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Test for the Integrity of Environmental Tractor Cab Filtration Systems

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Cab filtration systems can be used to protect vehicle operators from hazardous air contaminants. In a cab filtration system, a fan draws air through filters and pressurizes the cab with this filtered air. This article describes the application of a low-cost, optical particle counter to evaluate the performance of tractor cab filtration systems. The tractors were equipped with environmental enclosures to protect the operators from pesticide exposures that occur during air blast spraying in orchards. Prior to testing, all environmental tractor cabs underwent a complete maintenance overhaul followed by a careful inspection by the manufacturer's field representative. As part of this maintenance effort, 13 tractors with cab filtration systems were tested in an enclosure. A Met One model 227B two-channel optical particle counter was used to measure the aerosol concentration outside and inside the cab. Ambient aerosol and/or aerosol generated by burning incense sticks were used to challenge the stationary cab filtration system in an enclosure. The ratio of the outside to inside concentration (Co/Ci) is the exposure reduction attained by the cab system. Alternatively, the inside concentration divided by the outside concentration times 100 ($Ci/Co \times 100$) gives the percent penetration. All 13 tractors were tested for leak sites. Leak sites were identified and sealed. This process was repeated until each cab showed an exposure reduction ratio Co/Ci of at least 50 (aerosol penetration into the cab $Ci/Co \times 100$ was less than 2%) at the 0.3–0.5 μm particle size interval.

Keywords agricultural workers, environmental enclosures, tractor cabs

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In many occupational settings, workers who operate vehicles are exposed to hazardous air contaminants. Agricultural workers can be exposed to pesticides, dusts (organic and inorganic), mists, bacteria, fungi,

and endotoxin.^(1–4) During grain harvest, workers can be exposed to excessive concentrations of endotoxins and dust.⁽⁵⁾ Heavy equipment operators work in environmental enclosures (environmental tractor cabs and cab filtration systems are interchangeable terms) to protect themselves from airborne pathogens, crystalline silica, and other dust exposures during construction, surface mining, and other earth moving operations. During surface mining operations, these workers are in enclosed environmental cabs of earth moving equipment, rock drilling equipment, and rock trucks.^(6,7) Excessive crystalline silica exposures have been reported among surface mining workers⁽⁸⁾ who work in enclosed cabs. For these workers, a cab filtration system that supplies clean, filtered, pressurized air to the enclosed cab can be used to control air contaminant exposures.

For pesticide application, cab filtration systems are generally constructed from impervious materials so that workers are protected from dermal and respiratory exposures. Figure 1 schematically describes a typical cab filtration system used for pesticide applications. A fan moves air through filters and sorbent to efficiently remove air contaminants. Downstream of the fan, the air flows past the air-conditioner evaporator coil, which tempers the air, and then into the cabin. In some enclosures, a recirculation system is employed to further filter the air by recirculating it through a second set of filters and then past the evaporator coil. The air flows out of the pressurized cab through leaks and/or a vent port. A vent port is designed to allow air to leave the cab at a location that is shielded from the effects of the wind. Cab filtration systems have some air leakage due to the need for electrical and mechanical connections between the cab and the rest of the equipment, defects in welding sites, imperfections in caulking sealing, improper filter sealing, imperfections in gasket materials, deterioration of gaskets and other sealants, and so on.

In Figure 1, the space between the outlet of the filter and the inlet to the blower will have a negative static pressure. Holes and cracks in the structure that surrounds this space will cause

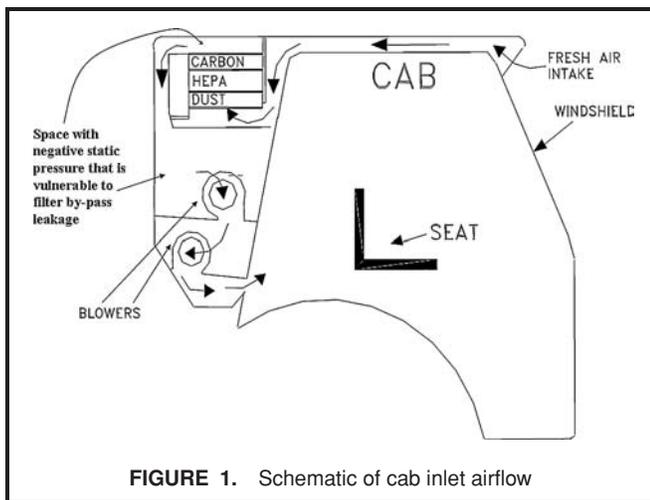


FIGURE 1. Schematic of cab inlet airflow

an airflow that bypasses the filters, increasing the operator's exposure to air contaminants. In addition, the mechanism for attaching the filter to the vehicle's heating, ventilation, and air-conditioning system is another source of possible leakage that allows airflow to bypass the filter. Usually, a gasket attached to the filter is compressed against a metal surface, such as a flange, to provide a leak-free connection between the filter and the duct connecting the filter to the blower. Deteriorated filter gaskets and bowed flanges have caused leaks, allowing airflow to bypass the filter.

The only standard that deals with environmental enclosures is the American Society of Agricultural Engineers (ASAE) S525 Consensus Standard,⁽⁹⁾ which confirms that the design and functionality of the cab filtration system works. Only a single cab needs to be tested to evaluate the cab's design and functionality. Presently, this standard does not address quality control and maintenance issues.

The ASAE consensus standard addresses the use of environmental enclosures for pesticide application; it describes performance requirements and testing procedures. The specifications contain some useful design parameters that can be modified to fit other exposure control scenarios. These design criteria are summarized in Table I, and the basis for this consensus standard has been published elsewhere.⁽¹⁰⁾ This standard was developed for pesticide application, and individuals need to exercise critical judgment in applying these design specifications to

other exposure scenarios. The amount of exposure reduction needed will change with user needs.

As advocated and discussed elsewhere,⁽¹⁰⁾ a most penetrating size aerosol (0.1–0.3 μm) should be employed for the performance specifications instead of a 2–4 μm aerosol as noted in the first specification in Table I. As discussed in aerosol science and filtration texts, filtration efficiency is a function of particle size.^(11–12) Particles smaller than the maximum penetrating particle size are generally collected by diffusion. Particles larger than the maximum penetration particle size are generally collected by interception and impaction. Thus, using a test aerosol in the 0.3–0.5 μm will overstate the penetration in the 2–4 μm range. Based on data on droplet sizes produced by atomization nozzles and droplet evaporation,^(13–14) 5–10% of the pesticide aerosol could be composed of particles smaller than 4 μm . Clearly this specification might need to be changed to account for exposure to all small respirable particles including crystalline silica. As described in Specification 5 (Table I), the ASAE S525 standard⁽⁹⁾ states that a cab must have a minimum pressurization of 58.8 pascals (6 mm of water). In evaluating compliance with this standard, testing is conducted at wind speeds not exceeding 16 km/hour. Experimentally, air infiltration into a cab increases when the wind's velocity pressure exceeds the static pressure⁽³⁾ of the cab. Static pressure requirements can be altered to reflect ambient wind conditions.

Evaluating compliance with the first specification in Table I is time consuming and awkward. Two optical particle counters are used to measure the particle number concentration in the range of 2.0–4.0 μm inside and outside the cab.^(1,2) The ratio of the outside concentration to the inside concentration (C_o/C_i) is termed exposure reduction (inverse of penetration). The test aerosol is the ambient air pollution and the particulate aerosol generated by the operation of the vehicle. The testing is conducted by driving the vehicle with the cab over an unpaved surface at 3–5 km/hour for four 30-min periods. The tractor cab is tested and evaluated at relatively calm air conditions. The test procedure requires that the maximum wind speed for a valid test shall not exceed 16 km/hour. For actual field pesticide applications, it is generally recommended that spraying should not be done when wind speeds exceed 16 km/hour in order to prevent spray drift. Further, the ASAE S525 test cannot be performed when ambient aerosol concentrations are too low (due to rain or other environment conditions).

TABLE I. Important Design Specifications from ASAE S525

1. A 50-to-1 reduction of ambient aerosol (ratio C outside/ C inside) in the 2–4 μm range or the penetration (ratio of concentration inside the enclosure to outside the enclosure) shall be less than 0.02 (1/50th or 2%) for particles larger than 3 μm when measured with suitable optical particle counters.
2. The intake filtration efficiency shall be at least 99% for particles larger than 3 μm .
3. Recirculating filtration (if used) must be greater than 95% efficient against 3- μm particles.
4. A minimum of 43 m^3/hour of filtered air per occupant is required.
5. The static pressure in the enclosure must be at least 6 mm of water.

The ASAE S525 standard requires a 2-hour mobile test to be performed. Such a time-consuming test is impractical for quality control or maintenance programs. Users need a simple, shorter testing procedure so that all cab filtration systems can be evaluated following routine maintenance to make sure the cab systems are functioning properly and have integrity. Manufacturers need such a test procedure for quality control programs. The incorporation of such a test into maintenance programs is needed because mechanical equipment inevitably deteriorates with time and use. Aging and inadequate maintenance can lead to cab deterioration. This case study describes stationary testing to evaluate aerosol penetration into in-service cabs. A single, low-cost, two-channel particle counter was used to measure cab system integrity (ratio of inside to outside aerosol concentrations) on in-use cabs. This fast, reliable method can be used for routinely testing cab integrity. The method could be used following maintenance operations and/or as a manufacturer's audit and quality control method. This stationary testing method uses aerosol generated by burning incense sticks as a very low-cost and convenient test aerosol in the 0.3–0.5 μm size range that is close to the maximum penetrating particle size for a filter. As discussed earlier, the penetrations at this particle size will be larger than the penetrations in the 2–4 μm size.⁽¹⁰⁾

During an evaluation of cab filtration systems for in-use tractors, a testing procedure was developed for testing and evaluating existing cabs in a maintenance environment. This article describes maintenance testing procedures and the outcomes of this testing. These procedures were used to identify the source of the leakage into the cab. Such sources included: filter efficiency compromise, inappropriately seated filters, cracks and holes in the metal cab, poorly welded seams, and gasket deterioration. The method described here is capable of providing a test method applicable to manufacturers' audit procedures.

The procedures presented here are based on determining particulate material in the cab. Gaseous pollutants in the cab were not addressed and specifically tested for but are an important criterion and part of the ASAE S525 test that uses an ethyl acetate test for determining the charcoal sorbents effectiveness. Strictly from a leakage point of view, any defect (e.g., bad seal) that would allow aerosol penetration into the cab would also allow gaseous infiltration into the cab. However, gaseous infiltration was not specifically determined with any testing procedure.

EXPERIMENTAL PROCEDURES

A field study was conducted at the facilities of a custom pesticide applicator who uses helicopters and tractors to apply pesticides to customers' fields in neighboring counties. This company has approximately 30 Nelson Spray Cabs (Nelson Manufacturing Co., Yuba City, Calif.) mounted on Massey-Ferguson tractors (model 398). The tractors evaluated during this study were less than 4 years old. The cabs were

mounted on the tractor by either the user or by Nelson Manufacturing. A typical installation of a Nelson Spray Cab retrofitted onto a Massey-Ferguson tractor is illustrated schematically in Figure 1.

Two fans move approximately 5.6 m³/min through the air inlet above the front of the cab, through the stack of filters (see Figure 2), past the air-conditioner coil, and into the cab. The air flows out of the cab through various cracks and crevices where the cab is mounted on the tractor. The cab contains a magnehelic static pressure gauge. The manual for this cab states that static pressures >7.5 Pa are necessary to protect the worker.

This cab was certified by California Environmental Protection Agency before the ASAE developed the S525 standard. The present ASAE S525 standard requires a minimum pressurization of >58 Pa for totally enclosed cabs with clean filters at the specified blower setting required for pesticide applications. Also, new and used HEPA filters and prefilter media used on the Nelson cab were evaluated in the laboratory at face velocities between 2–15 cm/sec.⁽¹⁵⁾ The HEPA filters were shown to have efficiencies of >99.97% for aerosol particles in the most penetrating particle size range of 0.1–0.3 μm at the face velocities used.

FIELD TESTING PROCEDURES

Before evaluating aerosol penetration into a tractor, the airflow into the cab was measured using a velometer (Velocalc; TSI, Inc., St. Paul, Minn.). Air velocities were measured at the airflow inlet that was located on top of the cab. The airflow volume was estimated as the product of the average velocity and the cross-sectional area of the inlet. Cab static pressure was recorded using either the static pressure gauge in the cab or with an electronic manometer (model MP20SR; Air Neotronics, Oxford, England). In a previous study, similar cabs were evaluated for aerosol penetration according to the ASAE S525 method.^(15,16)

STATIONARY TESTING PROCEDURES

The stationary method is used for screening the environmental cab for aerosol penetration into the cab. A Met One model 227B laser diode type optical particle counter (Pacific Scientific Instruments, Grants Pass, Ore.) was used to measure the number concentration inside and outside the cab. This instrument is factory calibrated. The instrument (manual mode) counts the number of particles larger than 0.3 μm and larger than 0.5 μm for a period of 1 or 2 min. The particle concentration in the 0.3–0.5 μm range is the difference between the two channels. The Met One employs a flow rate of 2830 cm³/min, and as each particle passes through the light beam, the particle scatters light that is detected by a photo multiplier tube. The instrument's electronics counts the number of light pulses and uses the amplitude of the light pulses to classify the particles into different particle size ranges.

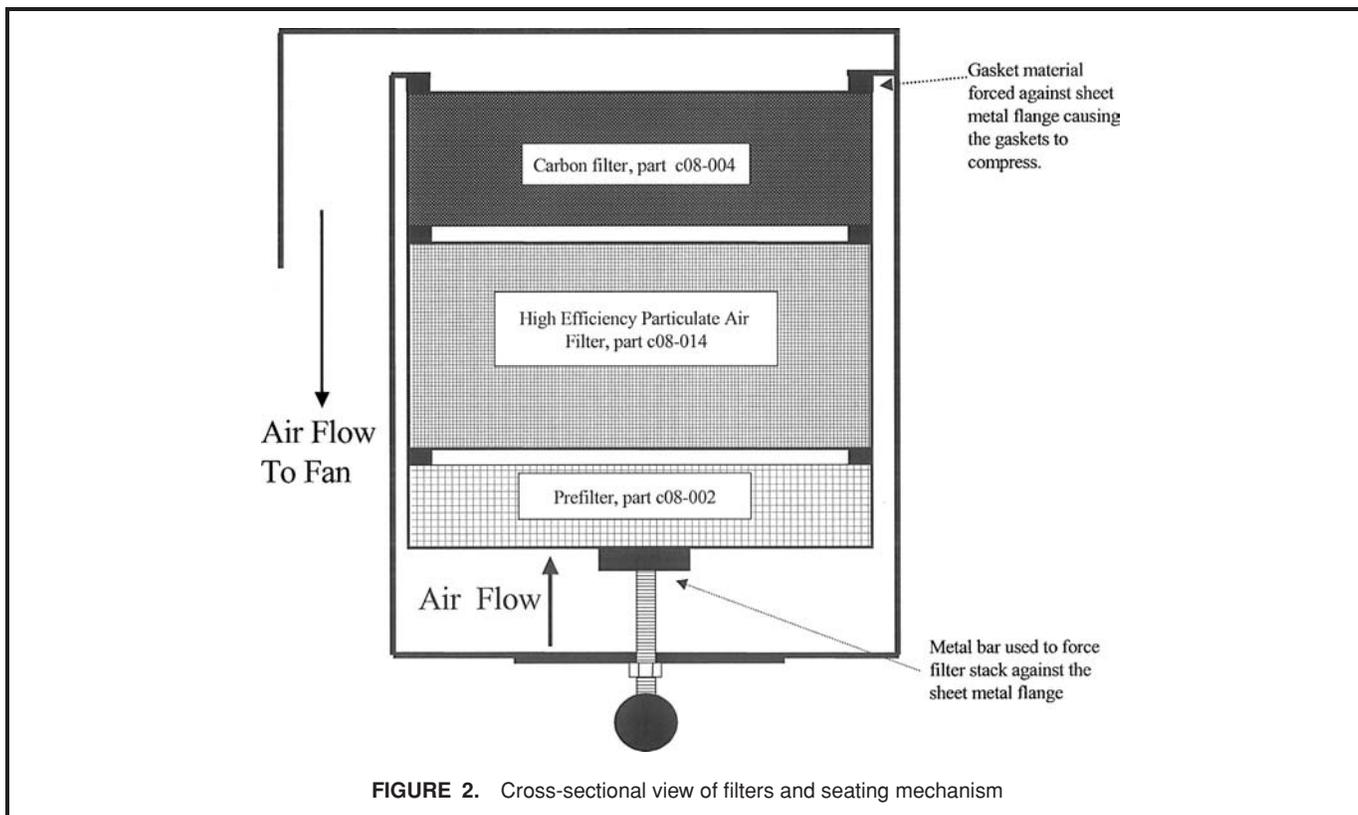


FIGURE 2. Cross-sectional view of filters and seating mechanism

The method consisted of measuring aerosol concentrations inside and outside the environmental cab while stationary but with the tractor's engine operating at 1800–2000 rpm and the cab's ventilation system operating (normal field spray

operational settings). The tractor was parked in an enclosure constructed of wood studs covered with a polyethylene vapor barrier (Figure 3). When ambient aerosol concentration was lower than approximately 120,000 counts per minute



FIGURE 3. Tractor in stationary testing chamber

(42 counts/cm³), one or two incense sticks were placed in cracks in the concrete floor and burned to create a small aerosol smoke stream.⁽¹⁷⁾ The entrance to this enclosure consisted of a roll of polyethylene vapor barrier that could be raised or lowered to adjust the aerosol concentration in the chamber. The enclosure is approximately 4.6 m long, 2.4 m wide, and 2.4 m high.

A Met One Model 227B counter was used for measuring the aerosol concentration inside and outside the environmental cab. Sampling lines of equal length (approximately 2.4 m long with an inside diameter of 0.32 cm) with appropriate connectors were positioned with the outside sampling line positioned at the airflow inlet to the cab and the other inside the enclosed environmental cab on the tractor's steering wheel. The inside sampling line was run through a bolt hole after the bolt was removed. The other end of each of the lines was run through the polyethylene barrier to the outside where the Met One was positioned. An absolute filter was briefly inserted into the sampling inlets of both hoses. If fewer than two particles were counted in 1 minute, the sampling lines did not leak and were acceptable. The cab was closed and the tractor's engine operated at 1800–2000 rpm. An exhaust vent line was run from the exhaust pipe to the outside to minimize diesel exhaust build-up in the chamber. A minimum 5-min period was used for warm-up and cab equilibration at normal operating parameters.

Subsequently, two 1-min Met One samples were obtained from inside and outside the cab at particle sizes of 0.3–0.5 μm . We simply sampled from the inside and outside lines during alternate runs. Two replications were made using the optical particle counter to sample through the different sampling lines. The lines were purged for at least 2 min prior to sampling from the inside and outside lines. Because the volume of sampling line was 192 cm³ and the instrument sampling rate was 2830 cm³/min, the sampling line was purged at least 30 times before data collection. The particle count ratio (inside concentration/outside concentration) was calculated for all particles greater than or equal to 0.3 μm , for particles in the 0.3–0.5 μm interval, and particles greater than or equal to 0.5 μm .

During the stationary test, if the particle number concentration measured by the Met One exceeded the 5% particle loss criteria due to coincidence, a dilutor was used. The manufacturer established limit for coincidence is 200,000 count/min (70 particles per cm³). All counts were kept below this value with a dilutor consisting of a capsule filter (part 12144; Gelman, Ann Arbor, Mich.) with a nominal 0.79-mm or 1.59-mm hole drilled in the wax, which seals one end of the filter cartridge. This allows some of the air to flow around the filter instead of through the filter media. When the dilutor was employed it was used both for upstream and downstream measurements.

Leak Identification Procedures

In a cab filtration system, leakage can occur when the static pressure is negative. The cab is designed to have positive static pressure. The cab static pressure is the static pressure in space where the worker sits. However, the spaces between

the outlet of the filter and the inlet to the blower in Figure 1 will inevitably have negative static pressure. Small holes in the metal enclosing these spaces, or an improperly seated filter will allow air to bypass the filter, reducing the protection that the worker receives. The Met One was used to identify these leak sites. The Met One was set to the concentration mode. The Met One sampled the air flowing out of the air distribution plenum, which was just on the downstream side of the filter system. A smoke tube, generally used for tracing airflow patterns, was used as an aerosol generator and was moved about the exterior of the cab to find leaks. When the Met One responded by indicating a concentration spike, a leakage site into the cab was identified and subsequently sealed. The smoke tube was then used to verify that the leak was sealed and the search for additional leakage points into the cab continued. This method was used to check the entire surface of the cab for leakage. Ultimately the cab was returned to the test chamber and tested for total cab integrity employing the stationary testing procedure described in the preceding section.

Comparison of Mobile and Stationary Tests

At a manufacturing site, mobile and stationary tests were conducted once on a new tractor and twice on an older tractor with different style filters.⁽¹⁶⁾ The stationary testing procedures previously described were used to evaluate aerosol penetration into the cab. The mobile test was conducted as described by ASAE standard S525. Grimm portable dust monitors (PDM, model 1108; Grimm Technologies, Ainring, Germany) were used to measure particle number concentrations inside and outside the cab. This 15-channel optical particle counter that measures particle number concentration over a range of 0.3–20 μm . One Grimm PDM was placed in the cab near the driver; one was attached with elastic cords to the steps outside of the cab. The tractor drove over a paved surface and the PDMs measured particle number concentration inside and outside the tractor's cab. After 30 min, the testing was stopped, the locations of the Grimm PDMs were switched, and the testing resumed. A total of four replicate measurements of penetration into the cab were made.

RESULTS AND DISCUSSION

The airflow into the tractor cabs were between 4.5–5.1 m³/min with cab static pressures (as measured by the cab magnehelic gauge) between 24.9–129.4 Pa. The cab static pressures measured with the electronic manometer measurements were between 17.7–67.7 Pa. This suggests that the magnehelic gauges may need periodic calibration. Cab pressurization simply indicates the maximum velocity pressure to which a cab can be exposed without the wind causing increased penetration into the cab.⁽³⁾ Cab pressurization is not always a true indication of cab efficiency and worker protection because the location of the leak is the critical factor.

The most critical leaks are the ones that occur from faulty filter sealing or holes in the negative air plenum (negative static

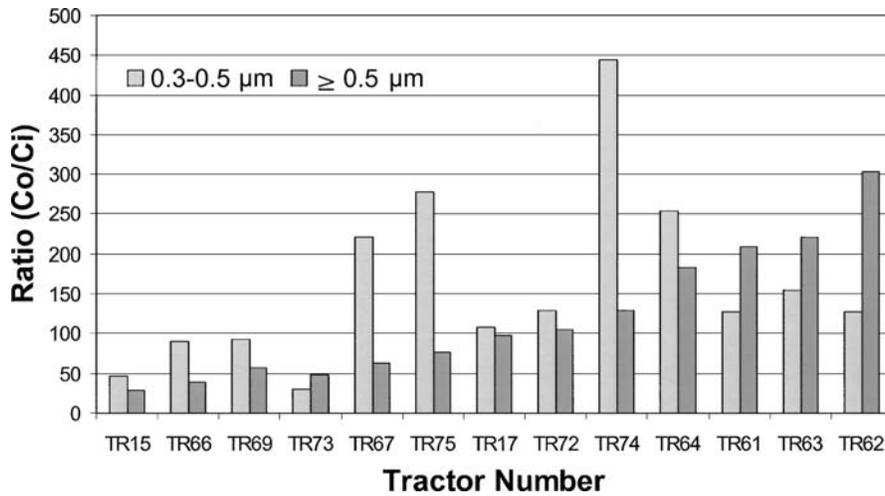


FIGURE 4. Met One stationary cab integrity test results

pressure exists from the filters to the inlet of the blowers). Small leak sites around the filters due to filter sealing problems (faulty gaskets, bowed flanges, etc.) cause air contaminants to bypass the filters. Also, leaks in the negative air plenum that carries the filtered air from the filter housing to the cab interior are critical. Leaks that are downstream from where the filtered air enters the interior cab are less critical but can be important.

Leak sites that have been routinely identified are: (1) faulty gasket materials around filters and doors, (2) holes from external line connections, (3) bowed flanges in the filter housing, (4) holes or faulty weld seams in the negative air plenum due to manufacturing or maintenance problems, (5) leaks in connections in the negative air plenum, etc. Some of these leak sites can be difficult to locate.

Thirteen Massey Ferguson tractors (model 398; Duluth, Ga.) fitted with Nelson Manufacturing cabs were evaluated using the Met One stationary test described earlier. Prior

to initial testing, each cab received routine maintenance by maintenance personnel in conjunction with a Nelson Manufacturing representative to seal the cabs and restore their integrity. After equilibrium, two aerosol concentration measurements were taken inside and outside the cab and the Co/Ci (aerosol concentration outside cab/aerosol concentration inside cab) ratios determined. The average of the two runs is presented in the bar graph (Figure 4). The ratio (Co/Ci) for the 13 cabs ranged from a low of 30 to a high of 445 for the particle size interval between 0.3–0.5 μm. The ratio (Co/Ci) for particles greater than or equal to 0.5 μm ranged from 28–304. Three cabs showed a ratio of less than 50 for one of the two particles size ranges for the Met One optical particle counter. These three cabs were designated as needing additional evaluation for correction of possible aerosol leak sites.

Figure 5 presents the initial and all subsequent Met One runs on tractor TR15. The initial ratio values (Co/Ci) were 47

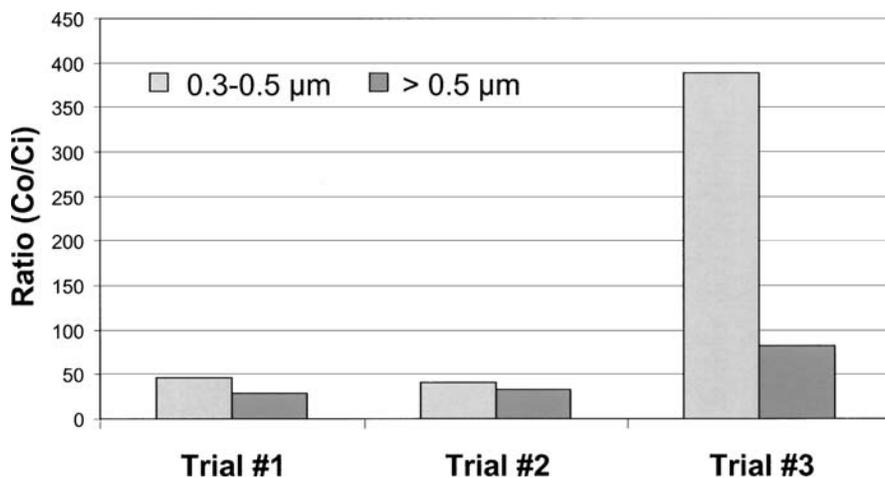


FIGURE 5. Met One stationary cab integrity test results for Tractor TR15

TABLE II. Comparison of Stationary and Mobile Test

Sample	Stationary		Mobile Test		Static Pressure (pascals)
	Met One Ratio (Co/Ci)		Mobile Test Ratio (Co/Ci)		
	0.3–0.5 μm	$\geq 0.5 \mu\text{m}$	0.3–0.5 μm	$\geq 0.5 \mu\text{m}$	
New tractor with new filter design	6	9	7	19	100
Older tractor, older filter design	137	143	113	344	40
Older tractor, new filter design	183	102	139	311	35

(0.3–0.5 μm) and 28 ($\geq 0.5 \mu\text{m}$). This tractor was unacceptable and taken back to the maintenance shop where it was completely re-examined by maintenance personnel and the on-site Nelson representative. The cab was sent for re-evaluation and similar cab integrity ratios were found as initially; the Co/Ci ratios were 41 (0.3–0.5 μm) and 33 ($\geq 0.5 \mu\text{m}$). Finally, the leak identification procedures described in the preceding section were used to identify and seal the leaks. The leaks appeared to be caused by weld seams that had small, barely visible gaps. For some of the small holes, the smoke was observed to flow directly into the hole. A complete check of the exterior of the cab was surveyed with the smoke tube, and all leak sites identified with the Met One were fixed and sealed.

The cab was ultimately returned to the test chamber and tested for total cab integrity employing the stationary testing procedure. On the third test, the ratio values (Co/Ci) were 389 for the 0.3–0.5 μm particle size interval and 82 for particles $\geq 0.5 \mu\text{m}$. The cab met the criteria of both ratio values being greater than 50 and was accepted. Thus, employing these procedures all 13 cabs were eventually upgraded with multiple testing and leak site identification and repair until all cabs gave ratios greater than 50 and would provide protection to the workers.

In another study of cabs at a manufacturing site,⁽¹⁶⁾ the same Met One procedure was employed, and subsequent field runs in conformity with ASAE S525 mobile test were also run for comparison. The data is presented in Table II. These data show that static pressure is not in itself a true indicator of protection since, in this case, the cab with the lower static pressure had less leakage than the cab with the higher static pressure. Also, the Met One static test at these particle sizes appears to be a good indicator of performance during a mobile test. The Met One stationary test requires only one instrument (less costly), and the test is fast enough to be used as an audit and/or quality control test during cab manufacturing.

CONCLUSIONS

The Met One or an equivalent optical particle counter can be used for stationary testing of enclosed cab filtration systems during maintenance and quality control programs to evaluate the total integrity provided by the filtration systems. Furthermore, this procedure can be used in conjunction with smoke tubes to isolate cab leak sites that need to be sealed.

This test uses one inexpensive optical particle and requires less than 15 min per cab. Only a short additional period of time would be required to incorporate such a test as a component in maintenance and quality control programs to ensure all cabs would provide the specified amount of exposure reduction. The Met One stationary test data and the mobile test data show similar trends for the ratio of aerosol concentration inside and outside the cab in the small particle size region. Further work is needed to establish the precise numerical relationship between the ASAE mobile test and the stationary test.

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