Doing the Math

THE EFFECTIVENESS OF ENCLOSED-CAB AIR-CLEANING METHODS CAN BE SPELLED OUT IN MATHEMATICAL EQUATIONS.

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Enclosed cabs are a primary means of reducing equipment operators' silica dust exposure at surface mines. The National Institute of Occupational Safety and Health recently performed a laboratory study to evaluate which factors on an enclosed-cab filtration system are most significant. The various factors evaluated were intake filter efficiency, intake air leakage, intake filter loading, wind infiltration, use of a recirculation filter, and the use of an intake pressurization fan.

The result of this laboratory testing has shown that the two most important factors for an effective filtration system on an enclosed cab were the efficiency of the intake filter and the use of a recirculation filter. A higher-efficiency intake filter considerably increased the quality of the intake air that was delivered into the enclosed cab. It also was determined that air leakage around the intake filter noticeably reduced its air cleaning effectiveness.

The second key factor is the use of a recirculation filter, which was shown to improve the air quality in the enclosed cab by six to 12.7 times more than the intake filter alone. The reason for the significant improvement was that the cab air was constantly drawn through the recirculation filter, thus continually filtering the dust out of the air.

The outcome of this laboratory study was the development of a mathematical equation to calculate enclosed-cab air-cleaning effectiveness with respect to specified filtration system components and operating parameters. This equation is useful to mine operators for examining cab performance specifications and allowing them to achieve a desired cab dust reduction effectiveness or protection factor.

Overexposure to airborne respirable dust, especially dust containing crystalline silica, is a serious health concern to the mining industry. The most frequent silica dust overexposures at surface mines are commonly overburden drillers and operators of mobile excavating equipment such as bulldozers, loaders and haul trucks. Enclosed cabs with heating, ventilation and air conditioning systems are typically integrated into surface mining equipment to protect the operator from the outside environment. Air filtration often is part of the HVAC system as an engineering control of airborne dusts.

The basic HVAC system mainly recirculates cab air through the heat exchangers for effective heating and cooling with some additional intake air drawn by recirculation fans through an exterior inlet. Dust filtration is usually performed on the intake air and sometimes on the recirculation air. Field studies of filtration systems on surface mine equipment cabs have shown varying degrees of success for lowering dust exposure to the operator.

Enclosed-cab air-cleaning effectiveness can be described by three relative measures that compare outside with inside dust concentrations: protection factor, efficiency and penetration. For this research, cab-air cleaning effectiveness is described by protection factor, or PF. This measure is most widely known for describing respirator effectiveness. Higher protection factor values indicate better cab-air cleaning effectiveness.

$$\textit{Protection Factor (PF)} = \frac{C_0}{C_i} \text{ (ratio)}$$

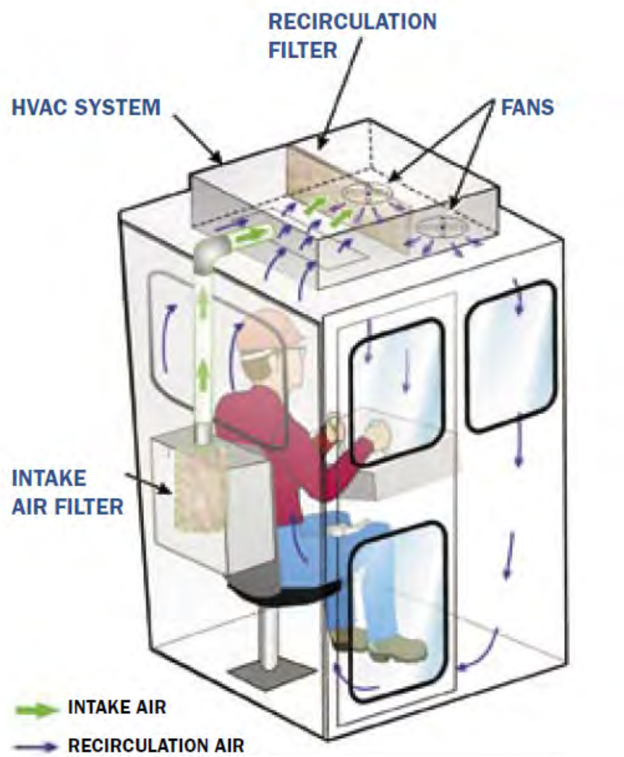
Where:
C_0 Outside cab concentration
C_i Inside cab concentration

For this study, NIOSH researchers built a 72-cubic-foot plywood enclosure with a mock-up HVAC system to replicate a typical operator cab found on mining equipment. Cab protection factors were determined from respirable particle count concentrations measured outside (Co) and inside (Ci) the cab. Respirable particle count concentrations also were measured in the cab intake airflow for determining intake filter efficiencies. The recirculation filter efficiency was measured separately from the cab experiments at comparable filter airflows. Cab pressure, intake air leakage, intake airflow, recirculation airflow and wind velocities also were measured to quantify the experimental cab operating conditions.

Table 1 shows average cab operating conditions and protection factors for the intake and recirculation filter test combinations without and with the intake pressurizer fan. The top and bottom half of the table shows the test results without and with a recirculation filter, respectively. The higher-efficiency intake filter significantly improved cab protection factors throughout all the test conditions as compared to the lower-efficiency filter. Also, the recirculation filter significantly increased the cab protection factor by 6 to 12.7 times more than provided by the intake filter itself, due to continual filtration of the cab air. The cab protection factor for the lower efficiency intake filter ranged from 1.5 to 1.7 without the recirculation filter, increased to a range of 9 to 13.4 with the recirculation filter. The cab protection factor for the higher efficiency intake filter ranged from 13.3 to 14.4 without the recirculation filter, increased to a range of 162.2 to 168.4 with the recirculation filter.

The recirculation filter also noticeably decreased the time needed for the cab interior concentrations to decrease and stabilize after the door was closed; this is known as decay time. The average decay time ranged from 17 to 29 minutes without the recirculation filter and from 7 to 9 minutes with the recirculation filter. This decrease in decay time also was achieved with a higher cab protection factor. Thus, a cab recirculation filter subsequently reduced respirable dust concentrations and time of exposure inside the cab.

Intake-filter loading and wind infiltration were the two least-important factors found in this study. However, a loaded intake filter reduces both intake airflow and cab pressure, making wind infiltration more likely. Using the intake-pressurizer fan increased the cab's intake airflow quantity and pressurization, thus decreasing the potential for wind blowing outside contaminants into the enclosed cab.



Both an intake and recirculation filter were incorporated into a basic HVAC system.

One of the experiments' objectives was to develop a practical mathematical equation of these test results to be used by mine operators in achieving desired cab performance specifications. The equation describes cab protection factor in terms of intake filter efficiency, intake-air quantity, intake-air leakage, recirculation-filter efficiency, recirculation-air quantity and wind-quantity infiltration.

TABLE 1: AVERAGE CAB PERFORMANCE VALUES FOR FILTER COMBINATIONS TESTED

Intake Filter (%Efficiency)	Recirculation Filter (%Efficiency)	Intake Airflow ft^3/min	Intake Air Leakage %	Recirculation Airflow ft^3/min	Cab Pressure inches w.g.	Decay Time min	Protection Factor C_o/C_i
Low (38%)	None	37.3	2.0	366	0.17	17	1.7
[P] Low (34%)	None	55.1	2.3	363	0.27	20	1.5
High (>99%)	None	18.1	3.6	386	0.07	29	13.3
[P] High (>99%)	None	30.3	3.5	379	0.11	22	14.4
Low (38%)	Yes (72%)	41.0	2.6	328	0.19	8	13.4
[P] Low (34%)	Yes (72%)	65.8	2.2	322	0.31	9	9.0
High (>99%)	Yes (72%)	23.2	4.9	338	0.08	8	168.4
[P] High (>99%)	Yes (72%)	35.6	3.8	338	0.14	7	162.2

[P] *Cab test stand operated with intake pressurizer fan.*

It determines the cab protection factor after it reaches its lowest inside concentration under equilibrium conditions, with doors and windows closed.

$$PF = \frac{Q_I + Q_R n_R}{Q_I(1 - n_I + l n_I) + Q_w}$$

Where:

PF ***Protection Factor, ratio***

Q_I ***Intake air quantity into the cab ($Q_I > 0$), volume per unit time***

n_I ***Intake filter efficiency ($N_I < 1$), fractional***

I ***Intake air leakage, fractional portion of intake air quantity***

Q_R ***Recirculation filter airflow, volume per unit time***

n_R ***Recirculation filter efficiency, fractional***

Q_w ***Wind quantity infiltration into the cab, volume per unit time***

This equation requires that air quantities be expressed in equivalent units and filter efficiencies and air leakage be expressed as fractions, not percentages. Wind-quantity infiltration can be assumed to be zero when the cab pres sure exceeds the wind velocity pressure.

In the following example, a cab-filtration system has an intake-air filter, which is 95% efficient on respirable-size dust and is operating at 40 cubic feet per minute of airflow. This system recirculates 200 cubic feet per minute of cab air without a recirculation filter. The mathematical equa tion can be used to determine the baseline PF of this cab and evaluate several cab performance changes.

This 72-cubic-foot enclosed cab test stand was used in the filtration system experiments.

$$PF = \frac{40 + (200 \times 0)}{40(1 - 0.95 + (0 \times 0.95)) + 0} = 20$$

1) Baseline design.

$$PF = \frac{40 + (200 \times 0)}{40(1 - 0.95 + (0.05 \times 0.95)) + 0} = 10$$

2) A 5% intake air leak around the intake filter gasket

$$PF = \frac{40 + (200 \times 0.75)}{40(1 - 0.95 + (0.05 \times 0.95)) + 0} = 49$$

3) Adding a 75% efficient respirable dust recirculation filter with the 5% intake leak.

$$PF = \frac{40 + (200 \times 0.75)}{40(1 - 0.95 + (0 \times 0.95)) + 0} = 95$$

4) A 75% efficient respirable dust recirculation filter with no leak.

These example calculations show that the cab protection factor increased from 20 to 95 by using a 75% efficient recirculation filter in a system with no leaks. They also illustrate how the cab protection factor can be noticeably diminished by an intake air leak. A 5% intake air leak reduced the cab protection factor from 20 to 10 without the recirculation filter and from 95 to 49 with the recirculation filter. Other enclosed cab filtration system specifications that can be examined with this equation are various intake and recirculation airflows.

These cab protection factor calculations represent operating conditions at steady-state conditions within a sealed, pressurized cab (doors and windows closed). Actual cab protection factors over a working shift will vary below this calculated value, depending on the frequency and time that the operator opens the cab door and win dows. Therefore, keeping the cab tightly sealed and pres surized is a key aspect in achieving the highest protection factor for an operator. The higher the protection factor achieved on a cab reduces the operator's exposure to the outside dust. Finally, an effective cab filtration system reduces the dust and dirt that infiltrates the HVAC system, increasing its thermal effectiveness and reducing wear on its internal components.