John A. Organiscak[1] *and Michael Schmitz*[2]

A New Concept for Leak Testing Environmental Enclosure Filtration Systems*

ABSTRACT: A method (patent pending) has been developed to determine the quality of environmental cab filtration systems. This method utilizes specially configured filter cartridges to remove carbon dioxide from the ambient air with the environmental cab's air filtration system. A real-time gas monitor is placed inside an unoccupied cab with the filtration system running to time decay the carbon dioxide to its lowest concentration or equilibrium level. The outside carbon dioxide concentration level can be measured concurrently with another gas monitor or with the same inside cab gas monitor during a representative period before and after the inside sampling is conducted. Cab filtration system leakage is comparatively deduced from the difference between the special cartridge filter efficiency and overall cab efficiency. Laboratory trials have illustrated that desirable high efficiency test filter configurations (greater than 99 % efficiency) can be devised, but have air quantity and test time limitations. These trials also demonstrated that CO_2 penetration was reflective of controlled air leaks around a high efficiency filter under equilibrium conditions. This report examines the elements of this patent pending method.

KEYWORDS: cab enclosure, filtration system, air leakage test, ambient air, carbon dioxide

List of Notations

Symbols and Abbreviations

V	Cab enclosure volume	η	Fractional filter efficiency
Q	Air quantity	Δ	Differential
x	Inside cab enclosure concentration	p	Air pressure
c	Outside cab enclosure concentration	s	Measured standard deviation
t	Time	n	Number of sample measurements
l	Fractional air leakage	ppm	Parts per million
P	Fractional cab enclosure penetration		
Indices			
g	Gas	l	Leak
o	Initial	f	Filter

Introduction

Enclosed operator cabs are employed on all types of industrial vehicles to offer various levels of worker risk reduction against the hazards of the operational environment that are inherent in mining, construction, and agriculture. These industrial operations usually have physical, audible, dermal, and respiratory hazards. The Roll Over Protective Structure (ROPS) and the Falling Object Protective Structure (FOPS) are usually part of an enclosed cab system to provide the worker with physical safeguards from the operation. The cab enclosure itself is shelter against weather conditions and provides the basis for heating, ventilation, and air conditioning (HVAC) for maintaining a comfortable temperature and a breathable quantity of outside makeup air for the operator. The cab also provides the surrounding boundary for implementation of noise isolation controls. Another critical component of these enclosed cabs is its filtration system for

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[1] Mining Engineer, National Institute for Occupational Safety and Health, Pittsburgh, PA

[2] Clean Air Filter®, Defiance, IA

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improving the ventilation quality of outside air from airborne pollutants such as dusts, chemical aerosols, and vapors. Filtration system integrity is sometimes very difficult to assess given concealed ventilation components and the invisible nature of some of the respirable airborne pollutants.

Various U.S. regulatory agencies are involved in limiting worker exposure to dusts, chemical aerosols, gases, and vapors. The Mine Safety and Health Administration (MSHA) has regulatory authority over the mining industry [1,2] and the Occupational Safety and Health Administration [3] has regulatory authority over construction, agriculture, and other industries. Both these agencies set worker exposure limits for many substances found in the work environment. Exposure sampling of the work environment is conducted on a regular or as need basis, or both, by both of these agencies. Another agency that sets requirements over chemical agent use is the Environmental Protection Agency (EPA) with its Worker Protection Standard (WPS) [4]. This standard specifies personal protection equipment (PPE) to lower the risks of agriculture workers and pesticide applicators. In some cases, such as in agricultural spraying of pesticides, the EPA permits the use of equivalent engineering controls such as enclosed cabs with a governmental agency's or manufacturer's declaration of its performance equivalency to the PPE specified. Thus, occupational health regulations are either exposure or PPE performance based.

Reducing operators' health exposure risk is a universal issue regarding various industrial vehicle cabs. Enclosed cab filtration system performance has been studied and can be difficult to measure in practice. The American Society of Agricultural Engineers (ASAE) devised a consensus standard on enclosed cab performance test procedures for assessing its PPE equivalency during pesticide applications. These procedures use optical particle counters inside and outside the cab to examine 2 to 4 μm ambient air particulate penetration into the cab as it drives along on an end use tractor [5]. Previous studies show that inconsistent and low ambient particle counts or low dust concentrations during cab testing can give inaccurate performance results [6,7]. Internal cab particulate generation such as dirty floors and abraded blower motor brushes can also interfere with measuring external cab dust penetration [8,9]. These studies indicate that exterior cab particle counts or dust levels need to be at least two orders of magnitude higher than inside the cab to thoroughly measure its performance. They also show that these cab test conditions can be consistently difficult to achieve.

In response to develop alternative cab performance test methods, NIOSH entered into a Cooperative Research and Development Agreement (CRADA) with Clean Air Filter® (CAF) (Defiance, IA) to "Develop Field Test Methods for Evaluating Environmental Integrity of Enclosed Cabs." This research was conducted to develop expedient, simplified, quantitative, and reliable field test methods for quality control assessments of enclosed cab filtration system integrity (external air leak testing). Alternative vapor cab filtration system leak testing had been previously undertaken by CAF on agricultural tractor cabs using high efficiency carbon cab filters inside a laboratory test chamber challenged with ethyl acetate. In this CRADA a field test method was sought that used a measurable airborne agent around the test vehicle which would pose minimal health and safety risks to the user. Under these desired attributes the gases present in ambient air were examined as a potential cab leak test medium. Carbon dioxide was selected for enclosed cab leak testing because of the availability of instrumentation and absorbent media for filtration development. Also, concentrated carbon dioxide is readily available for localized spraying of suspected cab leakage areas. This paper describes the patent pending development "Method and Apparatus for Leak Testing an Environmental Enclosure" and examines testing applications [10,11].

Mathematical Modeling of Cab Filteration System Leaks

A mathematical model was initially formulated to relate the basic enclosed cab filtration system design parameters and any system leakage to interior and exterior cab air concentrations as a means for examining its operational performance. A basic mathematical model of an enclosed cab air filtration system, including air leakage, is a time related material balance of the measured concentrations in the cab and the amount of additional intake air concentrations infiltrating the cab filtration system. Figure 1 shows an illustration of a basic cab enclosure and filtration system. It includes an external filter, duct work, fan, and enclosure volume. The basic mathematical decay model for relating time, air quantity, air quality, and concentration levels for a particular volume is shown below [12]:

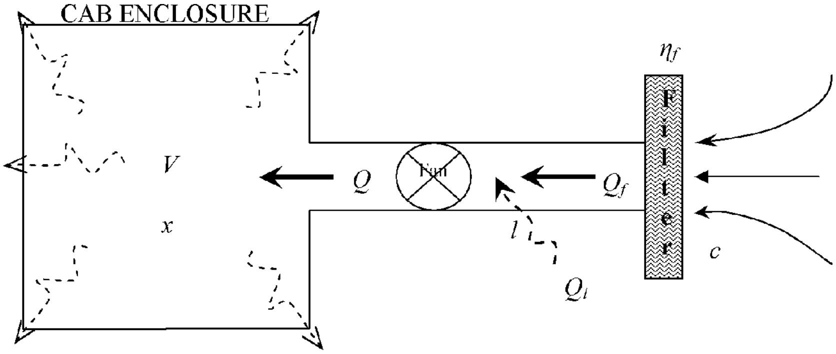

FIG. 1—*Basic cab enclosure filtration system.*

$$Vdx = Q_g dt - Qxdt \tag{1}$$

where V is the volume of the enclosure, x is the concentration of the tracer gas inside the enclosure, Q_g is the volumetric inflow rate of tracer gas into the enclosure, Q is the total volumetric flow rate of air through the ventilation system (including filtered airflow and leaks), and t is time.

Rearrange Eq. 1 for integration yields:

$$\int_{x_o}^{x} \frac{dx}{Q_g - Qx} = \frac{1}{V}\int_{t_o}^{t} dt \tag{2}$$

Solving Eq. 2 yields:

$$\ln \frac{Q_g - Qx}{Q_g - Qx_o} = -\frac{Q\Delta t}{V} \tag{3}$$

The quantity of outside gas infiltrating the cab filtration system Q_g with a theoretical 100 % filter efficiency (η_f) would be due only to air leakage. In this special case Q_g into the cab would be equal to $Q_l c$ or Qlc, where Q_l is the quantity of air leaking into the ventilation system, l is the fractional leakage of outside air into the total quantity flow (Q) of the cab ventilation system, and c is the concentration of the tracer gas outside the filtration system (in percent by volume). If the filter efficiency (η_f) is less than 1 or 100 %, the gas concentration penetration of $(1-\eta_f)c$ through the filter airflow (Q_f) would have to be added to the gas leaking into the ventilation system. Thus, in the more general case Q_g would be equal to $Q_l c + Q_f(1-\eta_f)c$. Since $Q_l = Ql$ and $Q_f = Q(1-l)$, Q_g would end up equaling $Qlc + Q(1-l)(1-\eta_f)c$ or simply $Q(1-\eta_f + l\eta_f)c$.

Substituting this into Eq. 3 and simplifying would yield:

$$\ln \frac{(1-\eta_f + l\eta_f)c - x}{(1-\eta_f + l\eta_f)c - x_o} = -\frac{Q\Delta t}{V} \tag{4}$$

Solving Eq. 4 for the time period (Δt) of concentration change would yield:

$$\Delta t = -\frac{V}{Q} \ln \frac{(1-\eta_f + l\eta_f)c - x}{(1-\eta_f + l\eta_f)c - x_o} \tag{5}$$

Solving Eq. 4 for concentration (x) with respect to time period would yield:

$$x = [(1-\eta_f + l\eta_f)c] - [(1-\eta_f + l\eta_f)c - x_o]\exp^{(-Q\Delta t/V)} \tag{6}$$

The basic cab filtration system model equations above relate all the key parameters to the changing inside concentrations with respect to time. One assumption in this model is that the outside concentration is a constant. Given this constant outside concentration assumption, the inside concentration over time would decrease to an equilibrium or steady-state concentration. As Δt gets larger the exponential term in Eq. 6 gets small and goes to the limit of zero. Thus the inside cab concentration in Eq. 6 at equilibrium could be simplified to:

$$x = c(1 - \eta_f + l\eta_f) \tag{7}$$

which can be expressed as a steady-state gas cab penetration measure:

$$P = \frac{x}{c} = (1 - \eta_f + l\eta_f) \tag{8}$$

Cab performance can be defined or gaged by using one of the above mathematical model equations. The time related concentration equations (Eqs. 5 and 6) can be used to relate all the basic cab parameters to time and inside concentration, but may be more difficult to apply. These equations will require good information on enclosed cab volume (V), filter efficiency (η_f), total volumetric flow into the cab (Q), outside concentration (c), time period (Δt), and inside cab concentrations (x and x_o) to measure or benchmark the performance of the cab air filtration system. A target or benchmark cab fractional or percent leakage (l) would be the likely parameter to be tested to. Therefore, a lesser gas removal time period or inside concentration achieved as compared to the mathematical determined levels would indicate lower cab leakage than the benchmark or target leakage used in the model. In using the time related model it is recommended to utilize a final concentration one unit above the theoretical inside cab equilibrium concentration (Eq. 7) so the time period (Δt) does not go off to infinity approaching the exact mathematical steady-state limit.

One of the most influential parameters in using the time related concentration equations is cab airflow quantity. Given that total volumetric flow into the cab (Q) can be the most difficult parameter to quantify in the field, modeling errors can occur during field evaluations. Within the confines of a congested cab filtration system, a pressure differential measured across the filter would be a more prudent parameter that can be related back to the airflow across the filter. Since $Q=Q_l+Q_f$ and $Q_l=Ql$, solving for Q with respect to Q_f would yield:

$$Q = \frac{Q_f}{(1 - l)} \tag{9}$$

This approach would indirectly require predetermining the filter airflow quantity (Q_f) relationship with respect to the differential pressure (Δp) across the filter at a measured filter efficiency (η_f). Thus the special gas absorbing filter would need efficiency, quantity, and pressure differential performance specifications for the cab leak test.

A more simple or direct approach to determining cab leakage in the field would be to measure the inside and outside cab concentrations at equilibrium or steady-state conditions. Under these conditions the measured cab penetration can be more simply related to leakage and filter efficiency (see Eq. 8). If essentially a 100 % filter efficiency can be achieved ($\eta_f=1$), the penetration ratio would be just the portion of filtration system leakage around the filter, which could be expressed in percent. Although the time period before equilibrium (Δt), cab volume (V), and intake air quantity (Q) would not be necessary for a field evaluation, a 100 % filter efficiency performance quantification would be very beneficial for the cab evaluation. This can be accomplished by cab evaluation under a verifiable 100 % efficient filter at an airflow rate ceiling, quantified by a separate filter efficiency measurement at the differential pressure ceiling (Δp) across the filter for field testing purposes. In this cab testing approach, only gas concentrations and filter differential pressure measurements would be needed to determine cab filtration system leakage.

These mathematical models or equations formulated above were examined through validation trials with carbon dioxide monitors while developing specially constructed filters collecting ambient level of carbon dioxide. This testing was primarily conducted to study and devise practical cab field testing procedures. The testing was conducted mainly on CAF's laboratory cab test stand with some limited testing on a tractor cab.

Filter and System Leakage Testing

Development of the ambient air cab filtration leak test concept with carbon dioxide and the examination of a mathematical cab performance model was conducted by NIOSH and Clean Air Filter® (CAF) under a Cooperative Research and Development Agreement at their laboratory test facilities in Defiance, IA.

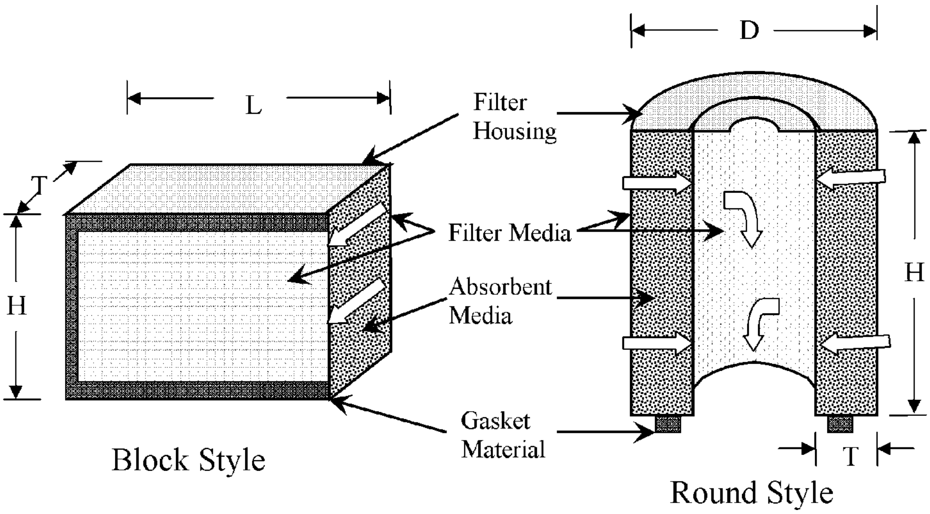

FIG. 2—*Filter styles initially tested on CAF test stand.*

NIOSH contributed sampling and analytical resources while CAF contributed test filter developments and cab system test facilities for this research.

CAF facilities consisted of a well sealed 1.49 m^3 cab filtration test stand set inside a 68.0 m^3 test chamber room. The cab filtration test stand was similarly configured to the layout in Fig. 1. Dual dc variable speed centrifugal blowers draw air through the filter housing and discharge it into the cab test stand. The 68.0 m^3 test chamber room is for controlling the surrounding environment of the cab filtration system test stand or a manufacturer's tractor cab during ethyl acetate vapor testing. This test chamber room is equipped with ethyl acetate sampling instrumentation, ventilation fans, humidity, and vapor generating capabilities.

Early on in the CRADA several vapor agents were considered for field testing. Ammonia and ethyl acetate were two considerations because their filter technology and instrumentation was fairly developed. However, applications of these agents outside of a test chamber to quantify the amount of air filtration system leakage presented an enormous challenge. Also, these agents posed corrosive and flammability issues that would have to be dealt with in widespread industrial use. Therefore, NIOSH suggested examining the components in ambient air for cab leak testing measurements. Carbon dioxide was the primary gas choice decided upon in this CRADA because of the availability of instrumentation for field measurements and filter media (absorbents) for filter development. Finally, ambient carbon dioxide poses much less health and safety risks to its users.

Carbon dioxide absorbents and filters are used for recycling exhaled air by humans in self-contained breathing apparatuses. These CO_2 filters for breathing apparatuses were designed to operate at much lower air quantities and higher CO_2 concentrations exhaled from humans than would be filtered by a cab air filtration system in ambient air [13,14]. Prior breathing apparatus filter technology testing indicated that CO_2 filter efficiency is affected by absorption media formulation and bed thicknesses (T). Therefore, these filter design parameters were considerations for the development of highly efficient CO_2 air filters for cab leak testing.

Initial development work consisted of NIOSH acquiring a couple of Telaire 7001 series CO_2 instruments (Goleta, CA)[3] and some soda lime absorbent media for filter development and testing. The Telaire 7001 series CO_2 instruments were hand-held passive diffusion monitors (no active sampling pump) with a numeric display and an analog output port for data logging capabilities. These instruments were zeroed set or calibrated with nitrogen by the procedures specified by the instrument manufacturer before testing. CAF also acquired some soda lime absorbent media and devised several styles of test filters to be studied on their cab test stand. These filters were constructed similar to CAF's patented contiguous filters used for containing granular absorbents such as activated charcoal [15]. The two types of cab intake filter designs initially tested were the flat panel cartridge (block style) and the cylindrical cartridge (round style). Absorbent media initially tested included Puritan Bennett (PB) soda lime (Lenexa, KS) and DragerSorb

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[3] Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

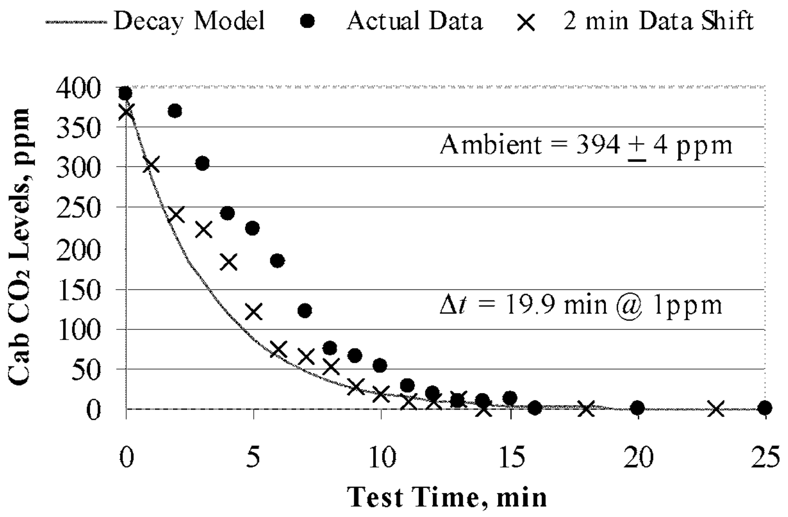

FIG. 3—*Block filter performance with PB soda lime on cab test stand at 7.41 L/s of airflow.*

400 (DS) soda lime (Pittsburgh, PA). Closed cell foam gaskets were bonded onto the test filters to provide a reasonably good seal between the air filtration system. Figure 2 shows a one-half sectional cutaway of these two types of filters tested with the filter airflow direction illustrated. These filter tests were conducted on the CAF test stand to examine what CO_2 filter efficiencies could be achieved for a range of cab make-up air quantities or cab intake airflows. Intake test stand airflows were centerline measured inside a 76.2-mm diameter intake air supply pipe with a TSI Model 8345 VELOCICALC Air Velocity Meter (St. Paul, MN). Inside and outside test stand CO_2 concentrations were measured for test filters over time durations to reach inside test stand equilibrium. The test data presented in this paper only show the higher efficiency filters devised in the laboratory and many of the test examples illustrated in the patent pending application “Method and Apparatus for Leak Testing an Environmental Enclosure” [10,11].

Filter Efficiency and Cab System Model Trials

The first couple of test filters constructed were made with PB soda lime. Time decayed CO_2 concentrations measured inside the cab test stand for these filters are shown in Figs. 3 and 4. Average ambient CO_2 concentrations measured outside the test stand or tractor cab during the test are shown with their 95 % confidence levels on the test figures shown in this report. Figure 3 shows the 7.41 L/s airflow test through a 55.6 mm (T) by 406.4 mm (L) by 152.4 mm (H) block filter containing 2.72 kg of PB absorbent. During this first test only one Telaire instrument was available without a data logger. Eight display readings were manually recorded every 30 s for 4 min before the instrument was placed inside the enclosure test stand.

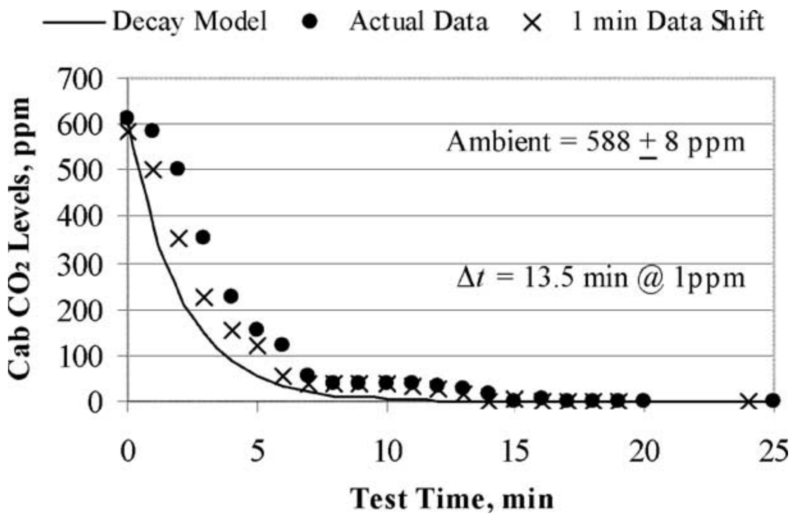

FIG. 4—*Round filter performance with PB soda lime on cab test stand at 11.8 L/s of airflow.*

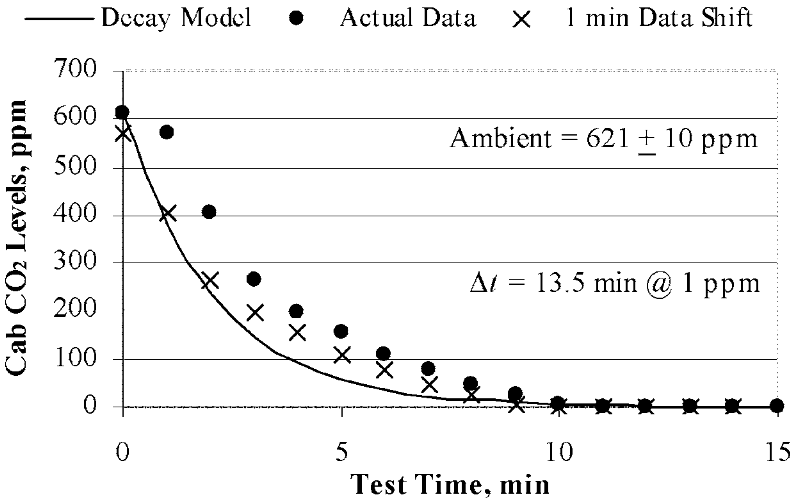

FIG. 5—*Block filter performance with DS soda lime on cab test stand at 11.8 L/s of airflow.*

The outside enclosure readings were observed to be very stable, yielding 394±4 ppm before running the filter test. A virtual 100 % filter efficiency was observed for this filter test. The inside cab concentrations (x) modeled by Eq. 6 are shown with the solid continuous line computed to reach 1 ppm (x_o) with the average ambient air concentration (c), cab test stand volume (V), and intake airflow (Q). The model time interval (Δt) to reach 1 ppm was computed to be just under 20 min using Eq. 5. The Telaire CO_2 display concentrations manually recorded every minute during the test are shown with the dots. The x's show the concentration data shifted by 2 min of measurement time, indicating a much better visual fit to the mathematical model than the actual data. This 2-min data offset is likely a result of both the slow response time characteristics of this particular passive diffusion instrument and the slow mixing of 7.41 L/s intake air quantity inside the 1.49 m^3 cab test stand enclosure. The Telaire response time is specified as less than 60 s for 90 % of step or concentration change.

Figure 4 shows a round type test filter with 11.8 L/s of airflow test through a 273.0 mm (D) by 177.8 mm (H) round style filter containing 4.67 kg of PB absorbent. During this test two Telaire CO_2 instruments were used simultaneously with one inside and outside the test stand enclosure. Their analog output concentrations were electronically collected on a data logger and their 1-min measurements are shown as dots during the test. A virtual 100 % filter efficiency was achieved. Equation 5 modeled concentrations are shown with the solid line reaching 1 ppm by 13.5 min using the average ambient air concentration, cab volume, and intake airflow. The x's show the concentration data shifted by only 1 min of time, which more closely fits the mathematical model as compared to the actual data. A 1-min data shift visually fits this mathematical model better and is believed to be primarily from the slower response time of the passive diffusion monitor. The higher intake airflow of 11.8 L/s achieved in this test reduced the 1.49 m^3 cab test stand volume air changeover time by more than 1 min which likely improved inside air mixing and diffusion to the carbon dioxide monitor.

More testing was also conducted on block and round style filters constructed with DS absorbent. Again two Telaire instruments were data logged with one inside and outside of the cab test stand. Figures 5 and 6 show the inside cab test stand concentration models and measured data for the 55.6 mm (T) by 406.4 mm (L) by 152.4 mm (H) block filter containing 2.54 kg of DS absorbent operated at 11.8 L/s and 18.9 L/s, respectively. The 11.8 L/s air flow through this filter resulted in a virtual 100 % efficiency and the time computed to reach 1 ppm was 13.5 min. The 18.9 L/s airflow rate through this filter resulted in a 95 % efficiency and its computed time to reach 28 ppm was 6.5 min. The minute time shift inside cab concentration data again showed closer agreement with the mathematical models for these tests.

Comparative cab test stand and tractor cab testing was studied with a 1.74 mm (D) by 304.8 mm (H) round style tractor cab filter filled with 3.58 kg of DS which was operated at the comparable air flow rates of 22.5 L/s. In order to determine filter airflow on the tractor, this filter housing was designed with a hose pressure tap between the outside top housing and inside the open channel of the round filter. Various filter airflows and static pressure drops were measured on the cab test stand and are shown in Fig. 7. This figure illustrates a predictable linear relationship between filter airflow and static pressure drop in the measured

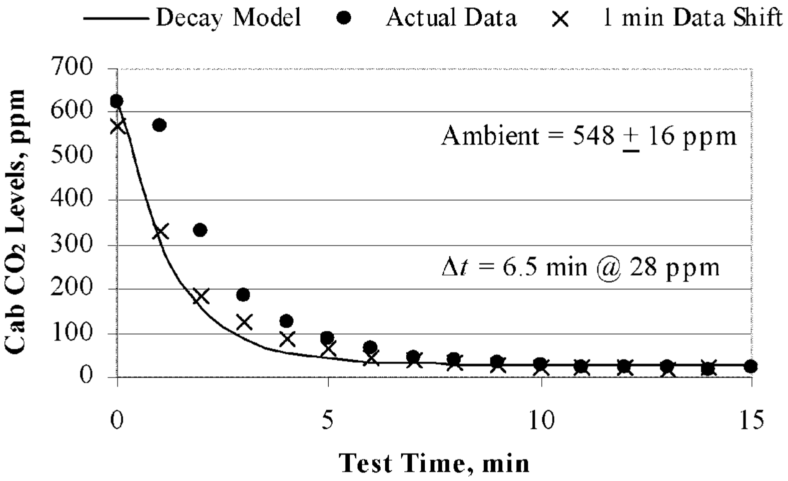

FIG. 6—*Block filter performance with DS soda lime on test stand at 18.9 L/s of airflow.*

range of this particular filter. This information was in turn used to determine filter airflow on the tractor cab. It must be noted, however, that this relationship is filter and range specific. A nonlinearity relationship would be expected for measurements made over a wider range of filter flow regimes.

Figure 8 shows the mathematical models and the measured CO_2 concentrations inside the cab test stand and the tractor cab, using the same filter at the same static differential filter pressure of 114 Pa and corresponding airflow rate of 22.5 L/s. Both the inside and outside Telaire instruments were electronically data logged on the cab test stand, but were manually recorded every minute from the display during the tractor field test. The cab test stand data showed a virtual 100 % filter efficiency that could be expected on the tractor at this airflow rate.

The tractor cab was an original equipment manufacturer's cab found on a John Deere 7800 series tractor. Since the tractor cab volume (V), intake airflow (Q), and filtration system leakage (l) were unknowns, a cab performance model had to be devised based on assumptions made about the actual CO_2

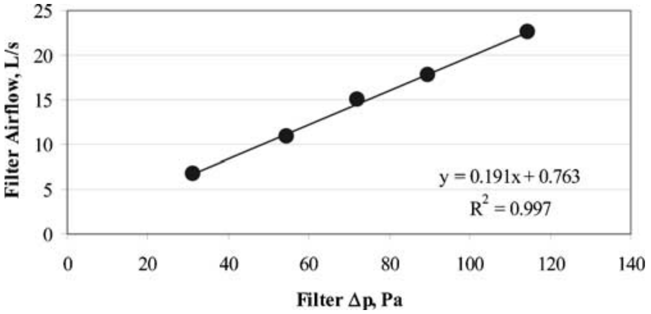

FIG. 7—*Round filter pressure and airflow relationship with DS soda lime.*

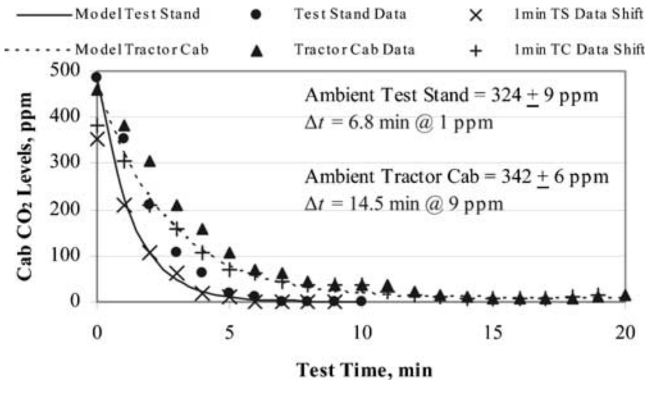

FIG. 8—*Round DS soda lime filter test stand and tractor cab performance comparisons.*

sampling data. The cab model was primarily derived from the time interval to reach a minimum inside cab CO_2 concentration, the average outside CO_2 test concentration, and the test filter airflow. Since the cab test filter was operated at the same static differential pressure (114 Pa), airflow (22.5 L/s), and efficiency (100 %) as on the test stand, air filtration system leakage could be attributed to the cab penetration at steady state by using Eq. 8. The tractor cab's intake air quantity could be determined from filter quantity and cab leakage by Eq. 9. This information along with the time interval to reach the measured minimum CO_2 concentration are used in Eq. 4 to calculate the tractor cab's inside volume. The tractor cab CO_2 decay concentration model shown in Fig. 8 was based on this calculated volume (3.74 m^3) and air leakage (0.02 or 2 %). As can be seen on both the cab test stand and the tractor cab the 1 min data shift has the closest fit to the mathematical decay models. Again this is believed to be mostly due to the slower response of the diffusion type carbon dioxide instrumentation.

Steady-State Cab Leak Penetration Trials

The time related concentration mathematical models illustrated in the examples above require fairly reliable cab parameter information to accurately gage cab performance. A direct or more practical approach for field testing would be to measure the penetration at the cab steady state or equilibrium conditions, as done in the previous tractor cab example for applying the time concentration model. This would reduce the number of cab parameters that have to be known, assumed, or measured, reducing the propagation of errors in quantifying cab performance.

Steady-state leakage trials were conducted on CAF's cab test stand to compare measured CO_2 penetration results with air leakage around the filter. A 101.6 mm (T) by 406.4 mm (L) by 152.4 mm (H) block filter with 4.57 kg of PB soda lime was used to ensure a very efficient filter for multiple leak testing trials. During these experiments a 50.8-mm diameter PVC pipe was used as a leak conduit downstream of the filter. Centerline air quantity measurements were made with another TSI VELOCICALC Model 8346 Air Velocity Meter inside the 50.8-mm diameter pipe. The CO_2 penetration measurements were made with both the Telaire hand-held instruments data logging every 15 s. The trials tested were zero leakage, a targeted leak of 5 %, and a targeted leak of 10 %. The Telaire instruments were rotated between the inside and outside the test stand during these controlled leak test trials. Before instrument rotation, the filter efficiency would be checked with no leak.

During each test the inside concentrations were decayed down to equilibrium. Thirteen concurrent inside and outside equilibrium samples were then averaged to determine the penetration rate. The standard deviations of these samples were also computed to determine the standard error of estimate of cab penetration with these particular hand-held instruments. This random penetration error can be estimated by using the propagation of error formulation shown below in Eq. 10, assuming uncorrelated or independent random error between instrument measurements [16]. Table 1 shows the statistical results for these trials.

$$\left(\frac{s_P}{P\sqrt{n}}\right)^2 = \left(\frac{s_x}{\bar{x}\sqrt{n}}\right)^2 + \left(\frac{s_c}{\bar{c}\sqrt{n}}\right)^2 \qquad (10)$$

The results in Table 1 show that the CO_2 penetration relatively detected the air quantity leakage around the filter. However, differences in measured penetration were observed when the instruments were switched between sampling locations. CO_2 penetrations were observed to be higher than the controlled air leakage portions when sampling with the Telaire 2 instrument inside and the Telaire 1 instrument outside the test stand (Trials 2 and 3). CO_2 penetrations were observed to be lower than the controlled air leakage portions when sampling with the Telaire 1 instrument inside and the Telaire 2 instrument outside the test stand (Trials 5 and 6). After Trial 6 the inside instrument would not zero when the air leak was sealed, indicating that the high filter efficiency started to degrade. Trials 7 through 9 confirm that the filter was degrading, illustrating that penetrations were all higher than Trials 1 through 3 with the same instrument configuration. The use time on the filter after Trial 6 zero check was more than 2 h with a measured filter efficiency of 99.5 %. After about another hour of leak testing the filter efficiency was measured to be around 95 % after Trial 9. Very high filter efficiency ($99.5\ \% < \eta_f$) was observed to be limited to a few hours of testing. This agrees with previous work that as the total volume of air put through the CO_2 filter

TABLE 1—*Controlled air leakage and CO_2 measurements on CAF's laboratory cab test stand.*

	CO_2 Instrument Location Telaire #1 or #2		Cab Air Flow	Leak Around Filter	Portion of Air	Inside Concentration ($n=13$)		Outside Concentration ($n=13$)		CO_2 Penetration	
Trial	Inside	Outside	L/s	L/s	Leakage	$\bar{x}$ ppm	s_x ppm	$\bar{c}$ ppm	s_c ppm	P[b]	$\frac{s_P}{\sqrt{n}}$[c]
1	#2	#1	11.93	Sealed	0	0	0	502	10	0.000	BDL[a]
2	#2	#1	11.84	1.13	0.095	58	7	527	16	0.110	0.004
3	#2	#1	11.79	0.61	0.052	37	2	540	5	0.069	0.001
Filter Check	#2	#1		Sealed	0	0	0	539	5	0.000	BDL
4	#1	#2	11.79	Sealed	0	0	0	692	6	0.000	BDL
5	#1	#2	11.89	0.57	0.048	9	6	711	2	0.013	0.002
6	#1	#2	11.84	1.13	0.095	44	5	625	2	0.070	0.002
Filter Check	#1	#2		Sealed	0	3	2	603	5	0.005	0.001
7	#2	#1	11.79	Sealed	0	12	4	588	8	0.020	0.002
8	#2	#1	11.79	0.61	0.052	38	4	518	11	0.073	0.002
9	#2	#1	11.75	1.18	0.100	61	6	506	5	0.121	0.003
Filter Check	#2	#1		Sealed	0	26	4	524	6	0.050	0.002

[a] BDL=Below detectable level or instrument sensitivity (random errors immeasurable below 1 ppm).

[b] Penetration $P=\bar{x}/\bar{c}$

[c] Standard error of estimate $s_P/\sqrt{n}=P\sqrt{(s_x/\bar{x}\sqrt{n})^2+(s_c/\bar{c}\sqrt{n})^2}$; assumes random errors are uncorrelated.

increases, its efficiency decreases over time [13]. This filter performance depletion occurs more slowly with time for lower airflow rates and becomes quicker as airflow rates increase for a given filter design and CO_2 absorbent media.

The leak test trials in Table 1 also show that the standard error of estimates for penetration were less than or equal to 0.004. This indicates that the random error portion of these penetration measurements were relatively low in these trials. The key penetration differences observed from alternating instruments for similar leak trials were instrument bias and decreasing filter efficiency performance over time. The penetration measurements for the first six trials more clearly reflect the cab test stand penetration from the controlled leaks, since the intake filter operated at its highest filter efficiency ($99.5\ \% < \eta_f$). Later trials showed higher cab test stand penetrations at the same controlled leakage conditions and were attributed to a measured decrease in filter efficiency. Since cab penetration (P) measured at steady-state conditions are mathematically related to both leakage (l) and filter efficiency (η_f) (see Eq. 8), cab leakage can be ascertained from cab penetration and filter efficiency measurements. Thus, steady-state or equilibrium cab test conditions reduces the number of cab parameters that need to be measured and their associated propagation of errors for determining cab performance by the time related mathematical model.

Conclusions

A new patent pending environmental cab filtration system leakage measurement concept was devised. This method uses a special filter to remove one of the ambient air gases out of the cab intake air for inside and outside cab measurement of the filtration system performance. Carbon dioxide was used as the ambient air gas to study the application of this concept because of the availability of instrumentation and CO_2 absorbents to develop special test filters. The inside cab concentrations and cab performance parameters were mathematically modeled and showed conformity during laboratory filter development and testing. Filter efficiency showed a dependency on the media used and airflow put through the filter. Higher intake filter airflows result in a smaller time period to reach inside cab equilibrium or steady-state conditions. Differential pressure and airflow measurements made across a particular intake test filter illustrated a strong linear relationship within a limited measurement range, indirectly providing a means for filter airflow measurement (static pressure) at predetermined filter efficiencies for field testing. Although the time related inside cab concentration model was validated, the cab operating parameters require fairly reliable information to accurately reflect model performance targets.

A more direct or practical approach of cab performance testing is measuring the CO_2 penetration at cab steady-state or equilibrium conditions. This type of testing would simplify and exclude cab parameter measurement errors from the performance testing. Controlled air leakage trials were conducted in the laboratory on CAF's test stand at steady-state conditions and showed that CO_2 penetration was detectable. Switching instrument locations (inside and outside) during these trials indicated a high or low systematic error or bias in the penetration measurements as compared to the leak. The estimated propagation of random error in these penetration measurement trials showed that the standard error of estimate was less than or equal to 0.004. This error appears to be noticeably smaller than the systematic error or bias observed when switching the instruments between the inside and outside locations. These trials also revealed that high efficiency filter performance is achievable for a limited amount of time or number of tests. Cab penetration measurements with a high efficiency filter more simply exemplifies air leakage around the filter, but cab leakage can be determined from both cab penetration and filter efficiency using the steady-state cab penetration equation. Although the steady-state cab filtration system leak testing appears to be more functional, additional research is needed to refine the level of accuracy that can be achieved with the instrumentation and test filters.

References

[1] Federal Coal Mine Health and Safety Act of 1969, Public Law 91–173, 91st Congress, S. 2917, December 30, 1969.

[2] Federal Mine Safety and Health Act of 1977, Public Law 91–173 as amended by Public Law 95–164.

[3] Occupational Safety and Health Act of 1970, Public Law 91–596, 84 STAT. 1590, 91st Congress, S. 2193, December 29, 1970.

[4] Environmental Protection Agency. Title 40, Code of Federal Regulations, Part 170—Worker Protection Standard, U. S. Government Printing Office, Revised as of July 1, 2004.

[5] American Society of Agricultural Engineers (ASAE). *Agricultural Cabs—Environmental Quality, Part 1: Definitions, Test Methods, and Safety Practices*, [Standard S525–1.1], St. Joseph, MI, ASAE, 1997.

[6] Heitbrink, W. A., Hall, R. M., Reed, L. D., and Gibbons, D., "Review of Ambient Aerosol Test Procedures in ASAE Standard S525," *Journal of Agricultural Safety and Health*, Vol. 4, No. 4, 1998, pp. 255–266.

[7] Organiscak, J. A., Cecala, A. B., Thimons, E. D., Heitbrink, W. A., Schmitz, M., and Ahrenholtz, E., "NIOSH/Industry Collaborative Efforts Show Improved Mining Equipment Cab Dust Protection," *SME Transactions 2003*, Vol. 314, Society for Mining, Metallurgy, and Exploration, Inc., Littleton CO, 2004, pp. 145–152.

[8] Cecala, A. B., Organiscak, J. A., Zimmer, J. A., Heitbrink, W. A., Moyer, E. S., Schmitz, M., Ahrenholtz, E., Coppock, C. C., and Andrews, E. H., "Reducing Enclosed Cab Drill Operators's Respirable Dust Exposure with Effective Filtration and Pressurization Techniques," *J. Occup. Environ. Hyg.*, Vol. 2, 2005, pp. 54–63.

[9] Heitbrink, W. A., and Collingwood, S., "Aerosol Generation by Blower Motors as a Bias in Assessing Aerosol Penetration into Cabin Filtration Systems," *J. Occup. Environ. Hyg.*, Vol. 2, 2005, pp. 45–53.

[10] Organiscak, J. A., et al., "Method and Apparatus for Leak Testing an Environmental Enclosure," International Application No. *PCT/US2003/033506*, Publication No. WO/2004/038358, 2003.

[11] Organiscak, J. A., et al., "Method and Apparatus for Leak Testing an Environmental Enclosure," United States Patent and Trademark Office, USA Application No. *10/532,483*, Publication No. US-2006–0154371-A1, 2006.

[12] Hartman, H. L., *Mine Ventilation and Air Conditioning*, John Wiley & Sons, New York, 1961, pp. 37–38.

[13] Bernard, T. E., Kyriazi, N., and Stein, R. L., "CO_2-Absorption Characteristics of Mine Rescue Breathing Apparatus," U. S. Bureau of Mines Report of Investigations 8342, 1979, 13 pp.

[14] Kyriazi, N., "Effects of CO_2-Absorbant Canister Design on LiOH Efficiency in Closed-Circuit Breathing Apparatus," U. S. Bureau of Mines Report of Investigations 8513, 1981, 13 pp.

[15] Schmitz, et al., "Air Filter," United States Patent No. 5,423,903, 1995.

[16] Bevington, P. R., *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill Book Company, New York, NY, 1969, pp. 61–62.