than the sealing of a leaky vent in the roof after 240 days. This vent had become dislodged just prior to the visit from an exterior wash-down procedure and did not pose an issue during prior tests.

Particle counting analysis method.

The particle counter output contains an estimate of counts in sized bins for each minute of testing. The PF is highly dependent on the time for inside concentrations to reach steady state, which is a function of intake and recirculation airflows as well as inside and outside concentrations. Researchers made every effort to minimize door openings as much as possible (Cecala et al., 2014). Due to operational constraints, the tests ranged from 20 to 60 min in length, but researchers evaluated data only between 14 to 17 min of each test in order to maintain a consistent analysis.

Cab pressure monitor data.

Monitoring the cab pressure — pressure differential between the interior of an enclosure and the outside ambient environment — can provide useful information on the performance of an enclosure in mitigating dust exposure. First, cab pressure provides an indication of cab integrity, which is foundational for an effective filtration system (Organiscak and Cecala, 2008). Wind infiltration into the cab can occur when wind velocity pressure is greater than the cab pressure (Heitbrink et al., 2000). Changes in booth pressure can be used for a real-time evaluation of the filtration system performance, with slowly falling pressures indicating when it may be necessary to change filters, or sudden rapid increases in pressure, suggesting that a filter has become damaged (Cecala et al., 2014). Real-time cab pressure can also provide an indirect record of door openings (Cecala, Organiscak and Noll, 2012), as door openings allow an in-rush of outside particles which must then be filtered out, the timing of which depends on the booth parameters: internal air volume along with intake and recirculation airflow quantities.

To quantify the performance of multiple manufacturers' units, three monitors were colocated in the crusher booth: a Dwyer DM-2000-LCD differential pressure transmitter (Dywer Instruments, Michigan City, IN), a Hummingbird HMPS1000BKIT cabin pressure monitor (Hummingbird Electronics, Taylors Beach, New South Wales, Australia) and a Sy-Klone KT-CABPRES-EL1-ENG electronic pressure monitor system (Sy-Klone International, Jacksonville, FL). In addition to the units tested, a Dwyer 616WL-4-LCD differential pressure transmitter (Dwyer Instruments, Michigan City, IN), which is a National Institute of Standards and Technology (NIST) traceable monitor, accurate to within +/− 0.5 percent of full scale, was used as the standard reference.

Sampling results

Gravimetric sampling was conducted on seven separate occasions with typical sample lengths of 6.5 h on average. Due to expected slower production and associated dust generation rates, 15.6-h sampling was conducted during the final measurements to ensure that enough mass was present on the filters to give a meaningful measurement. Table 2 shows the summary results of this gravimetric sampling. The results demonstrate that, on average, the installation of the CAF filtration and pressurization system resulted in a protection factor of 18.2, compared to an average of 1.0 with the original system. PFs equal to 1 indicate that the inside concentration is the same as the outside concentration, while PFs less than 1 indicate that there is actually more dust inside than out and may be possible if the enclosure ventilation system acts to pull dust-laden air inside without an effective filtration component to remove that dust.

The monthly particle count testing allowed NIOSH researchers to quantify the performance of the system as the filters loaded during routine use. For particles smaller than 1 µm, the F95 rated filters averaged a PF of 106.8, compared to the F99 filters which averaged 22.9, differing by a factor of 4.7. The performance of both filters generally decreased as they loaded (Fig. 2).

The airflow data in Fig. 3 show a similar trend to that of the PF data, with steadily decreasing airflow with increased filter use. New filters were installed on March 25, 2015, July 23, 2015, and April 28, 2016. The F95 filter had nearly 1.7 times the average intake airflow compared to the F99 filter (67.3 versus 40.5 m^3/h). On average, the recirculation air was 1.9 times as great as the intake quantity. The improvement in protection factor with the F95 filter is due in large part to the substantial increase in volumetric airflow that it allows relative to the F99 filter.

To provide a long-term look at system changes including filter loading, booth pressure was monitored throughout the duration of the test at the limestone mine. In February 2016, a rack holding four simultaneously sampling pressure monitors was installed for comparison and the sampling lasted approximately 4.5 months. Sustained changes in cab booth pressure are an indication that the system is changing, as illustrated by Fig. 4. Gaps in the pressure data indicate that the system was not operational. All of the monitors correlated well with the reference unit, reading just under the true value by [−0.018, −0.013, −0.012] in w.c. for the Dwyer, Sy-Klone and Hummingbird units, respectively. As shown in Fig. 4, the pressure shows a continual decreasing trend as the filter loaded with dust, and by knowing the protection factor with both new and used filters it is possible to then recommend a preventative change threshold.

Conclusions

As shown in this case study, installing an operator's compartment alone is not enough to control respirable dust levels. Baseline testing with gravimetric sampling showed that the original booth installation produced an average PF of 1 — the interior concentrations were equal to the outside concentrations, meaning zero protection from respirable dust. A single-filter pressurization and filtration unit was then installed on the existing booth. Gravimetric testing inside and outside the booth after installation revealed that protection was improved by a factor of 18.5 times, meaning operator exposures would be reduced by approximately 95 percent.

Once the booth protection had been improved through the installation of the CAF system, the performance was monitored in an active mining environment for a period of 15 months, examining the differences of two filter types as they loaded. In these monthly tests, the F95 filter offered an average protection factor that was 4.7 times that of the F99 filter. The vast improvement in airflow more than made up for any difference in filter efficiencies.

Three different models of cab pressure monitors were evaluated against an NIST traceable monitor to evaluate their accuracy in reporting low-level cab pressures. While differences do exist between the units, any of the monitors would be effective as an indication of cab interior pressure. The fact that every instrument errored on the low side of the true pressure reading is good from a safety aspect — erroneous under-readings would indicate that less pressure exists than in reality, possibly accelerating maintenance schedules. In addition to the benefits of accuracy provided by these units, operators may want to consider the benefits of the different manufacturers' offerings that may fit a particular mine's application, such as adjustable alarm settings, programmable logic output signals or touchscreen interfaces.

In this study, the protection against respirable dust was greatly improved through the objective performance characterization of a booth filtration system. As the primary measure, a particle counting method was used at regular intervals to accurately track the protection factor over time as the filters became loaded. For everyday performance tracking, a cab pressure monitor was installed and provided valuable insight on both the amount of filter loading and booth integrity. Regardless of the method chosen, it is highly recommended that the performance of filtration and pressurization systems be quantified to ensure adequate protection to the worker. Analogous to the concept of respiratory fit testing, quantifying the protection factor of enclosure filtration systems ensures their function. For enclosures, the door, window and vent seals, airflow quantities, filter efficiency and leaks all affect the performance of the system. This performance is critical to lowering the respirable dust hazards for enclosure occupants in the mining industry.

Limitations

The results clearly show that in this specific filtration and pressurization system, the F95 filter provides a substantial advantage over the F99 filter. Filter efficiency is one parameter of filtration system performance that can be described by a mathematical model to predict the protection factor (Organiscak and Cecala, 2008). In this case, the F99s improved filtering efficiency was overshadowed by the negative impact of the pressure restriction on the airflow quantity. In comparison, the slightly less efficient filtering with the F95 filter produced lower respirable dust levels and improved air quality within the booth because of the increase in the air quantity which was filtered.

Acknowledgments

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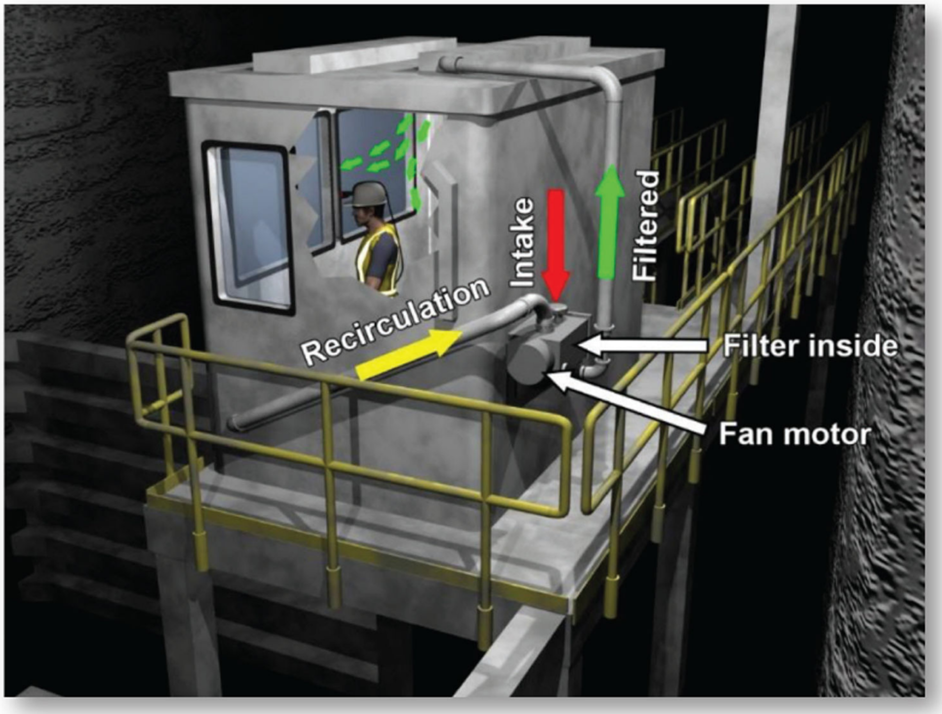

Figure 1.
Rendering of the crusher booth.

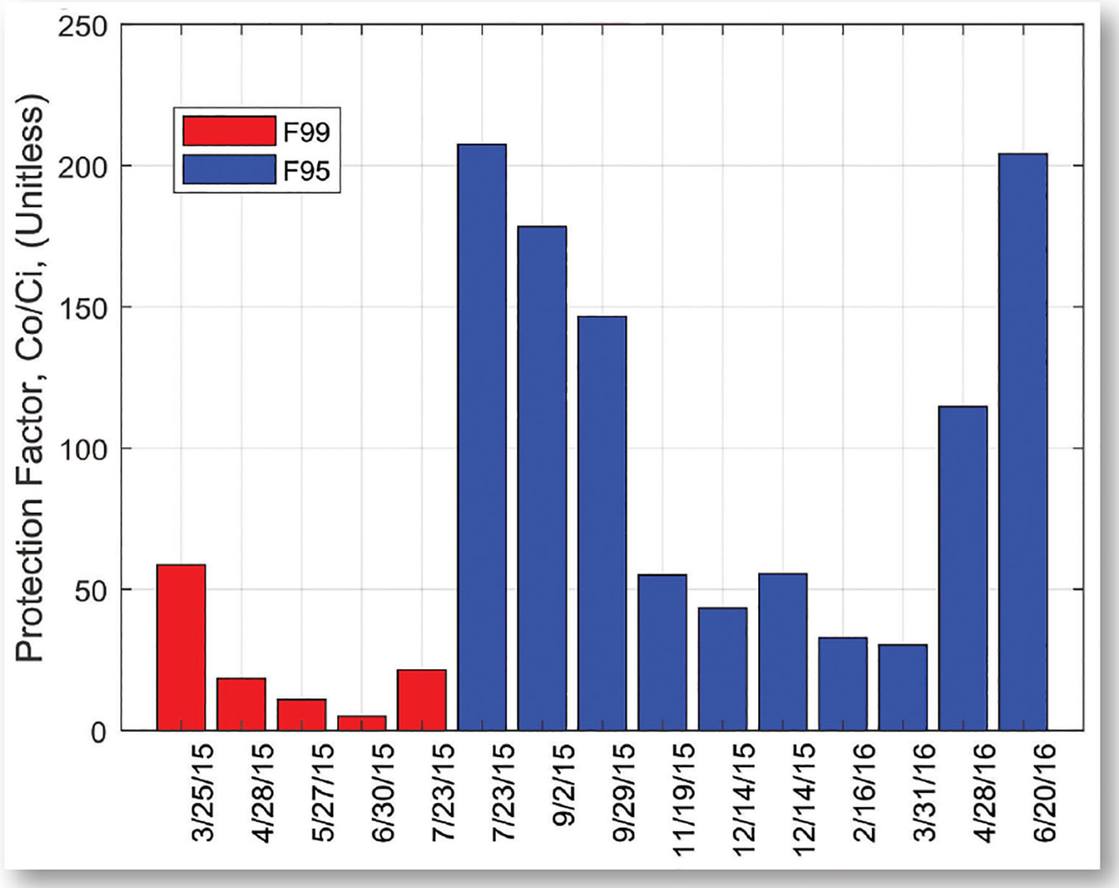

Figure 2.

Monthly protection factors (underground crusher booth, particle counting results for sizes < 1 μm).

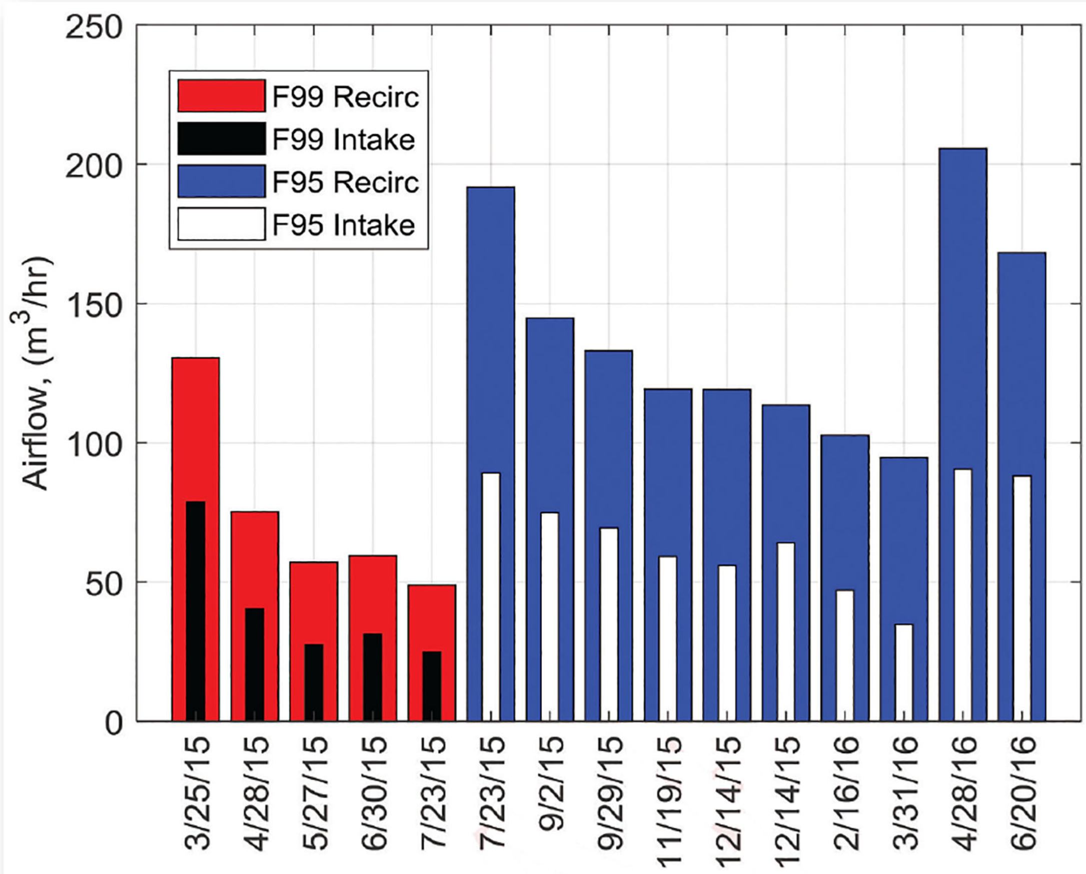

Figure 3.
Monthly airflow quantities.

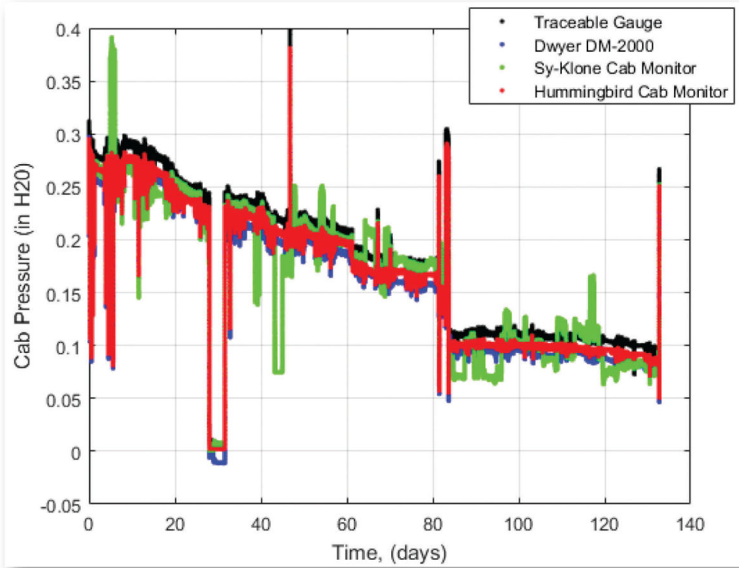

Figure 4.
Pressure monitor data.

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Table 1

Initial particle counts at crusher booth with no pressurization and filtration system installed (PF = protection factor).

Test no.	Condition	Outside counts	Inside counts	PF
1	Baseline (fan ON)	183,637	1,269,356	0.14
2	Baseline (fan ON)	293,771	512,255	0.57
3	Baseline (fan ON)	430,276	639,281	0.67
4	Baseline (fan OFF)	410,244	300,001	1.37
5	Baseline (fan OFF)	451,658	356,974	1.27

Table 2

Summary of gravimetric sampling results for the crusher booth (C_o = outside concentration, C_i = inner concentration).

System	Filter (new condition)	Date	Time (min)	C_o	C_i	Power factor (PF)
Original	None	Feb. 11, 2014	364	0.357	0.335	1.1
Original	None	Feb. 12, 2014	407	0.318	0.592	0.5
Original	None	Feb. 13, 2014	387	0.354	0.282	1.3
CAF	F99	Nov. 12, 2014	409	0.256	0.027	9.5
CAF	F99	Nov. 13, 2014	385	0.346	0.022	15.7
CAF	F99	Jun. 21, 2016	936	0.401	0.024	16.7
CAF	F95	Jun. 22, 2016	941	0.369	0.012	30.8