**Aim 1: Determine the effectiveness of PHEAF devices to capture particulate matter at a construction site.**

**Hypothesis: HEPA filters used in PHEAF devices capture at least 99.97% of airborne particles 0.3 μm in diameter.**

**INTRODUCTION**

Renovation, repair and rebuild often occur in occupied buildings. Without appropriate dust control interventions, building occupants are at risk for exposure to particulate matter (PM) during renovation activities. To minimize occupant risk of adverse health effects, portable high-efficiency particulate air filter (PHEAF ) devices are often used to control PM emissions during construction and renovation activities (Abdul Salam, Karlin, Ling, & Yang, 2010). PHEAFs are also used as a temporary pollution control technology during abatement of hazardous materials (e.g. mold, lead-based paint, asbestos-containing materials).

Manufacturers market high efficiency air filtration filters (HEPA) as having 99.97 percent efficiency for capturing PM sized 0.3 μm in diameter. A HEPA filter operating below the intended filtration effectiveness may cause unintentional consequences to human health. With the exception of nuclear-grade filters, the selected particle penetration test method is at the discretion of the manufacturer or end-user.

As an engineering control, the PHEAF devices are used in various configurations depending on the project’s complexity and building dynamics. Preferably, the PHEAF unit is exhausted outside of the building. However, the absence of window or door openings or the distance from the building openings to the containment zone can prevent such configurations. In these circumstances, the filtered air is ducted outside of the containment zone and recycled into the building envelope.

There is no certainty that filtration performance is as advertised (Cherry & Smigielski, 2002). When shipped the filter can be dropped or damaged. If the filter is improperly installed, particles can leak around the filter’s gasket or through holes in the filter media. The effectiveness of the HEPA filter is conditional to external factors and operational parameters; hence, leak tests are conducted to determine the integrity of the filter system. The military, nuclear, biomedical, and pharmaceutical industries require leak testing of the HEPA filter upon installation and periodically thereafter. HEPA filters used in these industries are installed in stationary systems, however, unlike portable HEPA units, which are frequently relocated between project sites.

Portable HEPA devices can be mishandled and are subject to extreme operating conditions (e.g. elevated relative humidity, particle concentrations), which can damage the integrity of the HEPA filter. Additional concerns are noted when the airflow of the PHEAF’s device exceeds the HEPA filter rating. While HEPA filters are marked with the rated airflow rate and pressure drop, proper application of the HEPA filter is subject to the end-user.

Presently, no consensus standards or nationally recognized practices exist in the United States for in-place leak testing of PHEAF equipment. This is unfortunate, because portable units are subject to more mishandling than permanent HEPA filters devices. For this reason, the end-user may not recognize that the unit’s capture effectiveness is less than the manufacturer’s rating. Akbar-Khanzadeh and Smigielski (2009) explain that the techniques necessary to determine the effectiveness of HEPA filters have not been sufficiently communicated among health and safety professionals. Such a finding may explain the absence of applied research discussing the PHEAFs filtration performance in a field setting. Instead, the end-user may presume that the unit is effectively capturing PM as intended. Without validating the effectiveness of the HEPA filter, the end user may neglect preventative maintenance, repair, or inappropriately use the engineering control.

Adding to the practical aspect of the research is that the units under study were measured in the field, absent of the controlled environment of a laboratory setting. As such, the sample population was subject to the physical conditions typically imposed on PHEAF units. By measuring the capture effectiveness of a PHEAF unit over time, data will be analyzed to compare field performance with its theoretical design. Environmental and operational factors will be modeled to determine their effects on capture effectiveness.

For this study, a sample of PHEAF devices will be analyzed for effectiveness to capture at least 99.97% of airborne particles at 0.3 μm in diameter. Capture effectiveness is a function of the PHEAF system (filter condition, filter alignment), which is affected by airflow velocity, ambient temperature, and relative humidity. Each of these variables can influence the measured result. For example, elevated air flow velocity can increase particle penetration. Incorrect measurement of air flow velocity can bias the accuracy of the measurement. Although measurement error can be minimized through training of the test administrator; use of the same measurement instrument; and adherence to a written test protocol, literature indicates residual error is inherent to the test method. For these reasons the test method will be evaluated for interferences from airflow velocity, temperature, and relative humidity. Adding to the practical aspect of the research is that the units under study were measured in the field, absent of the controlled environment of a laboratory setting. As such, the sample population was subject to the physical conditions typically imposed on PHEAF units.

**METHODS**

**Portable high efficiency air filtration units**

A sample population of PHEAF devices were analyzed for effectiveness to capture at least 99.97% of airborne particles at 0.3 μm in diameter. The PHEAF units under study were employed to control PM during interior renovation of a building. The scope of work entailed demolition and replacement of typical building materials (concrete, gypsum wallboard, vinyl tile). The PHEAF units were staggered throughout twelve building levels with the number of units per floor determined by project need. We selected PHEAF devices of the style common to the asbestos abatement and similar industries. The PHEAF units were of similar sizes, although representative of different manufacturers. Most units were of metal construction with a 2’ x 2’ cabinet that housed a HEPA filter and squirrel cage type blower rated from 600 cfm to 2,000 cfm. The construction contractor was responsible for maintenance and servicing of the PHEAF units. Several times per month, a trained technician inspected the operating condition and if necessary replaced the pre-filter based on visual appearance.

For purposes of comparing efficiencies by equipment design, two control units constructed of high-density, polyethylene cabinet and a motorized impeller were included in the study. One control unit has variable speed motor with an airflow of 300 cfm to 900 cfm, caster wheels, coarse particulate pre-filter, and pleated particulate filter inserted in front of the HEPA filter. The other control unit has a variable airflow up to 500 cfm and is fitted with a coarse particulate pre-filter in front of the HEPA filter. The control units have a documented history of performing at or near HEPA effectiveness.

For testing, each unit was operated at its highest airflow rate. If the unit was not operating upon arrival the industrial hygienist would toggle the switch to the highest airflow and turn the unit on and wait for at least one minute to warm-up before further evaluation. Next, a visual inspection of the PHEAF device was performed to identify the unit’s condition (e.g. prefilters are missing, damage to the cabinet, odors). Observed deficiencies were noted on the field record. Prior to conducting airflow measurements the pre-filter and second stage ring panel filter were removed from the PHEAF device.

Field data was recorded on forms unique to the measurement instrument and test procedure. Field data included location and operating condition of the PHEAF device (e.g. floor number), test administrator, and the unit identification number were also recorded. Field measurements were manually inputted into a customized FileMaker Pro database ~~(~~FileMaker Pro Version 12, FileMaker, Inc, 2012) for data management. Specific sets of data were extracted from this database for analysis. Statistical analysis of the data was performed in STATA Statistical Software (Stata Statistical Software: Release 13, StataCorp. 2013) and R version 3.2.4 ( R: A language and environment for statistical computing. R Core Team, 2016. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/).

**Airflow and Ambient Coditions**

Air flow was measured by hot wire anemometer (TSI VelociCalc 9545-A), balometer capture hood (Alnor EBT731, TSI, Incorporated), and filter pressure differential. The TSI VelociCalc measures air velocity from 0 to 6,000 feet per second with an accuracy of ±3%. The balometer capture hood is designed to measure airflow volume ranging from 25 cfm to 2,500 cfm (±3% of reading).

Using the hotwire anemometer intake airflow was measured approximately 1 inch from the PHEAF’s face guard. Intake measurements were taken across 9 equal size sectors of the filter face. The PHEAF device’s intake airflow volume was calculated by averaging the nine sector measurements. Exhaust velocity was measured by placing the probe tip along the centerline of the exhaust plenum to approximate the mean. Measured velocity values were computed to volumetric airflow by multiplying the velocity measurement by the PHEAF intake or exhaust area. When determining volumetric airflow by the balometer technique, the capture hood was placed over the face of the PHEAF’s intake and exhaust. The device’s operating pressure differential was recorded if the PHEAF was equipped with a magnehelic gauge or manometer. Pressure differential was measured in inches water gauge (in. w.g.). Subsequent to recording the airflow measurements, the pre-filter and second stage ring panel filter were properly replaced into the PHEAF device.

Ambient temperature and relative humidity were measured using a TSI VelociCalc 9545-A, (TSI, Incorporated). The device can measure temperature from 14°F to 140°F, relative humidity from 0% to 95%. The accuracy of the temperature and relative humidity measurements are ±0.3C and ±3% relative humidity.

**Leak Test Using the Aerosol Photometer**

There are various aerosol methods for measuring particle penetration of PHEAF equipment and the PHEAF device’s capture effectiveness.  Each method uses a combination of an aerosol generator and a photometer. For this study, field testing of the complete PHEAF device was performed using a photometer to measure penetration of a known concentration of PAO aerosol through the unit’s HEPA filter. An ATI TDA-4B (Air Techniques International) aerosol generator was used to produce the PAO challenge agent. The TDA-4B incorporates 6 Laskin nozzles, each capable of generating an aerosol concentration of 5.10 mg/l at 23 psig. When this aerosol is diluted with 135 cfm of air, the aerosol concentration becomes approximately 100 micrograms per liter. For this study, PAO aerosol was generated using 2 Laskin nozzles.

Particle penetration was detected using an ATI 2H photometer (Air Techniques International). The instrument has a particle sensitivity detection range of 0.1 µm to 600 µm with a dynamic range of 0.00005 μg/l to 120 μg/l. The ATI photometer was factory calibrated to read “27” when aerosol generated from 2 Laskin nozzles was diluted into 1,000 cfm of air. This is a convenient airflow rate since it is a common air volume moved by PHEAF equipment used in the asbestos, lead and mold remediation industries, as well as Type II Biosafety cabinets

During measurement of PHEAF equipment, the actual air volume moved (conveyed) by the PHEAF equipment was measured. If the measured volume exceeds 1,000 cfm, e. g. 2,000 cfm, then the setting on the photometer is reduced to 13.5. Conversely, if the measured volume is 500 cfm, then setting on the photometer is increased to 54.  By changing the setting on the photometer, the reading that appears on the photometer will reflect the actual concentration of aerosol per 1,000 cfm.

Prior to beginning the test, a measurement of ambient particle concentration was taken using the aerosol photometer. To evaluate the PHEAF device’s capture effectiveness, particle concentrations at the PHEAF exhaust were measured by a 2-person team. The known concentration of aerosol was injected using an open ended flexible tube held 1 inch from the filter face. Applying the sampling strategy used for velocity measurements, the HEPA filter was divided into 9 segments or zones. For each measurement the flexible tube was traversed across the filter sector at approximately 2-5 cm/sec. While injecting the PAO aerosol, another industrial hygienist held the photometer probe at the exhaust centerline and parallel to the direction of airflow. A sampling probe with a rectangular inlet opening was used to measure particle penetration. Such probes are marketed by the manufacturer as having an isokinetic nozzle appropriate for faster filter scanning and is accepted for NSF/ANSI 49-2002. Readings on the meter indicate percent of the known aerosol concentration penetrating through the PHEAF device. The highest percent particle penetration observed within the filter sector was recorded.

The PHEAF device was categorized as passing if the measured capture effectiveness was 99.97% or greater in accordance with NSF/ANSI 49. In order to calculate the effectiveness of the PHEAF device, the photometer reading is divided by 27, and the result subtracted from 1 and then multiplied by 100 to make it a percentage. For example, if the photometer reading was 0.0027 mg., then the effectiveness of the PHEAF device would be 1- 0.0027/27 or 99.99%.

When the aerosol generation rate was calculated by hotwire anemometer, the percent particle penetration was weighted to calculate capture effectiveness. For each filter sector, effectiveness was determined by subtracting the weighted average concentration of aerosol penetration from the known challenge concentration and then dividing that by the challenged concentration. The weighted average concentration of aerosol penetration was determined by multiplying the percent particle penetration by the sector’s velocity and dividing by the average velocity of the 9 filter sectors.

Ambient concentration of particles sized between (indicate range of photometer) were estimated with the photometer. DESCRIBE HOW THE PHOTOMETER ESTIMATES BACKGROUND WHEN ITS READINGS ARE INDICATED AS A PERCENT OF A KNOWN AEROSOL .NOTE THAT SEVERAL BACKGROUND VALUES EXCEED 1.

**RESULTS**

A total of 86 PHEAF devices, which included 2 control units were evaluated from May 2012 through March 2015. Repeated sampling was conducted over nine test rounds; although testing of PHEAF devices was not conducted on fixed time intervals. Instead testing was conducted depending on on-going construction activities and available equipment and staffing. For example, units that could not be located or were taken out of service (e.g. purposefully removed from the site or inoperable due to damage) at the time of the site visit were not sampled. This consequently resulted in different sample sizes for each piece of equipment. To illustrate the variability of the sample population, 50 PHEAF devices were sampled during round 1, whereas 34 units were tested in the last round (i.e. round 9). Of the 354 individual tests conducted, 20 PHEAF units were tested 3 or fewer times, whereas 24 devices design were tested at least 6 or more occasions. On average each unit was tested 4 times during the study period.

The sample population consisted of PHEAF devices of 7 different manufacturers. Six units were not labeled with the manufacturer’s nameplate, but their design was consistent with common PHEAF devices. Eighty three percent of the tests were on the same make and model having an advertised airflow volume of 2,000 cfm. The second most commonly tested unit was marketed with a 2,100 cfm airflow and represented 6% of the test population. The majority of the design configurations measured approximately 33 inches (length) x 26 inches (width) x 26 inches (height) in size.

**Ambient Conditions**

Ambient building temperature and relative humidity parameter measurements were taken near each PHEAF device. Ranging from 60°F to 91°F with a mean temperature of 75.4°F (*SD*=6.6) the fluctuations reflected ambient conditions found outside of the building. Relative humidity had a mean of 34% (*SD*=16.4). Linear regression was applied to evaluate if relative humidity and ambient temperature predict capture effectiveness. The model showed a slightly positive correlation, although the association between capture effectiveness to relative humidity and temperature was not statistically significant. Thus as capture effectiveness increased, humidity and temperature neither increased nor decreased systematically.

**Airflow Measurements**

Airflow was measured at the face of the PHEAF device’s intake and centerline exhaust port by hotwire anemometer or balometer capture hood. Design configuration of the two control units were not suitable for the balometer capture hood technique, therefore the airflow volumes were determined by hotwire anemometer. Hotwire anemometer measurements were recorded for 244 tests and balometer capture hood measurements were taken during 177 tests. To analyze the relationship between hotwire anemometer and balometer measurements, both techniques were employed consecutively on the same unit for 68 tests.

Over the course of the study, measured actual airflow volumes were observed to be substantially less than rated capacities. As measured by the hotwire velometer, the calculated average intake volumes of the PHEAF units were ranged from 25.9% to 60.3% less than the PHEAF devices’ rated value. For example, a manufacturer’s model with an advertised flow rate of 2,000 cfm had an actual average flowrate around 1,482 cfm. Similar findings were observed with measurements made with the balometer capture hood.

Comparing measurements collected on the same unit indicated exhaust volumes were 14.8% (*SD*=26.6) less on average than the calculated intake volumes as measured using the hotwire anemometer technique. These measurements ranged from a maximum of 65% to a minimum of 82.5%. A possible contributing reason for this over-estimate is the filter grating on the face of the equipment, which could affect air flow through each quadrant or measurement error from radiant heat loss (i.e. near wall effect). Intake volumes averaged 9.3% (*SD*= 0.6) less then exhaust volumes when measured by balometer capture hood. The intake volume ranged from a maximum of 13.5% to a minimum of 26.3%.

Anemometer volumes (i.e. intake+exhaust/2) were 26%higher than the average balometer capture hood volumes (intake+exhaust/2). Moreover, the average anemometer volumes are 36% more variable than the average balometer readings. The variability between the measurement techniques ranged from a maximum of 44.55 % to a minimum of 5.5% (*SD*=9.4). In this paired experiment where both techniques are measuring the same airflow, the balometer capture hood appears to be more reliable given its smaller variability.

Figure XX. Air volume measurements by anemometer and balometer technique



~~Of the volumetric measurements taken, variability was highest at the PHEAF’s intake. The coefficient of relative variation for intake (~~*~~CV~~*~~=.56) and exhaust measurements (~~*~~CV~~*~~=0.49) by hotwire anemometer technique showed greater variance relative to their mean compared to intake (~~*~~CV~~*~~=0.34) and exhaust (~~*~~CV~~*~~=0.33) measurements taken by the balometer capture hood.~~

Table XX. Comparison of average percent difference between intake volume and exhaust volume between datasets

|  |  |  |
| --- | --- | --- |
| Measurement Technique | All measurements | Measurements taken on same unit |
| Anemometer | Intake 15.7 % (*SD*= 60) less than exhaust | Intake 14.8% (*SD*=27) greater than exhaust |
| Balometer | Intake 12 % (*SD*=10) less than exhaust | Intake 9.3% (*SD*=0.6) less than exhaust |

Variability was seen across the 9 filter sectors with average velocity ranging from 398 feet per minute (fpm) to 432 fpm. The lowest velocity measurement was associated with the smallest variability, which was observed in the center of the filter face.

TABLE X. Velocity measured at 9 filter sectors during the study period, excluding control units



Comparing the middle center velocity measurements to the measurements of the other eight sectors, we find that at lower velocities the measurement values are similar, but at higher velocities the perimeter (corner sectors) are consistently higher. This suggests that at higher velocities there is greater variability and a positive bias in measurements at the perimeter sectors compared to the center of the filter.

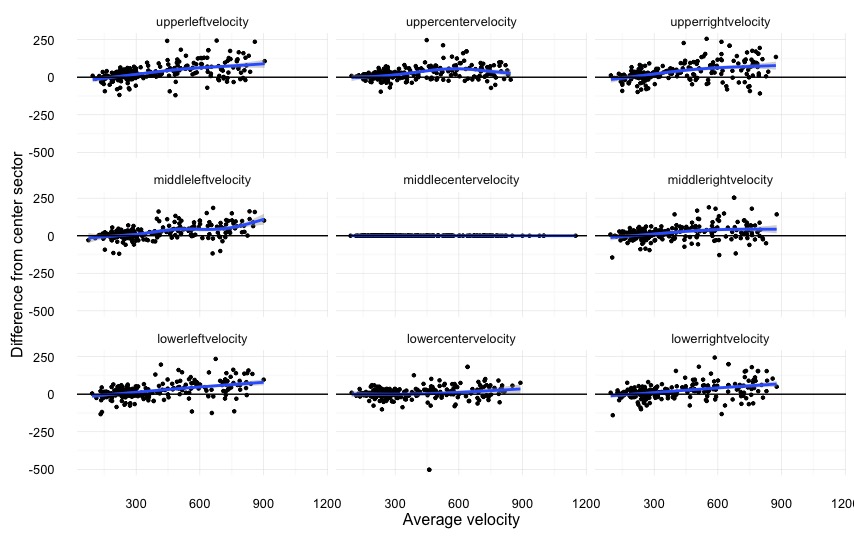


Figure 1: Bland-Altman plots of the balometer velocities for each of the 8 sectors compared to the center sector. The solid horizontal like represents no difference, and the blue line is a loess smoother applied to the data. The Bland-Altman plots the average of the two measurements on the x-axis and the difference between the measurements on the y-axis.

To assess the degree of agreement between the two techniques, for each paired test the proportional difference of the hotwire anemometer compared to the balometer capture hood paired measurements was plotted against the mean of the two measurements, in a Bland-Altman plot (Bland JM, Altman DG (1986). ["Statistical methods for assessing agreement between two methods of clinical measurement"](https://www-users.york.ac.uk/~mb55/meas/ba.pdf) (PDF). *Lancet* **327** (8476): 307–10). While the majority of the data points were within ± 2 SD of the mean difference, 4 paired values exceeded the model's limits of agreement, indicating that the anenometer readings may be too variable compared to the balometer capture hood. On average the hotwire anemometer technique measured proportionally higher than the balometer capture hood technique. This positive bias is more prominent for measurements between 1,500 cfm and 2,000 cfm, meaning measurment bias changes with airflow. Since the line of equality is outside of the 95% confidence interval of the mean difference (i.e. limits of agreement) suggest a significant systematic difference between the two techniques.

Graph XX. Bland Altman plot of differences between hotwire anemometer and balometer capture hood



Multiple analyses performed in this study suggest the balometer capture hood technique is more accurate (accurate or reliable??) than the anemometer technique. Indeed, evidence presented indicates that the anemometer readings may consistently be overestimating the volume of air passing through the PHEAF device.

The aerosol photometer’s internal reference value was computed based on the intake volume as measured by the anemometer or balometer technique; however, evidence from analysis of the volumetric measurement data suggests the balometer capture hood exhaust measurements better approximate the true airflow measurement. Therefore, the aerosol concentration value needs to be adjusted to calibrate with balometer capture hood exhaust measurements for tests where this technique was not used to measure airflow. To accomplish this adjustment factor, we fit a regression model to predict the balometer exhaust volume from the anemometer intake readings where measurements were taken using both techniques. This model will be used to predict the balometer exhaust volumes (=230.9+ 0.59 x anemometer intake) for the tests where only the anemometer readings were taken. These predictions will be used for the computation of the aerosol internal reference values derived from anemometer intake measurements.

**Capture Effectiveness**

PHEAF capture effectiveness was measured during 354 tests representing a dataset comprised of 325 tests on the PHEAF study group and 15 tests performed on the PHEAF control units. 14 measurements from 8 units in the study group had a negative capture effectiveness value measured in one of the filter sectors. These anomalies were random and were observed during tests made before and after replacement of the HEPA filter. Except in two instances, once a negative capture effectiveness value was observed in a unit, subsequent tests had a negative capture effectiveness value. These 14 measurements were excluded from the analysis. One test of the control unit was excluded from analysis with reported airflow volume that exceeded the unit’s theoretical operating capability.

Ambient particles levels as measured with the aerosol photometer ranged from 0.0002 units? to 2.6 units?, with a mean of 0.098 units (*SD*=0.212). A simple linear regression was calculated to predict capture effectiveness based on background concentration. The fitted regression line had a slope=0.0017 indicating that there was no relationship between background aerosol concentration and capture effectiveness.

Over the period of study the capture effectiveness for the study units averaged 97.74% (*SD*=5.6), whereas the control units had a mean capture effectiveness rating of 99.99% (*SD*=0.01). Approximately 14 months after study commencement, the operator of the PHEAF units replaced a portion of the unit’s HEPA filters. Of the 54 units where the filter was replaced, only 11 units had measurements collected before and after filter replacement. This means that after filter replacement the affected unit was not placed back into service or the unit was not placed into service until after the filter was changed.

Table XX. Average capture effectiveness by group before and after HEPA filter change replacement

|  |  |  |
| --- | --- | --- |
| Mean capture effectiveness | Before filter change | After filter change |
| Study group | 99.99% (n= 10, *SD*=0.01) | 99.99% (n=5, SD=0.003) |
| Control group | 97.8% (n=218, *SD*=6.2) | 97.6% (n= 107, *SD*=4.4) |

11.2% of the study group met HEPA standards having a measured capture effectiveness of at least 99.97 percent.

Table XX. Average capture effectiveness by filter sector (#5 center sector)



**Analysis of capture effectiveness by filter sector**

Capture effectiveness of a PHEAF device is quantified by averaging percent particle penetration measured at the 9 filter sectors. To observe how each filter sector contributes to the unit's overall performance, leak tests results from the study sample (i.e. no control units) were categorized by their measured capture effectiveness. Group 1 included 33 tests outcomes where the measured capture effectiveness met HEPA performance standard (99.97%); Group 2 included 43 test outcomes with measured capture effectiveness ≥99.9%; and the third group encompassed 135 test outcomes where capture effectiveness measured between 99.0% to 99.9%.

We considered three levels of filter effectiveness. These were effectiveness > 99.97% (the HEPA standard), 99.9-99.97% and 99-99.9%, to see how well or poorly the filters were performing. When a unit met the HEPA standard, so did most of the individual sectors; at least 6 of the 9 sectors met HEPA levels in 96.97% of the passing units. However, even when the overall effectiveness was slightly reduced, most of the units showed that at least 3 of the sectors failed. Within Groups 2 and 3, at least one sector always failed the HEPA standard. This finding suggests most of the filter sectors must perform at the desired efficiency for the PHEAF's overall capture effectiveness to pass the HEPA criteria.

Table XX. Number of sectors meeting the HEPA standard, stratified by overall capture effectiveness level.

|  |  |  |  |
| --- | --- | --- | --- |
| Number of filter sectors meeting group criteria | Group 1 -99.97% or greater (n=33) | Group 2 - 99.9-99.97% (n=14) | Group 3 - 99.0% to 99.9% (n=135) |
| At least 6 of 9 | 96.97 | 57.14 | 5.93 |
| At least 7 of 9 | 93.94 | 35.71 | 2.96 |
| At least 8 of 9 | 69.70 | 21.43 | 1.48 |
| 9 of 9 | 45.45 | 0.00 | 0.00 |

For each group, the filter's middle center sector had the highest occurrence of meeting or exceeding the group's capture effectiveness threshold. For example, in Group 3 the filter's middle center sector met the capture effectiveness criteria (e.g. 99.97%) in 60.7% of the tests, whereas other filter sectors satisfied the group criteria less than 36% of the test occurrences. Graphs XX- XX illustrate the capture effectiveness range for each leak test by group. For each test, the filter's middle center sector is represented by a darkened dot. The dotted horizontal line is the 99.97% HEPA standard. The graph for Group 1 show for each test a limited spread among filter sectors, whereas Group 2 and Group 3 reveal greater variability among the filter sectors. These graphs imply capture effectiveness measured between 99.0% - 99.9% is obtainable despite variability between filter sectors; however, capture efficiency at HEPA performance standards is more rigorous, defined by less tolerance among the filter sectors.

Graph XX. Group 1 -99.97% CE by filter sector

Graph XX. Group 2 -99.9% CE by sector filter



Graph XX. Group 3- 99.0% <CE > 99.9% by filter sector



A paired t-test was performed to compare the mean capture effectiveness measured at the middle center sector compared to other filter sectors. Table X provides results from the 8 t-tests reported simultaneously in one table. The results suggest a significant difference in capture effectiveness performance among the filter perimeter sectors compared to the filter's middle center sector. Among the findings of statistical significance, the average capture effectiveness of the perimeter filter sectors is 1.1 to 2.3 percentage points lower than the middle filter sector.

Table Table X. Average difference between middle center filter sector and other filter sectors

|  |  |  |
| --- | --- | --- |
| -0.72 | -1.13\*\* | -1.83\*\*\* |
| 0.15 | 0 | 0.28 |
| -2.26\*\*\* | -2.29\*\*\* | -1.75\*\*\* |

\* p<0.05 \*\*p<0.01 \*\*\*p<0.001

A chi-square goodness-of-fit test was performed to determine whether the differences of capture effectiveness by filter sector was attributable to random measurement error. The test hypothesized equal expected occurrences of any filter sector being the most effective filter sector. The test was statistically significant: χ2 = ??.?, p < 0.0001, suggesting that there are significant differences between capture effectiveness performance between filter sectors. In this study, the middle center sector having the highest measured capture effectiveness (n=120) compare to other filter sectors appears does not appear to be associated to random measurement error.

## A suggested new method for screening PHEAF units for failure

PHEAF units are tested for effectiveness based on 9 sectors on the face of the box, and the overall effectiveness is based on the average effectiveness over the 9 sectors. This is considered the gold standard. In this study, we looked at 325 measurements of 86 units, of which 33 measurements passed the HEPA standard of 99.97% effectiveness.

The center sector typically showed effectiveness above the average effectiveness, and compared to the gold standard measure, a test just seeing if the center sector passes has a negative predictive value (NPV) of 99.32%. So it would be an effective way to screen for bad units, but not really a good way to test for passing units, since it only had a positive predictive value (PPV) of 16.84%.

Next, we looked at a test based on the lowest computed effectiveness across sectors, i.e., the minimum value of the 9 sectors. We did a ROC (receiver operating curve) analysis, varying the threshold that we would consider “passing”, to see if we could find a good test to identify good units. The ROC curve is shown below. This curve has an area under the curve of 0.996, showing that it is a good discriminative test. The optimal cut-off was determined from the curve to be 99.83. Using that as a cut-off for a test, i.e., a unit is called passing if the lowest sector-wise effectiveness is at least 99.83, has a PPV of 72.72% and a NPV of 99.66%.



If we combined these two tests, i.e., call a unit passing if both the center sector has at least 99.97% effectiveness and all the sectors have at least a 99.83% effectiveness, gives us a PPV of 79.49% and a NPV of 99.33%.

Finally, we realized that a test that passed a unit if at least 7 of 9 sectors passed would give a PPV of 67.39% while maintaining a NPV of 99.28%. Combining this with the previous test, i.e. a unit is called passing if (a) the center sector passes, and (b) all sectors have at least 99.83% effectiveness, and (c) at least 7 of 9 sectors pass, has a PPV of 100% and a NPV of 99.02%. What is the implication of this as a screening test? This means that if either (a) the center sector doesn’t pass, or (b) one sector has less than 99.83% effectiveness, or (c) 3 or more sectors fail, we can call the unit a “fail”. This has the potential to reduce the time for a test, since a failure could be called without testing all of the sectors – it is effectively an early stopping rule. To call a unit passing, however, you would still need to test all the sectors.

The reason we didn’t stop just at testing the center sector is the low PPV of that test. Just because the center sector passes does not assure us of a passing unit, so even with a passing center sector the unit could be a failure. We needed to ensure a high PPV as well to ensure that the screening test would effectively screen for a bad unit.

**Manometer as a predictor of PHEAF performance**

The manufacturer of the model representing 84% of the PHEAF study population recommended replacement of the HEPA filter when the unit’s magnehelic gauge indicated a pressure differential greater than 2.5 in. w.g. A Chi-Square test of independence was calculated comparing the frequency that capture effectiveness measured at or above 99.97% when the unit's manometer reading was less than 2.5 inches water gauge. In a sample of 204 units, 88.9% of the PHEAF units tested with a capture effectiveness below 99.97% (i.e. fail) when the manometer indicates a pressure differential of less than 2.5 in w.g.

**DISCUSSION**

Variability with the anemometer could be attributed to operator error (e.g. probe placement) while taking velocity measurements at the 9 filter sectors. Measurement variability observed with the anemometer and balometer capture hood could be associated with air infiltrating between the PHEAF housing and the filter grating. The volume of air bypassing between the PHEAF housing and the metal HEPA faceguard could vary between tests; hence the variability as seen in both measurement techniques. Since no gap exists at the PHEAF’s exhaust port, the accuracy of the airflow measurement is better compared to the intake measurement. Indeed, measuring the exhaust airflow using the balometer capture hood permits proper seal around the exhaust port resulting in complete capture of the airflow.

The evidence from analysis of the volumetric measurement techniques suggest the anemometer readings overestimate the volume of air passing through the unit. That is the actual air volume going through the filter was less than measured. Accordingly, the volumetric aerosol concentration is higher than what the photometer was measuring, meaning the effectiveness of the PHEAF unit is overestimated. Consequently, aerosol generation values were adjusted as a function of the PHEAF’s exhaust volume as measured by balometer capture hood.

There is some scientific justification for the balometer being better. 1. The balometer is factory calibrated and covers the whole unit. It is generally not significantly affected by operator variability. 2. The anemometer readings are subject to the operator’s perception of placing the anemometer the correct distance from the filter face. The findings agree with other literature indicating that the anenometer has more variability than the balometer capture hood technique.

Lees operator error and the inherent variability in the data eg. Stats leads one to conclude that the balometer readings are more accurate. In fact, commissioning of HVAC systems require the use of balometers to achieve accurate system balance.