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# Air cleaning performance of a new environmentally controlled primary crusher operator booth

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## Abstract

The National Institute for Occupational Safety and Health (NIOSH) cooperated with 3M Company in the design and testing of a new environmentally controlled primary crusher operator booth at the company's Wausau granite quarry near Wausau, WI. This quarry had an older crusher booth without a central heating, ventilation and air conditioning (HVAC) system, and without an air filtration and pressurization system. A new replacement operator booth was designed and installed by 3M based on design considerations from past NIOSH research on enclosed cab filtration systems. NIOSH conducted pre-testing of the old booth and post-testing of the new booth to assess the new filtration and pressurization system's effectiveness in controlling airborne dusts and particulates. The booth's dust and particulate control effectiveness is described by its protection factor, expressed as a ratio of the outside to inside concentrations measured during testing. Results indicate that the old booth provided negligible airborne respirable dust protection and low particulate protection from the outside environment. The newly installed booth provided average respirable dust protection factors from 2 to 25 over five shifts of dust sampling with occasional worker ingress and egress from the booth, allowing some unfiltered contaminants to enter the enclosure. Shorter-term particle count testing outside and inside the booth under near-steady-state conditions, with no workers entering or exiting the booth, resulted in protection factors from 35 to 127 on 0.3- to 1.0-μm respirable size particulates under various HVAC airflow operating conditions.

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## Introduction

Enclosed cabs are an engineering control that can provide a safe, comfortable, and healthy work environment for equipment operators. Most modern-day enclosed cabs have heating, ventilation and air conditioning (HVAC) systems for maintaining a comfortable temperature and a breathable quantity of air for their occupants. Various levels of filtration can be incorporated into the HVAC system to improve the quality of the air inside the cab by removing airborne pollutants such as dusts and diesel particulates. Previous enclosed cab dust filtration system field studies were conducted on mobile equipment by the National Institute for Occupational Safety and Health (NIOSH) at mining operations, and these studies showed that the respirable dust reduction or protection factors, defined as the ratios of outside to inside concentrations, ranged from 3 to 89 (Chekan and Colinet, 2003; Organiscak et al., 2004; Cecala et al., 2004; Cecala et al., 2005; Cecala et al., 2012). The two key components attributed to the more effective cab dust control results were an efficient filtration system and an effectively sealed cab, meaning good cab integrity, for achieving positive interior pressurization (Cecala et al., 2014).

Laboratory experiments were also conducted by NIOSH to methodically study the key design factors of effective cab filtration systems. The results of this testing showed that intake filter efficiency and recirculation filter use were the two most critical factors on cab filtration system performance (Organiscak and Cecala, 2008a, 2008b). The addition of a recirculation filter to the cab's filtration system significantly reduced its particulate penetration by an order of magnitude and noticeably reduced, by approximately 60 percent, the time needed for the cab interior to reach its lowest steady-state concentration after the cab door was closed. A two-filter mathematical model was developed from these experiments that describes cab particulate penetration in terms of intake filter efficiency, intake air quantity, intake air leakage, recirculation filter efficiency, recirculation filter quantity and wind penetration (Organiscak and Cecala, 2008b; Organiscak and Cecala, 2009).

Control rooms and/or operator booths at metal/non-metal mines and industrial mineral processing plants are other areas where air filtration and pressurization systems can be applied to reduce dust exposures. Dust source studies conducted in an underground limestone mine and gold mine indicated that the highest dust concentrations were near the crushing and dumping operations at these mines (Chekan, Colinet and Grau, 2003). U.S. Mine Safety and Health Administration (MSHA) dust compliance sampling data from 2009 to 2012 also indicate that 8.9 percent of the crusher operators in metal/nonmetal mines and mills exceeded the 100 $\mu g/m^3$ respirable silica dust limit, with 24.8 percent of these operators exceeding a 50 $\mu g/m^3$ silica dust level (U.S. Department of Labor, 2013). Crusher operators are usually located in control rooms or booths adjacent to the crushers to oversee and control their operation. Some of these control rooms or booths are larger than the enclosed cabs on mobile equipment and typically have a wall- or window-mounted air conditioner unit designed without a high-quality air filter and a separate intake pressurizing fan, thereby providing ineffective control room or booth air filtration and pressurization.

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A field study was conducted to examine the performance of such a crusher booth and compare it with the performance of a newly designed replacement booth having both effective filtration and pressurization. The 3M Company in cooperation with NIOSH conducted this field study to replace an old gyratory crusher operator booth at its Wausau granite quarry with a new environmentally controlled operator booth. This paper describes the field study performance of the old and newly installed environmentally controlled booths.

## Pre- and post-testing of crusher booth designs

A gyratory primary crusher is used at the 3M Wausau granite quarry to initially reduce the mine's ore size and to stockpile it as feed material for the processing plant. The granite ore from the stockpile is further crushed, cleaned and sized by the processing plant to produce the fine stone aggregate used on roof shingles. Figure 1A shows the old primary crusher booth overseeing the truck dump into the crusher. The crusher operator inside the booth turns the crusher on when the trucks arrive and manipulates a hydraulic jackhammer to clear jams in the crusher periodically when it becomes necessary. The crusher operator also controls the flow of the crushed ore to the stockpile with an adjustable conveyor, using video camera displays in the booth. This operator booth was not equipped with a dust filtration and intake pressurization system. Figure 1B shows the unfiltered window air conditioner unit mounted into the booth's back wall. The window air conditioner unit was used in the summer months to cool the booth interior, while a portable electric floor heater (not shown) was used to warm the booth interior during the winter months. This booth basically kept the crusher operator out of the weather and provided him with some air temperature control, noise control, and shielding from flying crusher debris. This booth was dust sampled during two working shifts and the particles in the air counted at the end of one working shift to establish baseline conditions for comparison with the new booth installation.

After baseline testing was completed, this old crusher booth was replaced by a new tightly sealed, preassembled booth (Noise Barriers LLC, Libertyville, IL) having 368 cu ft of interior volume, which was similar in size to the old booth. Figure 2A shows the new replacement booth overseeing the truck dump into the crusher. A modification was made to this booth to install a new Polar high-capacity, through-the-wall HVAC system (Model P. 5225.H.230.3P, Polar Mobility Research Ltd, Alberta, Canada). This unit is an industrial-grade HVAC system constructed with stainless steel housing, corrosion-resistant copper coils, long-life variable-frequency drive-controlled compressor, and sealed brushless fan motors, operating on 240-V alternating-current, three-phase power (Fig. 2B). It also incorporated an optional filtration and pressurization system consisting of two RESPA–CF Vortex HyperFLOW intake air filtration pressurizer units and two internal RESPA–CFX recirculation air filtration units (Sy-Klone International, Jacksonville, FL). Figure 3 shows these optional fan-powered RESPA filtration units incorporated into the Polar HVAC system. The RESPA–CF Vortex HyperFLOW intake air filtration units cleaned all the intake air into the HVAC system, and the RESPA–CFX recirculation air filtration units cleaned only a portion of the recirculated air within the HVAC system. Figure 3 also shows the unfiltered bypass airflow path (orange arrow) for maintaining sufficient operational airflow

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through the heat exchanger when the filtered airflow becomes restricted. The RESPA filtration units used cylindrical cartridge filter elements having an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) minimum efficiency reporting value (MERV) of 16, with efficiency > 95 percent down to 0.3-μm particle sizes (ASHRAE, 1999).

The fan-powered RESPA units could be individually operated to change the intake and recirculation airflow quantity balances within the HVAC system. Post-dust sampling was performed during several working shifts with all the RESPA units operating and with only one intake RESPA unit operating. Particle count testing of the air quality inside and outside the booth was usually performed after several of the production shifts without the operator inside the booth. Additional particle count testing was conducted for all RESPA operating combinations during a maintenance shift while gyratory crusher rebuilding activities were being performed outside the booth without the crusher operator present. The four different RESPA operating combinations tested included: two intake and two recirculation units operating (2I+2R); one intake and two recirculating units operating (1I+2R); one intake and one recirculation units operating (1I+1R); and one intake unit operating (1I+0R). These various particle counting tests were conducted to determine the optimal filtration system airflow balance for this booth.

## Testing procedures

Dust samplers were placed outside and inside of these booths during several working shifts to measure their interior respirable dust reduction performance. Optical particle counters were also used to measure particle concentrations outside and inside these booths under more optimal steady-state conditions, without people entering and leaving the booth. The particle counters provided optimum shorter-term (one-hour) testing of the new booth with the HVAC system running under different airflow conditions, using one to four RESPA units. Total airflow into the booth and recirculation airflow out of the booth were also measured under the different airflow conditions using a hot wire anemometer. The interior to exterior differential booth pressures were measured as well as the interior and exterior temperature and relative humidity.

## Respirable dust sampling

Respirable dust samples were collected at two outside booth locations, front and back, and two inside booth locations, front window and back wall near door. A sampling rack consisting of three gravimetric and one instantaneous dust sampling instruments was placed at each location. The gravimetric dust samplers were comprised of an ESCORT-Elf constant flow air sampling pump (Zefon International, Ocala, FL) pulling dust-laden air at 1.7 L/min through a 10-mm nylon cyclone (respirable dust classifier) and depositing the respirable fraction onto a pre-weighed 37-mm polyvinyl-chloride filter (SKC Inc., Eighty Four, PA). Instantaneous dust concentrations were measured with a personal Data-RAM particulate monitor (model pDR-1000AN, Thermo-Fisher Scientific, Waltham, MA). The instantaneous dust concentration data were time-recorded every 10 seconds in the monitor's internal memory, then downloaded to a computer after testing was completed. The instantaneous

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dust concentrations were calibrated to their adjacent gravimetric samplers by multiplying the recorded dust data by the gravimetric to pDR dust concentration ratio, determined by dividing their average dust concentrations measured over identical sampling periods. The average outside concentrations around the booth were divided by the average inside concentrations to determine and compare the protection factors provided by the old and new booths during the working shifts sampled.

## Particle counting methods

The particle count instruments used during this study were hand-held MetOne Model HHPC-6 six-channel instruments (Hach Ultra Analytics, Grants Pass, OR). These instruments count airborne particles within the six channel size ranges of 0.3 to 0.5 μm, 0.5 to 0.7 μm, 0.7 to 1.0 μm, 1.0 to 3.0 μm, 3.0 to 5.0 μm, and greater than or equal to 5.0 μm. The instruments operate at an airflow rate of 2.83 L/min and have selectable air sampling periods that are stored in a 500-sample rotating buffer (sample memory). These instruments provide particle count data in either concentrations or total number of particles measured in differential or cumulative sized sample statistics. The instruments' specified coincidence error is 5 percent for 2,000,000 particles/cu ft or 70,670 particles/L.

Booth testing was conducted using two Model HHPC-6 particle counters to simultaneously sample and record the inside and outside particle size concentrations for 1-minute periods over a 30-min test, as previously discussed in NIOSH's laboratory cab experiments when using a recirculation filter (Organiscak and Cecala, 2008b). The outside particle counter was located near the inlet of the HVAC system and the inside particle counter was located on a table closer to the center of the booth. Inside and outside instruments were alternately switched during a subsequent 30-min test replicate. Instrument rotation between the inside and outside booth locations for the two 30-min test replicates was intended to average out any instrument biases. The last 15 min of cumulated 0.3- to 1.0-μm particle size data from each test replicate were used to calculate the average particle concentrations outside and inside the booth at the time of the lowest steady-state particle concentrations reached inside the booth. These average concentrations were used to determine the booth protection factors (PF) or reduction ratios for each test replicate. The booth's protection factor for a particular test configuration was determined from the average of the two test replicates. The 95 percent confidence levels of these protection factors were determined by calculating the propagation of standard error estimate (for a two-variable ratio) during each test replicate and pooling these standard errors by using Satterthwaite's standard error approximation as previously described by Organiscak, Cecala and Noll (2013).

## Booth operating parameter measurements

The booth's airflow, temperature, humidity and pressurization parameters were also measured during field testing. A VelociCalc Model 9555 hotwire anemometer (TSI Inc., Shoreview, MN) was used to measure the average air velocity for a 1-minute moving traverse over the cross-sectional area of the 25¾-in. by 8¾-in. discharge duct into the booth and the 26½-in. by 3¾-in. recirculation inlet duct from the booth. The recirculation airflow quantity leaving the booth was subtracted from the total airflow quantity entering the booth

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to determine the net intake airflow quantity into the booth. Temperature and relative humidity measurements were recorded at 1-minute intervals with the HHPC-6 particle counters while particle counting tests were being conducted. A DP-CALC Model 5825 micromanometer (TSI Inc., Shoreview, MN) was used to measure and record the booth's inside to outside static pressure at 1-minute intervals during each day of testing.

## Field test results

Respirable dust sampling results indicated that the old booth provided negligible dust protection from outside concentrations, while the new booth provided protection factors of 2 to 25 from the outside respirable dust. Table 1 summarizes the average gravimetric dust concentrations measured at the outside and inside locations during each day of testing. As indicated in the table, the average outside dust concentrations remained below 0.09 mg/m$^3$ for the field study. These low respirable dust concentrations were a result of the unconfined airborne dust being quickly dissipated by the wind around the booth during the dumping of the ore into the crusher. Figure 4 illustrates this by showing the brief durations of peak pDR dust concentrations measured on April 8 at the various locations outside and inside the booth. The highest dust concentrations were measured at the outside front booth location closest to the crusher. These dust concentrations only reached 1 mg/m$^3$ for seven brief periods during the shift and remained below 0.1 mg/m$^3$ for most of the shift. The inside booth sampling locations had the lowest dust concentrations with very little variation. Given the low average outside dust concentrations measured during the sampled shifts, the booths' protection factors were not reliably quantified from the respirable dust measurements.

The particle counting test results showed that the filtration and pressurization system in the new booth is capable of providing significantly higher protection factors of 35 to 127 for the 0.3- to 1.0-μm respirable size particulates under various HVAC airflow operating conditions, compared with a protection factor of 3 for the old booth. Table 2 shows the particle counting test results for the various RESPA unit configurations and Fig. 5 shows a bar graph of the protection factors measured with their 95 percent confidence levels. As can be seen in the table, abundant outside particle count concentrations in the 0.3- to 1.0-μm size range (having low mass concentrations) were available for more reliable protection factor quantification of the booths. Figure 5 illustrates that the new booth with the filtration and pressurization system provided significantly higher protection factors with the various RESPA filtration units operating, compared with the old booth with unfiltered air. It also indicates that there were no significant differences in booth protection factor performance while operating two to four of the RESPA units, providing protection factors of 94 to 127. The protection factor of the new booth was significantly reduced to 35 and 44 while operating only one intake RESPA filtration unit compared with operating two to four RESPA units.

Operation of the various RESPA filtration units measurably changes the intake and recirculation airflows of the new booth HVAC system, with corresponding changes in booth pressure. Figure 6 shows a stacked bar graph of the intake and recirculation airflows and corresponding booth pressures, on the secondary y-axis, measured while operating the various RESPA filtration units. Booth pressures greater than 0.1 in. of water gauge (in. w.g.)

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were achieved at the highest HVAC airflows measured with all the RESPA filtration units operating (2I+2R). Lower booth pressures of 0.04 to 0.07 in. w.g. corresponded with lower HVAC airflows measured while operating only one of the RESPA intake filtration and pressurization units.

Although the operation of the various RESPA filtration units changed airflows and booth pressures, the HVAC system provided relatively consistent inside booth temperatures regardless of outside temperature levels. Figure 7 shows the inside and outside booth temperatures with their respective relative humidities during field testing. Inside booth temperatures were kept consistently higher (69.9 to 72.6 °F) than the outside booth temperatures (53.2 to 56.7 °F) in the April testing, while the inside booth temperatures (63.2 to 66.8 °F) were kept consistently lower than the outside booth temperatures (71.1 to 76.1 °F) in the August testing. Relative humidity inside the booth was lower than in the outside air during the April testing because of heating of the interior booth air. Relative humidity inside the booth was higher than in the outside air during the August testing because of cooling of the interior booth air.

## Conclusions

An older quarry crusher operator booth without an air filtration and pressurization system showed negligible airborne respirable dust protection and low submicron particulate protection from the outside environment. Installation of a new operator booth having a filtered HVAC system with multiple RESPA filter and pressurization units showed average respirable dust protection factors of 2 to 25 during five shifts of dust sampling with occasional booth ingress and egress. Some of this inconsistency in the respirable dust protection factors was due to the low gravimetric mass concentrations measured during the study. Shorter-term particle counting of 0.3- to 1.0-μm size particulates outside and inside the two booths at near-steady-state conditions, between booth entry periods, provided more reliable and quantifiable booth protection factors during this field study because of the higher submicron particle count concentrations available.

Particle count testing showed that the old booth had a protection factor of 3 while the new booth provided significantly higher protection factors of 35 to 127 during the operation of various RESPA filtration units incorporated into the HVAC system. Operating the booth with only one intake RESPA filtration and pressurization unit provided the lowest protection factors of 35 to 44, compared with the significantly higher protection factors of 94 to 127 achieved with the additional one to three RESPA filtration units operating. Although there were insignificant differences between the protection factors of 94 to 127 when operating two, three or four RESPA filtration units, measurable HVAC airflows and booth pressures were realized from these changes. Booth pressures decreased from greater than 0.1 in. w.g. when operating the two RESPA intake filtration and pressurization units to less than 0.1 in. w.g. when operating one unit. Inside booth temperatures remained relatively stable in the range of 63.2 to 72.6 °F during all HVAC and filtration system testing, thereby providing several RESPA filtration unit options for the HVAC system. Operating one intake and recirculation RESPA unit (1I +1R) provided one of the higher booth protection factors measured (98) while offering flexible RE-SPA utilization and servicing alternatives. The

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RESPA units could be alternately operated with idled units providing additional standby capacity and filtration system availability.

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**Figure 1.**
(A) Old crusher operator booth overseeing crusher, and (B) unfiltered AC unit.

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**Figure 2.**

(A) New crusher operator booth overseeing crusher, and (B) new booth's HVAC and filtration system unit.

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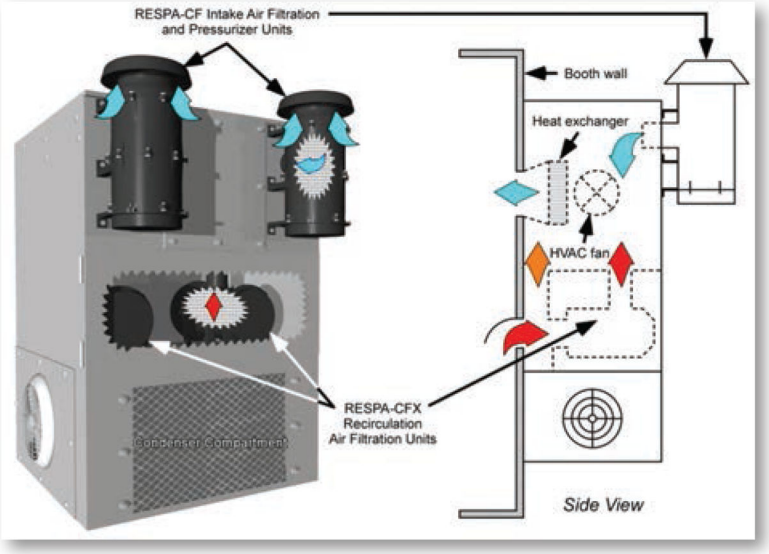


**Figure 3.**

Individual RESPA intake and recirculation filtration units shown within the HVAC system. (Blue arrows = intake airflow, red arrows = recirculated airflow, and orange arrow = unfiltered bypass airflow.)

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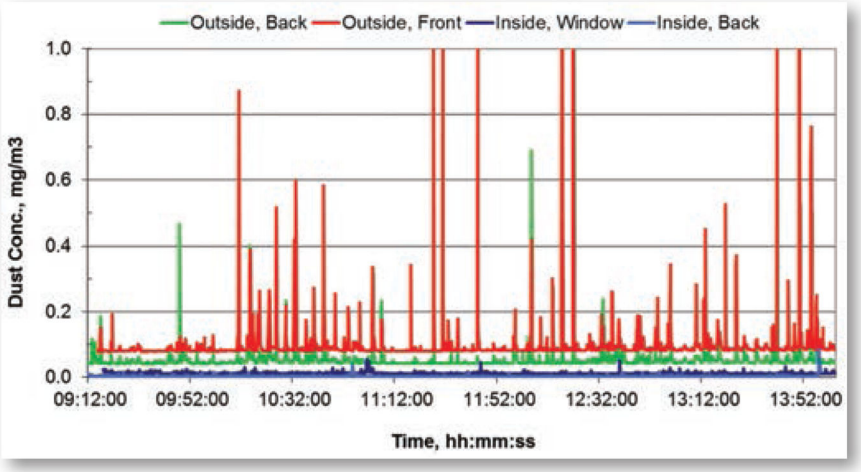


**Figure 4.**
PDR dust concentrations measured inside and outside of the new booth on April 8, 2014.

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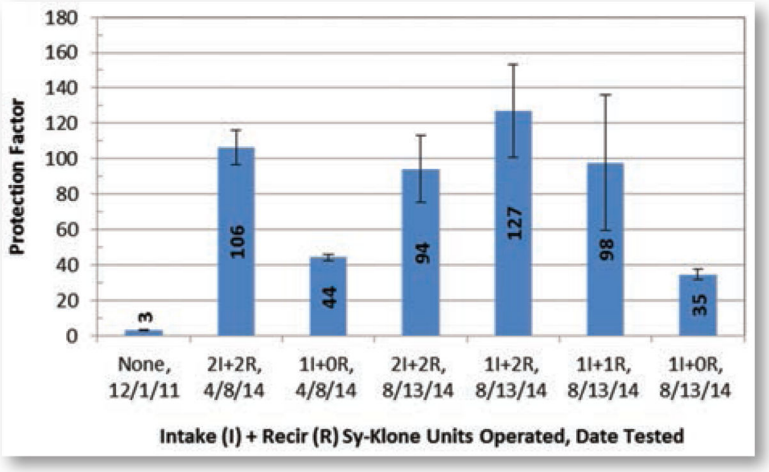


**Figure 5.**
Crusher booth particle counting protection factor results with 95 percent confidence levels.

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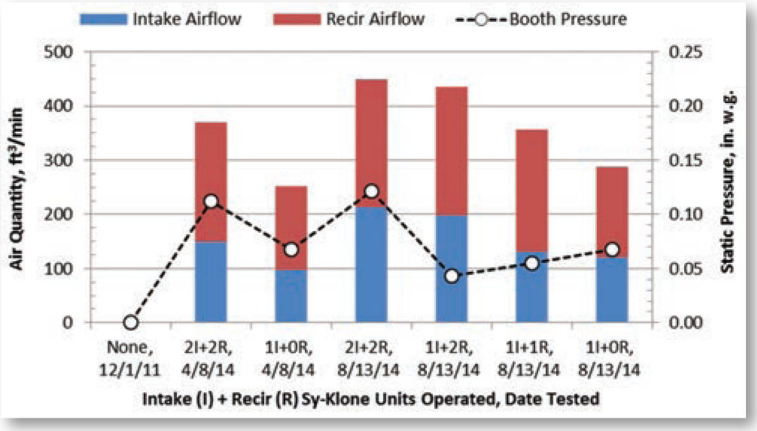


**Figure 6.**
Crusher booth airflow quantities and associated pressurization results.

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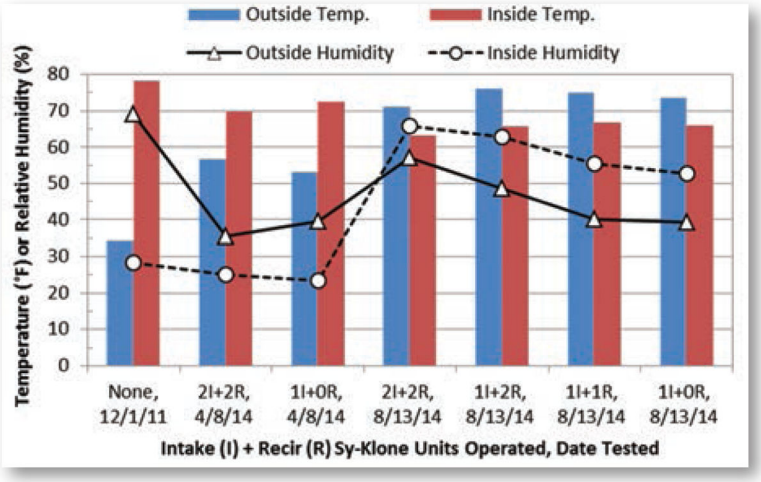


**Figure 7.**

Temperatures and relative humidities measured during crusher booth field testing.

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**Table 1**

Average respirable dust concentrations and booth pressures measured during several working shifts.

| Filtration system Intake+Recir | Test date (m/d/y) | Booth pressure (in. w.g.) | Outside dust concentration (mg/m$^3$) | Inside dust concentration (mg/m$^3$) | Protection factor |
|---|---|---|---|---|---|
| None | 11/30/2011 | N.A. | 0.040 | 0.040 | 1.0 |
| None | 12/1/2011* | N.A. | 0.005 | 0.039 | 0.1 |
| 2I+2R | 4/8/2014* | 0.11 | 0.080 | 0.007 | 11.4 |
| 1I+0R | 4/9/2014 | 0.06 | 0.040 | 0.013 | 3.1 |
| 1I+0R | 4/10/2014 | 0.08 | 0.064 | 0.029 | 2.2 |
| 2I+2R | 8/12/2014 | 0.14 | 0.017 | 0.008 | 2.1 |
| All combinations | 8/13/2014** | 0.08 | 0.088 | 0.004 | 25.1 |

*Particle counting tests performed after production shift ended.

**Particle counting tests performed during gyratory crusher rebuilding activities.

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## Table 2

Particle count concentrations measured at near-steady-state booth conditions without outside entry.

| Filtration system Intake+Recir | Test date (m/d/y) | Test no. | Particle concentrations* | | Protection factor (PF) | Average PF | 95% confidence level** |
|---|---|---|---|---|---|---|---|
| | | | Outside (particles/L) | Inside (particles/L) | | | |
| None | 12/1/11 | 1 | 154,367 | 45,524 | 3.4 | 3.2 | 0.2 |
| | | 2 | 129,374 | 41,808 | 3.1 | | |
| 2I+2R | 4/8/14 | 1 | 21,874 | 197 | 111.1 | 106.3 | 9.5 |
| | | 2 | 19,714 | 194 | 101.6 | | |
| 1I+0R | 4/8/14 | 1 | 28,441 | 534 | 53.2 | 44.1 | 1.6 |
| | | 2 | 21,880 | 625 | 35.0 | | |
| 2I+2R | 8/13/14 | 1 | 79,762 | 825 | 96.6 | 94.2 | 19.0 |
| | | 2 | 94,946 | 1,035 | 91.7 | | |
| 1I+2R | 8/13/14 | 1 | 73,975 | 496 | 149.2 | 127.0 | 26.3 |
| | | 2 | 47,947 | 457 | 104.9 | | |
| 1I+1R | 8/13/14 | 1 | 32,431 | 328 | 98.9 | 97.7 | 38.6 |
| | | 2 | 35,449 | 367 | 96.5 | | |
| 1I+0R | 8/13/14 | 1 | 30,406 | 787 | 38.6 | 34.6 | 3.1 |
| | | 2 | 24,837 | 814 | 30.5 | | |

*Particle concentrations of 0.3–1.0-μm particles averaged over the last 15 min of test.

**Confidence levels determined from pooling the propagation of error of the 1-minute sample variations measured during both tests.