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Measurement-Based Evaluation of Installed Filtration System Performance in Single-Family Homes

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April 3, 2014

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Executive Summary

Fine particulate matter ($PM_{2.5}$) causes the most health damage among non-biological air pollutants inhaled in homes. Particle-bound biological contaminants including allergens add to the health burden. Enhanced filtration and other particle removal systems – described in this document as "filtration" – can meaningfully reduce fine particle concentrations and exposures. Enhanced filtration technologies incorporated in various system designs are being installed in both new and existing U.S. residential buildings, and in some cases creating substantial new energy loads despite inconsistent effectiveness in reducing exposures. Research is needed to support guidance on effective technologies, system designs and controls. A key element of this research effort is the ability to quantify performance of filtration systems as installed in homes.

This guide provides background information on the factors that impact filtration system performance and specific guidance on how to implement installed performance evaluations. The guide is intended to inform building scientists, healthy homes researchers, and practitioners interested in conducting an evaluation or understanding an evaluation performed by others.

There are many physical and chemical processes that affect particle concentrations in a home of which filtration system performance is just one. Sources include infiltration of particles with outdoor air entry and indoor activities or use of products that emit particles directly into the home. Particles can be emitted directly, e.g. from the burning of candles, or they may result as the secondary products of chemical reactions. Particles are removed as air exits the home through exfiltration and ventilation and as they deposit or stick to indoor surfaces. Increasing passive or mechanical ventilation can increase indoor particles by bringing them in from outdoors faster or decrease indoor particle concentrations if levels indoors are higher than outdoors. Moving air through a filter or other particle removal device can dramatically increase particle removal rates from the indoor space and result in fewer particles entering from outdoors when supply air is filtered. Particles also may be removed as air infiltrates through small cracks and passageways in the building pressure boundary.

An essential element of performance assessment is metric specification: essentially, what are the measures of performance that should be assessed? For installed filtration system performance, the two main categories of metrics should address the *objectives* of *reducing in-home exposures to outdoor particles* and *accelerating the removal of particles already in the home*. The latter can address particles that have entered from outside or that have been emitted from an indoor source. This leads to the consideration of two measures of the protection a home provides: (1) the ratio of indoor-to-outdoor particle concentrations, and (2) the rate of removal of particles from the indoor space by the filtration system. Filtration system performance effectiveness should always be considered in relation to the particle concentrations that would exist if the enhanced filtration system were not present. It is important to establish a reference condition under which the filtration performance is assessed.

This guide discusses important study design issues to consider when conducting an on-site evaluation of filtration system performance. The two most important dichotomies to consider in developing a study protocol are (1) whether systems are being evaluated in occupied or unoccupied homes and (2) whether different systems are being compared in the same homes or if

the comparison is between systems installed in different homes. A study could be designed around any of the following basic approaches:

1. Quantify performance by comparing two or more systems in an unoccupied home.
2. Quantify performance by comparing two or more systems in an occupied home.
3. Quantify performance by comparing systems installed in two or more groups of homes, which may be occupied or unoccupied.

A critical part of evaluation is establishing and documenting conditions in the home. The goal is to keep the test and reference conditions as similar as possible. Parameters that cannot be controlled with certainty should be measured. When a study is performed in occupied homes, more factors will need to be controlled or measured because of occupant activities and indoor sources. In unoccupied homes, we recommend the following strategies to establish and maintain the same test condition.

- Set the *same mechanical ventilation rates*, meeting ASHRAE 62.2-2013 specifications. If possible, *measure air exchange rates* using tracer gas methods.
- *Keep all windows and doors closed*.
- *No use of cleaning products or other chemicals in the home* during or just prior to the start of the study period.
- To the extent that it is feasible for the systems being tested, try to set *identical mixing and air velocity conditions*.
- Use the *same thermostat program*. The program can specify uniform temperature throughout day or use the same schedule of temperature set points.
- Operate over *similar periods of outdoor weather*.
- *Measure or record outdoor weather conditions* and day of week for each test. Include T, RH, wind speed and direction.
- Measure test and reference systems on days with *similar outdoor particle levels or at least similar sources*. Traffic-related air pollution is likely the biggest concern, so sample on Monday through Thursday to avoid weekend effects.

When working in occupied homes, in addition to the above approaches to maintain the same test conditions, we recommend the following strategies to control influences from occupant activities and indoor sources:

- Use *thermostat program* to be as similar as occupants will allow.
- *Constrain opening of windows* for ventilation, ideally with no window opening.
- *Monitor (preferred) or log window opening and use of mechanical exhaust fans*.
- *Record all major indoor particle producing activities* (specific activities and methods for logging are discussed in a subsequent sub-section).
- *Limit use of cleaning products or air freshener*, which can react with ozone to produce particles, *and avoid large indoor chemical emissions* just prior to start of monitoring.

In addition, data collected from unoccupied periods of homes can be used to evaluate the filtration effectiveness against outdoor particles. When comparing systems across homes, it is important to consider differences in characteristics among the homes being compared. Between-home differences, such as the ratio of material surfaces to air volume, can affect the particle deposition rate and have major impacts on the particle concentrations indoors. It is difficult to properly account for these differences during data analysis because of the many interacting effects impacting particle dynamics in indoor environments. Instead, we recommend selecting homes of similar characteristics (e.g., square footage, floor plans, and construction types) when the study design calls for comparison of filtration performance between homes.

Finally, this document provides perspective and recommendations about a suite of implementation issues including the choice of particle measurement devices, selection of sampling locations, ways to control and/or monitor factors and processes that can impact particle concentrations, and data analysis approaches. Proper implementation of the field test, together with a well-planned study design, are important to collecting data that is scientifically sounded. The guidance presented here is intended to support anyone interested in studying the performance of filtration systems installed in homes; it is expected to be of greatest relevance to building science and healthy homes researchers. The data collected will help improve the design, installation, and operation of these systems, and eventually benefit our health from better indoor air quality.

1. Introduction

Fine particulate matter ($PM_{2.5}$) causes the most health damage among non-biological air pollutants inhaled in homes (Logue et al. 2012). Particle-bound biological contaminants including allergens add to the health burden. Enhanced filtration and other particle removal systems (described collectively in this document as "filtration") have the potential to reduce $PM_{2.5}$ concentrations and exposures (Barn et al. 2008; Macintosh et al. 2008). Recent studies showed health benefits from filtration in homes and commercial buildings (Fisk 2013), including some that may be linked to cardiovascular disease (Lin et al. 2011; Weichenthal et al. 2013), and other studies that found reduction in symptoms of asthma, allergies etc. (Sublett et al. 2010). Enhanced filtration technologies incorporated in various system designs (e.g., in-duct filtration, standalone air filters, etc.) are being installed in U.S. homes. However, particle removal efficiency and system energy consumption can vary depending on the filtration device and how it is installed and operated (Shaughnessy and Sextro 2006; Stephens et al. 2010; Walker et al. 2013). Field research data is needed to support guidance on effective technologies, system architectures and controls. A key element of this research effort is the ability to quantify performance of filtration systems installed in homes, which can differ from the efficiency rating of the filter because of actual airflow rate, system runtime, etc. (Stephens and Siegel 2012a). This guide provides background information on the factors that impact performance and specific guidance on how to implement in-home performance assessments.

There are many physical and chemical processes that affect particle concentrations in a home (Nazaroff 2004), of which filtration system performance is just one. Sources include infiltration of particles with outdoor air entry and indoor activities or use of products that emit particles directly into the home. Particles can be emitted directly, e.g. from the burning of candles, or they may result as the secondary products of chemical reactions. Particles are removed as air exits the home through exfiltration and ventilation and they deposit or stick to indoor surfaces. Increasing passive or mechanical ventilation may increase indoor particles by bringing them in from outdoors faster or decrease indoor particle concentrations if levels indoors are higher than outdoors. Airflow induced by recirculating air of the mechanical system can also affect particle concentrations in a home. Moving air through a filter or other particle removal device can dramatically increase particle removal rates from the indoor space and result in fewer particles entering from outdoors when supply air is filtered.

The exposure reduction from installing and operating an enhanced filtration system in a home depends on the performance of the system, on the sources of particles, and on factors that impact particle concentrations other than filtration (Macintosh et al. 2008). Filtration system performance should always be considered in relation to the particle concentrations that would exist if the enhanced filtration system were not present under the same home conditions. It is therefore critical to assess performance in comparison to a reference condition.

This guide provides an overview of the factors to consider when planning and implementing a measurement-based assessment of filtration systems installed in homes. It does not include step-by-step protocols, as implementing an effectiveness study requires consideration and planning around the specific constraints and within the opportunities provided of a study scenario. Rather, this guide describes several general approaches and offers specific recommendations for implementation. It discusses important aspects to consider in designing a study, such that the data to be collected will answer the research question that study aims to answer. Study design decisions include what conditions should be established as similar between the enhanced filtration and reference system tests, and what parameters should be measured or otherwise recorded to document the similarity of conditions. In addition, implementation issues that are important to the collection of scientifically sounded data using different instruments and sampling strategies are also discussed.

2. Motivation

Evaluations of installed filtration system performance are extremely valuable in developing guidance on effective and energy efficient designs. Whole house in-situ assessment enables an understanding of as-installed performance, providing an important complement to laboratory studies of component technologies and products and simulation model-based analysis.

Objectives for evaluation of installed filtration system performance may include the following:

1. Assess installed performance of a component or sub-system, e.g. to assess interactions with other installed components or to assess performance as installed and operated.
2. Evaluate performance of a specific system design – in relation to a relevant reference – under a variety of installed conditions, e.g. in homes of various size, location, etc.
3. Compare performance of several system designs in one or more homes, or for a specific application or challenge (e.g. for polluted urban areas).
4. Evaluate the benefits of variations in control algorithms for specified system designs or to address certain operation and maintenance issues.

A system evaluation that is conducted in an actual house provides results that likely will be more accessible and compelling to home performance contractors and to the general public in a way that complements modeling studies. A well-designed evaluation of a system as installed can capture the effects of interactions with other installed components and other factors that impact particle concentrations in homes. It enables assessment of performance under real conditions, providing insights to unforeseen challenges to achieving the performance predicted by theory and models.

3. Performance Metrics

An essential element of performance assessment is metric specification: essentially, what are the measures of performance that should be assessed? For installed filtration system performance, the two main categories of metrics should address the *objectives* of *reducing in-home exposures to outdoor particles* and *accelerating the removal of particles already in the home*. The latter can address particles that have entered from outside or that have been emitted from an indoor source.

Requirements for effectiveness depend on outdoor pollutant loads, indoor sources, occupant activities, the target pollutant to be removed (e.g., allergens, cigarette smoke, wildfire smoke, and/or $PM_{2.5}$ in general), and whether the goal is to reduce exposures for generally healthy individuals or to protect sensitive individuals. In addition, energy efficient design also requires consideration of the thermal conditioning and ventilation if filtration were integrated as one system.

Overall performance is thus described by the following *general* metrics:

1. The ratio of indoor-to-outdoor particle concentrations; and
2. The rate of removal of particles from the indoor space.

It is important to recognize that physical processes other than filtration cause time-averaged concentrations to be lower indoors than outdoors when there are no indoor sources. The ratio of indoor to outdoor concentrations must therefore be established for a reference condition of no enhanced filtration or use of a lower quality system that is standard equipment; the ratio obtained when the enhanced filtration system is employed is compared against this reference to assess filtration system effectiveness.

The indoor removal rate describes the overall clearance rate of the target pollutant. This clearance rate will include the effect of filtration and all other removal processes, such as removal by ventilation, deposition, and so on.

The indoor-to-outdoor ratio can focus primarily on outdoor particles, or include both indoor and outdoor particles. A filtration system that only removes outdoor particles, e.g. by filtering the supply air, will have less impact if indoor sources dominate, such as in homes that cook often. The indoor removal rate is the more important metric when the primary concern is particles generated indoors.

To evaluate the performance for removing particles of outdoor origin vs. removing both indoor and outdoor particles, we recommend the following specific metrics:

1. Ratio of time-averaged indoor to time-averaged outdoor concentrations.
2. Ratio of time-averaged indoor to time-averaged outdoor concentrations, focusing only on particles that are of outdoor origin.
3. Overall decay rate of particle concentrations following emission from an indoor source.

There are scenarios where the metrics listed above may not be suitable for the analysis. For example, if indoor sources were highly variable in occupied homes, (1) might only reflect differences in indoor source strengths between homes but not the filtration efficiency. Metric (3) requires some estimates of air exchange rates in order to relate the observed decay rate of particle concentrations to filtration efficiency. In addition, each of the metrics should be determined in reference to a set of common conditions when evaluating filtration efficiency. Most commonly, the comparison will be between an enhanced filtration system and a relevant reference system. In which case, the benefit of the enhanced filtration system is the improvement relative to the reference system.

4. Background

4.1. Particle characteristics

Particles suspended in air, also referred to as an aerosol, may be liquid or solid phase, or both. Typically they are complex mixtures of many thousands of individual chemical constituents that are considered in groups related to sources or chemical process, e.g. inorganic acids, organic compounds, elemental carbon, crustal materials, etc. Some particles are composed of or contain biological materials, such as allergens. The composition and concentration of outdoor particles depend on the sources (e.g., road dust, fuel combustion, industry emissions, agricultural activities, fires, etc.) and also on meteorology. Particles may undergo chemical and physical transformations (see Nazaroff and Alvarez-Cohn (2001) for an overview on particle dynamics). Extensive information about particulate matter, including sources, health effects and airborne concentrations is available on the website of the Environmental Protection Agency (USEPA 2013).

Airborne particles can range in size from a few nanometers (nm) formed of a cluster of molecules to fog size droplets on the order of 100 micrometer (μm). Even though it is common to describe particle size using an equivalent diameter, particles can have complex shapes, such as asbestos that are fibrous, and soot particles that are bundles of carbonaceous spheres that appear as microscopic bunches of grapes. In the context of measuring filtration efficiency in occupied homes, it is reasonable to describe particles based on aerodynamic equivalent diameter, i.e. the diameter of a spherical particle that has the same aerodynamic properties as the particle of interest. The focus on particle size should include one or more of these size ranges: ultrafine particles (UFP) with diameter <0.1 μm (100 nm), particulate matter with diameter <2.5 μm ($PM_{2.5}$), and particulate matter with diameter <10 μm (PM_{10}). Studies that focus on allergens may need to extend to even larger particles.

Ambient air quality standards and studies of adverse health effects from exposure to particles commonly use mass concentrations as the metric. For example, the National Ambient Air Quality Standard (USEPA 2012) for $PM_{2.5}$ is 12 $\mu g/m^3$ as an annual mean, and 35 $\mu g/m^3$ for 24-hour averaging time. Currently, there is no air quality standard for UFP, but a recent review (Kumar et al. 2010) suggests that there are adverse health effects associated with the exposure to UFP. Even though ambient air quality standards may provide a useful frame of reference, a strict comparison is likely inappropriate. This is because methods suitable for measuring particle concentrations for the purpose of evaluating filtration efficiency are different from the approved methods as specified in air quality standards. It will be difficult to collect data for sufficient durations to allow for a valid comparison with the air quality standards. Particle monitoring instruments appropriate to filtration field studies are discussed in a later section.

4.2. Indoor processes

An assessment of filtration system performance must recognize and in some way account for the many factors that can impact indoor particle levels other than the filtration system. Appendix A presents a “mass balance” model that describes mathematically how the different processes affect indoor particle concentrations. Broadly, there are processes that supply particles to the indoor space and those that remove particles. Supply processes include entry from outdoors, direct emissions from indoor sources and in-situ formation from the products of some chemical reactions. Removal occurs as indoor air is exchanged to the outdoors, by particles depositing onto indoor materials, by evaporation, and through engineered removal systems, i.e. filtration or exhaust. Individual particles may grow or shrink through interactions with gaseous species in air. Air temperature is important as it can affect evaporation, condensation and chemical reaction processes in addition to air movement and mixing. Air velocities impact deposition to surfaces. Surface temperature in relation to the air is also important because particles response to a force caused by temperature gradient, a process known as thermophoresis.

Particle entry from outdoors depends primarily on outdoor concentrations and the rates and pathways of air flowing into the home. The pathways of entry are important because particles may deposit as air infiltrates through the building shell, or as air is supplied through mechanical systems that include filtration. Air sealing of the building envelope may reduce indoor concentrations of outdoor particles by lowering outdoor air exchange rates. It could also reduce penetration of particles as outdoor air infiltrates through the envelope, as suggested by Stephens and Siegel (2012b) who found a positive correlation between building envelope air leakage and particle penetration factor from field measurements of 18 houses.

Particles generated indoors will differ in size and composition from the outdoor particles, partly because the sources are different. Major sources of indoor particles include smoking, cooking, gas and electric resistance cooking devices, burning candles, and fireplace use (Wallace 1996; Allen et al. 2003; He et al. 2004; Wallace et al. 2006; Clougherty et al. 2011; Morawska et al. 2013). In addition, larger, deposited particles can be re-suspended through activities like vacuuming and even walking. Activities that lead to these emissions tend to be intermittent and may occur at irregular frequency, which adds to the challenge of taking representative measurements in occupied homes. In addition, outdoor particles that enter indoors also vary temporally with diurnal, weekly, and seasonal patterns. Even though it is difficult to explicitly account for differences in particle characteristics when evaluating the efficiency of filtration system, it is important to acknowledge that they can influence the test results.

4.3. Filtration system types

Filtration systems can be categorized into two main types:

1. Systems that remove particles from the outdoor air as it enters into the building, and
2. Systems that remove particles from the indoor air as it recirculates through the filtration system.

Enhancing particle removal in homes typically involves modifications to one or more of these elements. The following list provides common examples of filtration enhancements:

- Upgrade filtration on air handler of recirculating thermal conditioning system (e.g., improvements to filter cabinet, installation of a higher performance filter, or installation of an alternate particle removal technology, such as an electrostatic precipitator);
- Install or upgrade filtration on supply ventilation;
- Operate air handler with filter using timed controller to increase the duration of use; or

- Operate in-room air filters (could be a portable device, or a fixed device that is installed on a wall).

Variants of the first type include supply and balanced ventilation systems, with the latter including heat recovery ventilation (HRV) or energy recovery ventilation (ERV) that have filtration on the supply side. A common mechanical design has the supply system or the HRV/ERV feed into the return side of air handler; a higher quality filter may be installed in the outdoor air intake line of the HRV/ERV or on the central air handler return loop downstream of the HRV/ERV tie-in. In homes with exhaust only ventilation, particles are removed as indoor air is exhausted from the building.

Common recirculating systems include enhanced filters and cabinets as part of the air handler, and standalone air filtration devices such as a portable air cleaner. It is important to point out that common furnace air filters are only designed to remove dust and very large particles to protect the equipment. They do not to not remove any health-relevant particles. However, the low efficiency filter can be replaced with a higher efficiency filter capable of removing fine particles. Very low pressure-drop filter boxes can also be added to the inlet side of a ductless or even a short-ducted mini-split.

Filters primarily remove particles by impaction and diffusion; but they may be charged to increase removal effectiveness. Recirculation filtration may alternately be accomplished with an in-duct electrostatic precipitator (ESP) instead of a conventional filter. Electrostatic precipitators charge particles by passing air through an ionization section, and the charged particles are removed from the air by a series of collecting plates that are oppositely charged. Besides in-duct application, ESP is also employed in some standalone air filtration units. However, recent studies suggestion some ESP may generate ultrafine particles and ozone as byproducts (Lin et al. 2012; Poppendieck et al. 2014), which raises concerns. Frequent cleaning is also required for ESP to maintain high removal efficiencies (Wallace et al. 2004). Filter media can be electrostatically charged to enhance removal efficiency. There also are products that generate ions to charge airborne particles and increase their deposition rates but do not include collection plate. The result is some incremental increase in particle removal onto indoor surfaces. Since the incremental deposition produces an equivalent amount of incremental soiling, this consequence should be considered before employing such a system. (Ion generators can also produce ozone and thus degrade air quality; the California Air Resources Board regulates these products and provides information on their web site[1]).

The overall effectiveness of these filtration systems described here depends not just on the particle removal efficiency of the filter or other particle removal device, but it also depends on its operation as installed. Bypass around a filter will reduce its effectiveness in reducing the indoor particle concentration. An enhanced filter on the air handler recirculation loop will help only when heating or cooling is required unless there is also a controller that ensures operation when no thermal conditioning is needed. The position of where filtration occurs also matters, whether

[1] http://www.arb.ca.gov/research/indoor/aircleaners/aircleaners.htm

it is sited directly downstream from the outdoor air supply, or if it is sited after the outdoor air has been mixed with the recirculating air.

4.4. Air filter and air cleaner rating

ANSI/ASHRAE Standard 52.2 (2007) is the test procedure used to determine filter removal efficiency under a controlled and specified test condition. The standard assigns a Minimum Efficiency Reporting Value (MERV) according to the ability of the filter to remove 0.3–10 μm particles. Removal efficiency is determined by measuring the particle counts upstream and downstream of the filter material. There are six test cycles, so that measurements are taken as the filter is loaded with more particles from one cycle to another. The lowest removal efficiency as calculated from the ratio of downstream-to-upstream particle counts will be used to determine the minimum efficiency of the filter. Filter testing has to be conducted at one of the seven airflow rates, ranging from 0.6 to 3.8 m/s, as specified in the Standard. The determined MERV rating will be stated with the air velocity at which the filter was tested.

Most residential systems currently use low to medium efficiency air filters with a MERV rating of 4 or lower. EnergySTAR requires homes to install MERV 6 or higher air filter in the air handler. Indoor airPLUS requires MERV 8 or higher filter efficiency.

The MERV rating refers to the removal efficiencies determined for particles in these three size ranges: (I) 0.3–1 μm, (II) 1–3 μm, and (III) 3–10 μm (see NAFA (2014) for more detail on particle size bins measured during test). When new, filters remove group (III) particles at 20% or less efficiency, and are largely ineffectively in removing group (I) or (II) particles. Medium efficiency air filters (MERV 5 to 8) are also commonly used in homes. They remove group (III) particles at a higher efficiency, ranging from 20–35% (MERV 5) to >70% (MERV 8). Their rated effectiveness towards group (I) and (II) particles is also limited per MERV rating definition. However, as particle loading increases with use, the filter is expected to capture some of the smaller particles. MERV 9 or higher filters are needed to remove group (II) particles. For removing group (I) particles, MERV 13 or higher filters are needed.

Some manufacturers label their products with other rating systems; these include the Filter Performance Rating (FPR) and the Microparticle Performance Rating (MPR). The correspondence between the three rating systems can be found on some filter suppliers' website (e.g., iallergy™ (2014), Nordic Pure® (2014)). Regardless of how a filter is labeled, the actual particle removal efficiency in-use is likely to deviate from its product rating because of the actual airflow rate, potential filter bypass, and particle properties differing from the test particles used for filter rating, for example. Performance can also vary substantially for different brands even if the filters were of the same rating.

Standalone air cleaners are rated by the Association of Home Appliance Manufactures (AHAM), using Clean Air Delivery Rate (CADR) as the effectiveness metric. CADR is a measure of the equivalent cubic feet per minute of contaminant-free clean air that is delivered by the air cleaner. ANSI/AHAM AC-1 (2006) describes the standard test method to determine CADR. The test is conducted in a chamber with specific size and characteristics. Three types of particles are tested: cigarette smoke (0.1–1 μm), fine test dust (0.5–3 μm), and pollen (5–11 μm). CADR is computed from the measured decay of the smoke, dust, and pollen particle counts, after adjusting for the natural decay of the particles due to other processes (e.g. deposition). There is also a procedure in the test method to calculate a recommended room size from the CADR. For this, the smoke particle test results are used because removal efficiency tends to be the lowest for particles in that size range.

4.5. Field measurements of filtration efficiency

Some of the past studies already cited in this document are examples that used the whole-house approach to measure filtration efficiency. Wallace et al. (2004) measured the removal rates of particles in an occupied townhouse due to forced-air circulation and the use of in-duct air filters, including conventional air filters and ESP (see also Howard-Reed et al. (2003)). Fine and ultrafine particles were measured over a 2-year period with the mechanical fan off, and fan on with and without air filter. Decay rates were estimated following the emissions of simulated sources (e.g., cooking, candle). Stephens and Siegel (2012a) used two methods to measure filtration efficiency at an unoccupied manufactured home. The whole-house method measured fine particle counts near the return air register following emissions of indoor particles from incense burning and dust released from a vacuum cleaner bag. Particle counts were measured with mechanical fan off, and fan-on with and without air filters of different MERV ratings. In addition, the study also used an in-situ method that measures particle counts upstream and downstream of the air filter, following ASHRAE Guideline 26 (2012). Filter removal efficiency was calculated as a function of particle size based on the difference in particle counts measured with and without the air filter (see also Stephens and Siegel (2013) for results on ultrafine particles following similar test procedures).

ASHRAE Guideline 26 (2012) is a test procedure for measuring the in-situ performance of air filters. Because the Guideline describes a method of quantifying filter performance by counting fine particles of 0.3 to 5 μm, it is intended for high efficiency air filters (MERV 11 and above). In addition to measuring the removal efficiency by particle size, the Guideline also describes measurement of the resistance to airflow. Careful installation of test equipment is needed for upstream-downstream sampling to minimize particle loss and measurement artifact. Stephens and Siegel (2012a) described several challenges of using the upstream-downstream method, such as the accessibility of the sampling location in a mechanical system, particle losses in the sampling lines and switching valve, measurement artifact from non-isokinetic sampling, and the turbulence conditions in ducts affecting the measurements.

5. Study Design

When designing a field study to evaluate the filtration system performance, it is important to consider the following characteristics of a home because they will affect particle concentrations indoors.

- Physical structure including construction type, envelope airtightness, size, furnishings and other materials in the home that impact removal during air entry and through indoor deposition.

- Presence and use of mechanical equipment that contributes to outdoor air exchange including ventilation equipment, clothes dryers, etc.
- Presence and use of range hood to exhaust cooking emissions.
- Use of windows for ventilation; this impacts both the air exchange rate and leads to 100% penetration efficiency for particles in air that enters through this pathway.
- HVAC system design and components that affect air exchange rate, temperature, outdoor air entry pathways, air velocities in the home (which affects particle deposition rates), etc.
- HVAC controls and operation algorithms.

Depending on the objective and approach of the study, some or all of the above will need to be measured in a diagnostic test, or monitored throughout the study period. When designing a study, it is important to decide which of the above factors may be controlled, and which of them will be allowed to vary. These decisions may be dictated based on the homes to which the research team has or can gain access.

A study could be designed around any of the following basic approaches:

1. Quantify performance by comparing two or more systems in an unoccupied home.
2. Quantify performance by comparing two or more systems in an occupied home.
    a. Controlled operation during periods of non-occupancy.
    b. Monitoring over periods of intermittent occupancy.
3. Quantify performance by comparing systems installed in two or more groups of homes.
    a. All homes are unoccupied.
    b. All homes are occupied.
    c. Some homes are unoccupied, some occupied

The implications of these variants and the opportunities presented by each design are discussed below. Studies conducted in occupied homes may require a human subjects protocol and review by an Institutional Review Board; researchers should consult with their institution and/or funding agency to determine if such a review is needed and how it should be pursued. Studies that may be deemed as covered under human subjects regulations include those that gather information from occupant survey and those that perform diagnostic tests, air sampling, and environmental monitoring in the presence of building occupants.

The two most important dichotomies to consider in developing a study protocol are (1) whether systems are being evaluated in occupied or unoccupied homes and (2) whether different systems are being compared in the same homes or if the comparison is between systems installed in different homes.

5.1. Occupied vs. unoccupied

Advantages of occupied homes. Working in occupied homes offers great opportunities and also presents substantial operational challenges. The main advantage of conducting a study in an occupied home is that performance is assessed under real conditions of use. This enables assessment of performance for a wider variety of indoor sources and as ventilation and thermal conditioning components are employed. For some systems, occupancy or simulated occupancy is particularly relevant. For example, there are in-room air cleaners whose operation is triggered by a sensor that is sensitive to certain particle properties. To the extent that such sensors are fundamental to the performance of the device, it is desirable to have such functionality impact the measured performance.

Advantages of unoccupied homes. Unoccupied homes are better suited to determine the efficiency of the filtration system in removing particles from the outdoors. Because the research team has control over the operation of the home, there are fewer variables that require monitoring. A better-controlled reference test condition can be set, such as at constant air temperature and operation mode by the air handler. Field tests that require very intensive sampling are more suited for unoccupied homes, because scheduling frequent visits with homeowners can be challenging. Since there are fewer variables that may influence the results in unoccupied homes, a shorter testing period typically is sufficient.

Recommendations. The main challenge of working in an occupied home is that the occupant activities can substantially impact particle levels. Variations in occupant activities across test conditions and homes can impact the observed performance of filtration systems being studied (Batterman et al. 2012), especially since conditions may differ between test and reference systems.

The following approaches are employed to address occupant-induced variability:

1. Control as many key factors as feasible.
2. Record or monitor activities and factors that are impacted by activities.
3. Monitor over longer time periods to capture more variations in behavior.
4. Identify through analysis some time intervals within each period of system operation that have similar properties and are thus suitable for comparison.

Typical control options for occupied homes include asking occupants to not open windows, setting thermostats to standard schedule, and requesting some limits on indoor activities that are particle sources, etc. These controls are discussed in more detail in a subsequent section. If the study allows discretion in selecting which homes are included, it is best to identify the factors that are desired or required for control and to only study homes for which those constraints do not present difficulties to occupants. Activities that substantially affect particle concentrations and are not suitable for limitation in an occupied home should be monitored or tracked in some way, e.g. by occupant self-reports. A common and effective approach is to ask residents to complete a daily log of major activities. The log should be easy to use and short. The specific activities to track are discussed in a later sub-section.

5.2. Comparing systems in the same home or across homes

Advantages of comparing systems in the same home. Comparing performance of an enhanced filtration system to a reference system in the same home has the primary advantage that many factors that affect particle concentrations will be the same or similar over time. Especially in occupied homes, the activities relevant to particle levels in homes vary much more between homes than over time within a home. This approach is more efficient as any home in which a system is tested must be characterized. Also, it can be a substantial amount of work to set up monitoring equipment in the home. The effort required by the researcher to conduct a longer sampling event or even more sampling periods in the same home (e.g. to switch back and forth between test system and reference) is generally much less than going to two different homes.

Advantages of comparing systems in different homes. If a group of homes are very similar in characteristics, or if standard reference conditions can be established, then it is reasonable to compare systems in different homes. There are some circumstances in which comparison across homes or groups of homes will be preferred or may present the only viable option. The most significant is if the filtration system being studied is not easily “turned off” in a home, i.e. if it is not straightforward to operate the home with the enhanced system in a manner that represents a valid reference condition. An example of this is a system that involves a major modification or installation of a different system, e.g. to compare filtration on supply ventilation to a reference of exhaust ventilation without enhanced filtration; this may not be possible if the home with the supply ventilation system does not have a ventilation exhaust fan. Minimizing the sampling time in each home is another reason for comparing systems in different homes. This will reduce the burden on study participants, especially when they are asked to limit their activities.

Recommendations. When comparing across homes, it is more challenging to establish consistent conditions. Different people living in the homes will have variable activities that emit particles or otherwise affect particle concentrations in homes. Therefore, it is particularly important to establish which conditions are being fixed as identical and to set protocols for monitoring or otherwise documenting those that cannot be fixed as similar. Even so, it is important to recognize occupants will have different varying tolerances for controls, and will introduce additional variability to the study.

5.3. Establishing test and reference conditions

A critical part of evaluation is establishing and documenting appropriate conditions in the home. The essential goals are that conditions should be as similar as possible for test and reference conditions and parameters that cannot be controlled with certainty should be measured. Controls vary by study approach and by systems being compared. A subsequent section discusses methods to measure and monitor for the parameters that cannot be controlled with certainty.

For monitoring in an unoccupied home:

- Set the *same mechanical ventilation rates*, meeting ASHRAE 62.2-2013 specifications.
- *Keep all windows and doors closed*.
- *No use of cleaning products or other chemicals in the home* during or just prior to the start of the study period.
- To the extent that it is feasible for the systems being tested, try to set *identical mixing and air velocity conditions* within the home.
- Use the *same thermostat program*. The program can be for same temperature throughout day or use the same schedule of temperature set points.
- Operate over *similar periods of outdoor weather*. Winds and outdoor temperatures affect infiltration part of AER and also how particles are transported and move in atmosphere. Weather becomes less important as the envelope is tightened. Consider alternating monitoring periods if doing replicates, e.g. reference; test; reference; test.

- *Measure or record outdoor weather conditions* and day of week for each test. Include T, RH, wind speed and direction.
- Measure test and reference systems on days with *similar outdoor particle levels or at least similar sources*. Traffic-related emission is likely the biggest concern, so sample on Monday through Thursday to avoid weekend effects.

When comparing systems installed in different unoccupied homes, we recommend using a common list of reference conditions provided above for a single unoccupied home.

When working in occupied homes, it is often possible to use daily periods of non-occupancy to collect data relevant to the assessment of indoor concentrations of outdoor particles. It is of course important to set conditions during those periods to be similar for test and reference systems. In this regard, the guidance provided above for unoccupied homes is applicable.

During periods in which the house is occupied or if the house is intermittently occupied without extended unoccupied periods, the options for controlling conditions are more limited. Here is the recommended minimum set of controls:

For monitoring in occupied homes:

- Set the *same mechanical ventilation rates*, meeting ASHRAE 62.2-2013 specifications.
- Use *thermostat program* to be as similar as occupants will allow.
- *Constrain opening of windows* for ventilation, ideally with no window opening.
- *Monitor (preferred) or log window opening and use of mechanical exhaust fans*.
- *Record all major indoor particle producing activities and occupancy* (specific activities and methods for logging are discussed in a subsequent sub-section).
- *Limit use of cleaning products or air fresheners*. Best to not have plug-in air fresheners as different ozone concentrations outdoors could lead to different amounts of particle formation from chemical reactions.
- *Avoid large indoor chemical emissions just prior to starting* any of the monitoring periods. Chemicals that react with ozone can sorb to surfaces and be available for reaction to form particles. Important to discontinue use of plug-in air fresheners several days before the experiment to allow time for clearance of chemicals sticking to surfaces.

When comparing systems across homes, it is important to consider the ratio of material surfaces to air volume, specifically to avoid comparing homes that are very different in this regard. This is because the surface to volume ratio has a major impact on particle deposition rates indoors.

Note that there are many retrofit measures that are likely to change the conditions of the home. For example, tighten the building envelope from air sealing is expected to reduce air infiltration. Air sealing likely reduce particle penetration as well (Stephens and Siegel 2012b). Installation of new exhaust fans, thermal conditioning system, will all impact the airflow and indoor environment to deviate from the reference condition.

While it may seem like a difficult request to constrain window opening for the multi-day sampling events required for a study in an occupied home, it is important to recognize that open windows conflict with the objective of enhanced filtration to reduce indoor exposures to outdoor particles. A household with enhanced filtration therefore may be amenable to window operation constraints.

6. Implementation issues

6.1. Particle measurements

Time-resolved particle concentrations can be measured using one or more instruments that measure specific characteristics of the aerosol. For evaluating filtration system efficiency, time-resolved instruments are preferable because indoor and outdoor concentrations are time varying. Some examples of commercially available instruments for measuring PM mass concentrations or counts are listed in Table 1.

Table 1. Examples of time-resolved instruments that measure particle concentrations.

Measurement principle	Instrument	Description of Particles Measured[1]	Approx. Cost[2]	Unattended operation duration
Particle count by light scattering of individual particles	Optical Particle Counter (OPC) BT-637 (MetOne)	0.3 to 10 μm particle counts resolved to six size channels	$4,000	1 week
	Particle Counter 985 (Fluke)		$5,000	1 week
Estimate of mass concentration by total light scattering	Personal DataRAM (Thermo Scientific)	Instruments capture particles in size range of 0.1 to 10 μm; Correlation to mass concentrations varies with particle size distribution and composition	$5,000	1 week
	DustTrak (TSI)		$5,000	1 week
Particle count including ultrafine particles that are "grown" by condensation	Water-based Condensation Particle Counter (CPC) (TSI)	0.006 to 3 μm size aggregated particle counts	$20,000	Few days
	Isopropoanol-based P-Trak (TSI)	0.02 to 1 μm size aggregated particle counts	$6,000	Few hours
Black carbon (soot) by light absorption (Aethalometer)	MicroAeth AE51 (AethLabs)	Signal not greatly affected by other types of particles; sample frequency scalable as concentrations vary	$6,000	1 day

[1] Many of these instruments may be outfitted with a special inlet to exclude particles larger than 2.5 μm in aerodynamic diameter. [2] Approximate cost. Contact vendors for pricing.

Particle instruments typically require annual calibration by the manufacturer because components (e.g., light source, sensor, etc.) can drift substantially over time. Most instruments may only be operated continuously unattended for a limited period of time before some simple checks should be performed, such as zero-check using a HEPA filter, and flow-check using a bubble flow meter. Additional maintenance steps are required for some of the instruments, such as refilling of working fluid for the condensation particle counters, and changing of filter element for the micro-aethalometer. All of the instruments above have limited internal memory for data logging; longer operations require the data to be logged externally.

Black carbon is a useful indicator of particles of outdoor origin because it responds almost exclusively to soot-like particles. The micro-aethalometer listed above is a new device that measures the rate of change in absorption of transmitted light due to continuous collection of aerosol deposit on a filter element. For the evaluation of filtration system efficiency, another instrument that can provide data on particle concentrations is needed.

Light scattering is the basic principle that the first three types of real-time instruments listed in Table 1 use. The instrument shines a light source at the flow of particles, and measures the signal that is scattered by the particles. The scattered light is focused onto a photo-detector by mirrors. The light source used in these instruments is commonly a laser diode. OPC counts particles by measuring the number of pulses that is sensed by the photo-detector, and also the height of the signal that is characteristics of the particle size. Total light scattering instruments do not measure individual pulses, but rather their combined signal.

The signal of individual pulses or total scattering is interpreted with the reference of a calibration that is performed by the manufacturer. Because the calibration is performed using some reference particle, such as latex particles of a known diameter, or a type of particles in a known size range, the conversion of signal to mass concentrations or counts is an important source of uncertainty. When instruments are used to sample ambient particles in indoor and outdoor air, the different shapes and scattering properties of particles mean that the conversion signal set by the manufacturer calibration may not apply. As mentioned earlier, soot particles are long-chained carbon rather than spherical. Soot particles also absorb light. Measurements from OPC and total light scattering instruments are likely to give unreliable estimates if these particles are dominant, such as in the ambient air near diesel emissions from vehicles. Other properties of particles in the presence of light, such as light refraction, diffraction, and phosphorescence, can also introduce uncertainties.

Ultrafine particles (UFPs) are difficult to measure because they are too small to scatter enough light to be detected. Condensation particle counters (CPCs) measure small particles by condensing water or other supersaturated vapor to increase the particle size so that they can be more easily counted. In indoor environments, water-based CPCs are preferable over alcohol-based alternatives, especially when gas-phase indoor air contaminants are being measured simultaneously.

Operation of CPCs require more care because of the dedicate conditions (e.g. temperature and flow controls during the wetting process) necessary for condensation to occur. There are more limitations on the operating conditions of the instrument because too hot or cold inlet temperature may interfere with particle condensation. When choosing an instrument, it is important to consider the capacity of the condensing liquid capacity to support for continuous sampling. It is possible to integrate a CPC with a spectrometer to measure particle counts that are size-resolved, but this will add substantial costs to the instrumentation budget.

PM mass measured by filter-based methods provides only time-integrated concentrations at a resolution of about 24 hours. While samples can be collected more frequently, the sensitivity of the gravimetric analysis (i.e. weighing of the filter before and after sampling) puts a restriction of the minimum sampling duration requires. Weighing of the filters requires a high accuracy microbalance in a temperature and humidity controlled environment, a labor-intensive process. Careful measurement of the sample volume is also required. Filter-based methods measure particle mass directly, so assumption about particle properties are not necessary. However, the lag time between sampling and weighing means that some volatile compounds may be loss, so this method is not free of sampling artifact.

There are instruments that use a filter tape that can be advanced automatically, and a more sensitive method to measure the particle mass collected on the filter (e.g., beta attenuation, oscillation frequency). But those instruments are costly, and their large size and operation noise is also a concern when use in occupied homes.

Besides knowing the instrument accuracy as reported by the manufacturer, it is important to evaluate their performance in the environment where they are used. For example, it is advisable to have at least two instruments of the same make and model available for a field study. This allows side-by-side comparisons of them in the field, where good agreement between the two or more instruments is an indicator that they are functioning well. Checking their agreement before and after each sampling event is necessary to detect any change in performance. If there are substantial changes in how well the instruments agree with one another, this drift can potentially be accounted for in data analysis.

6.2. Particle sampling locations

Selecting a suitable sampling location is important. It is often the case that only one indoor and one outdoor location can be monitored. The objective for the indoor location is that it represents the spatially averaged concentration in the home. A good option is to sample in a large, common area that is openly connected to other parts of the house, away from indoor sources, away from windows and doors, and in the middle third of the vertical dimension. Houses with open floor plans typically have a large room that fits this description. If measurements are being conducted in an occupied home, it is best if there are pathways for free air transfer between rooms, e.g. with open doors, adequate undercuts and/or transfer grills.

If an air handler is operating for at least a portion of every hour, the air in the home should be relatively well mixed and a good location is at or nearby to the return. If an air handler would not otherwise operate in this fashion for the system being tested, it should not be operated just for the purpose of the test. This is because the air handler operation could impact particle removal and thus particle concentrations. Duct leakage that may occur when the air handler is running can also affect the entry of outdoor particles into the homes.

The outdoor location needs to be sheltered from direct sun, rain, and other weather elements. It is important to compare the outdoor and indoor instruments side-by-side to make sure that they agree. Alternatively, the same instrument can be used to measure both the indoor and outdoor PM concentrations by installing a valve that switches between the two sampling lines. This method is more complicated to set up, so it is more suitable for longer-term monitoring (e.g. days to weeks) where the two instruments may drift apart.

Sampling of particles in high velocity air stream, such as inside a duct immediately upstream and/or downstream of a filter element, will require a nozzle that is designed to allow for *isokinetic* sampling, or sampling that does not result in particles being removed by rapidly changing the airflow pathway. This is needed to ensure that the air is disturbed as little as possible so that the same particles would be sampled had the nozzle not been there.

If the sampling points are located adjacent to one another, then the measurements may be more easily made at both locations using a single instrument. This eliminates the capital costs of purchasing two identical particle instruments. It also eliminates the need to frequently check for their differences due to measurement errors and drifts that may occur throughout the data collection. However, a switching valve has to be installed carefully to avoid losses in the sampling lines. For error checking and diagnostic, it is important to log the indoor or outdoor state of the sample data so that data parsing can be done correctly. Particle removal in long sampling lines (i.e., of more then a few feet) is also a concern, especially for ultrafine particles. It is important to avoid bends and minimize tubing lengths, and to select a suitable sample inlet diameter to minimize losses. The sample lines should be conductive to avoid static charge buildup that can increase particle removal.

6.3. Monitoring the factors that impact particle concentrations

In addition to measuring PM concentrations, other factors also need to be either measured or controlled. This is necessary to ensure that the reference conditions are maintained in the study homes as intended. Table 2 listed a few of the influential factors that require control, monitoring or some other way(s) to characterize or minimize their effects on the sample data.

Table 2. Approaches to account for factors that impact particle concentrations in unoccupied and occupied homes.

Factors	Controls and measurements in **unoccupied** homes	Controls and measurements in **occupied** homes
Mechanical ventilation	Set general ventilation rate to ASHRAE 62.2-2013 specifications. Set air handler on thermostat or timer.	
	No use of dryers or kitchen/bath fans.	Measure exhaust flow rates of all fans that affect air exchange with outdoors and monitor their use.
Envelope airtightness	Blower door test to measure air leakage.	
Air exchange rate (AER)	Tracer gas method to measure time-integrated or time-resolve AER. Alternately, use envelope airtightness and weather to model AER.	
Window use	Keep windows closed during study.	Ask occupants to keep windows closed during sampling. Monitor opening of windows with reed switch and data logger.
Indoor sources	No indoor particle sources.	Occupant interviews before and end of sampling; collect daily log of activities, e.g. cooking, smoking, candle use, etc. Temperature sensor to monitor cook stove and oven use; use power-meter to measure appliance usage.
Indoor environmental conditions	Set thermostat to maintain constant indoor environment. Measure indoor temperature and relative humidity.	
	N/A	Measure carbon dioxide concentrations.
Outdoor conditions	Measure outdoor temperature, relative humidity, wind speed on site. Alternatively, use weather data from a nearby weather station.	

Mechanical ventilation. Measurements of fan flow using a powered flow hood (see Stratton et al. (2012a) (2012b) for evaluation of airflow meter devices), and duct leakage per ASTM E1554-13 (2013), is preferred because the installed values may differ greatly from ratings. Researchers should record the mode of mechanical ventilation operation during the evaluation period (e.g., continuous or intermittent), and how the system is controlled (e.g., schedule or controlled by thermal conditioning need). Usage of the mechanical system may be estimated by monitoring its power consumption or current drawn by the device. Pressure sensors can also be used as indicators of airflow. Use of the clothes dryer may be monitored using either of these or with a temperature sensor placed on the appliance. It is important to note the brand and product identification number of the filter in the air handler, which is needed to find its MERV rating.

Envelope airtightness. Air leakage measurements should be made using a blower door test following ASTM E779-10 (2010). This is an important parameter because it affects both air infiltration and also the fraction of outdoor particles that enter indoors through the building envelope. If air leakage measurement cannot be made, then a typical value can be estimated from house characteristics (e.g., year built, floor area, location) using the ResDB calculator (2013).

Air exchange rate. Air exchange rate can be measured using tracer gas decay or constant injection per ASTM E741-11 (2011). However, it is costly to measure air exchange rate on a continuous basis. The alternative is to measure the building envelope air leakage and model the air infiltration rate (Sherman and Grimsrud 1980), assuming that windows remain closed during the study. In addition to calculating the air infiltration rate, estimate of the air exchange rate also needs to take into account the amount of outside air brought indoors by mechanical ventilation.

Window use. For the purpose of keeping the reference condition the same, occupants should be instructed to keep windows and doors closed. Opening of windows and doors can be monitored by magnetic contact reed switch. Some homes may already have these installed as part of the security system, but getting access to this data and logging it can be challenging. It is important to point out that even if window use information is available, there is no reliable way to convert the number of opened windows to estimate the amount of natural ventilation. But this information may still be useful as an indicator to determine when mechanical and natural ventilation dominates.

Indoor sources. Some activities such as the use of cook top, oven, and fireplace, may be monitored relatively easily using temperature sensors; other activities, such as burning of candles, need to be recorded by occupant logs and/or interviews. For the purpose of maintaining a reference condition, study homes should not have activities that are large sources of indoor particles, such as smoking or substantial candle use. Activities like cooking and vacuuming can also generate particles, so they need to be recorded in the survey or avoided during the study period. Occupants should be instructed to complete a lot once a day at a minimum to avoid recollection error. Ideally the log should be designed to collect information on indoor activities at different times of the day. Providing small monetary incentives to study participants to complete a daily survey and automatic reminders are useful strategies to encourage completion.

Indoor environmental conditions. The monitoring of air temperature and relative humidity at a central location in the home is needed to confirm that the reference condition stayed the same as intended. Measurements at additional locations can also provide valuable information. For example, air temperature and relative humidity measured at an air register can be used to infer heating and cooling use. Carbon dioxide concentrations measured in living room and bedrooms provide some indications of occupancy.

Outdoor conditions. In addition to monitoring the outdoor PM concentrations, outdoor air temperature, relative humidity, wind speed and direction are also useful for characterizing the outdoor conditions. This information is needed for estimating the air infiltration rate. Wind sensors are relatively low-cost (about $300), but installation will require time and safety training of the field technician. If a wind sensor cannot be installed easily, the measurements at a nearby weather station may provide reasonable approximation.

6.4. Data Analysis

When analyzing particle measurements to evaluate the filtration performance using different metrics, there are a number of important considerations that can affect the results. For example, selecting an appropriate averaging time is important when calculating the indoor-outdoor ratio. If particle counts were measured for different size bins, the analysis needs to retain this size resolution because most filtration systems will have different efficiencies in removing particles of different sizes.

For instruments that convert the optical signal to a mass concentration (see Table 1), the conversion assumes a certain particle density. It is important to describe what this assumed particle density is when reporting the results, and also recognized that the reported concentrations are not equivalent to regulatory mass concentrations.

Indoor-outdoor ratio. The indoor-to-outdoor concentration ratio should be applied over averaging times that are longer than the mean residence time of air in the home. For an air exchange rate of 0.3 h^{-1}, relevant averaging times are between 8 and 24 hours. The use of longer averaging time will help to ensure that the result is not impacted by short-term variations in particle concentrations. If multiple day data is available, the indoor-to-outdoor ratios can be computed at different averaging times to check the sensitivity of the results with respect to this choice.

In occupied homes with indoor sources, one of the more challenging metrics to obtain is the indoor-outdoor ratio focusing on particles of outdoor origin. One way to do this is to identify intervals within the monitoring that are not impacted by indoor sources. For example, based on occupant survey, it is probably reasonable to assume that indoor sources are at their minimum between 2 and 5 am. The duration over which indoor particle-producing activities impact indoor concentration is on the order of the inverse time constant for all indoor removal processes. For example, if the sum of all indoor removal processes (e.g., air exchange rate + deposition rate + filtration removal rate) is 1 h^{-1}, then it takes about 2 to 3 hours for the indoor generated particles to decay.

Decay rate following an indoor emission. Indoor emission events occurring in occupied homes provide opportunities to calculate the overall decay rate of particles. The overall decay rate (h^{-1}) can be estimated using a linear fit of the log-transformed particle concentrations with respect to time, following an indoor emission event. These overall decay rates can be calculated for each event, and also grouped by event types that emit particles of similar characteristics. This overall decay rate will vary with the size distribution of particles emitted. The key constraint is that air exchange rate and mixing in the home are similar, as both have major impacts on decay.

The overall decay rate is a sum of the particle removal rate by the filtration system and by other indoor processes (see Appendix B). So, to estimate the removal rate by the filtration system, it is necessary to know the air exchange rate during the event being evaluated. This means that this analysis requires measurements of air exchange rates at the time when the indoor emission occurred. Besides the air exchange rate, estimate of the deposition rate – which is a function of the particle size and indoor conditions (e.g., airflow, indoor surfaces) – also must be calculated or measured during periods when the filtration system is not operating.

The overall decay rate obtained during operation of an enhanced filtration system can be compared to values obtained for reference system for events of similar quality. The nature of emission events should be discernible from the activity log or monitors. During and immediately following an indoor emission event, indoor concentrations are likely to be dominated by that event, so small changes in outdoor particle concentrations can be ignored. Nonetheless, measurements of outdoor particle levels either throughout or at beginning and end of the indoor decay experiment should be analyzed to confirm this.

There are scenarios where the introduction of indoor sources may be warranted for testing the performance of the filtration system. There are standardized particle sources commonly used in calibrations, but they require additional equipment to be aerosolized. Alternatively, simple method such as burning an unscented candle of known composition might be a viable alternative.

It is important to note that immediately following an emission event that causes indoor concentrations to spike, processes such as volatilization and coagulation cannot be ignored. Time-resolved data used to calculate a decay rate should not include the period just after the event to avoid the impacts of these short-duration processes. This brief time delay also allows mixing to occur so that the indoor concentrations measured by the particle instrument are more representative of the well-mixed condition assumed by the analysis.

7. Conclusions

Filtration systems can be effective in lowering particle exposures in homes. There are a variety of systems available, but currently there is no standard way to measure and compare their effectiveness as installed. Rated or design efficiency is not reflective of actual in-use performance. This guide provides an overview on the important factors to consider when measuring filtration system performance in homes.

Having a common procedure is important to generate results that are intercomparable. This guide anticipates interest among building science and healthy homes researchers and potentially some practitioners to quantify the performance of filtration systems being installed. Eventually, the volume of data that may be collected using a common procedure will form a database where the performance of filtration systems can be compared.

In addition to particle removal efficiency, there are performance considerations that are equally important, e.g., maintenance required, robustness especially relating to imperfect or delayed maintenance, durability, and cost. Even though these aspects of filtration system are not discussed here, we recognize that they may drive adoption in the marketplace.

Besides particles, some air cleaning systems also remove other indoor air pollutants, such as the absorption of volatile organic compounds (VOCs) using activated carbon, by catalytic conversion, or by photocatalytic oxidation. Other air cleaners may use UV lamps to destroy biological contaminants such as bacteria growing on cooling coils, for example. This document focuses on particle filtration performance because it is most common, because particles generally represent a greater health challenge in homes, and because VOCs can more readily be controlled through source control and task ventilation.

This guide also does not address multi-family dwellings, as the airflow and pollutant transport between adjoining units pose special challenges to sampling and data analysis. Past research show large variability in indoor air quality between units (Noris et al. 2013) following retrofit measures that included adding a wall-mounted air cleaner to each unit. Sampling in different units is likely needed in order to properly characterize how the between-unit airflow may impact filtration system performance.

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Appendix A Mass Balance

The following mass balance describes how indoor processes affect indoor particle concentrations.

$$\frac{d(C_{in}V)}{dt} = C_{out}V\left[k_nP + k_w + k_v(1-\eta_v)\right] - C_{in}V\left[(k_n + k_w + k_v) + k_d + \sum_i k_i f_i \eta_i\right] + \sum_x E_x + \sum_y R_y \qquad \text{(A1)}$$

where: C_{in} = Indoor particle concentration (μg/m^3)
C_{out} = Outdoor particle concentration (μg/m^3)
V = House volume (m^3)
k_n = Air infiltration rate via building envelope (h^{-1})
P = Penetration factor through the building envelope (-)
k_w = Outdoor airflow rates through open windows (h^{-1})
k_v = Outdoor air intake rate through a mechanical system (h^{-1})
η_v = Particle removal efficiency at outdoor air intake (-)
k_d = Particle deposition rate (h^{-1})
i = Types of recirculating systems with some filtration capacity, e.g., whole-house furnace fan, standalone air cleaners, etc.
k_i = Air flow rate of filtration system i (h^{-1})
f_i = Fractional on-time of filtration system i (-)
η_i = Particle removal efficiency of filtration system i (h^{-1})
x = Types of indoor emissions of particles, e.g., cooking, candle use, etc.
E_x = Emission rate of particles generated indoors (μg/h)
y = Types of particle transformation processes, e.g., nucleation, condensation/volatilization, coagulation, etc.
R_y = Rate of transformation processes (μg/h)

Equation (A1) is a mass balance of indoor particle mass, where the change in concentration is due to the following elements:

- Outdoor particles entering into the home
- Indoor losses due to ventilation, deposition, and filtration
- Indoor generation of particles
- Transformation of indoor particles.

Equation (A1) assumes that the house is well mixed, meaning that C_{in} is uniform through the indoor space. Equation (A1) will need to be modified for multi-family homes or other multi-zonal settings, where indoor concentrations may vary in the building and the inter-zonal airflows will transport particles from one indoor space to another.

The steady-state solution to Equation (A1) is simply by setting $dC_{in}/dt = 0$. Under the conditions when C_{out} is stable, and if indoor emission and transformation can assume negligible, C_{in} would approach its steady-state value, as shown in Equation (A2). The time scale of approaching steady state is determined by the inverse of the sum of the rate constants, as shown in the denominator of Equation (A2).

$$C_{in} = \frac{C_{out}\left[k_n P + k_w + k_v\left(1-\eta_v\right)\right]}{\left(k_n + k_w + k_v\right) + k_d + \sum_i k_i f_i \eta_i} \tag{A2}$$

Rate constants, such as the air exchange rate, will likely need to be monitored during the field study. In some cases, however, it is suitable to simply reference typical values as reported in the literature instead. For example, estimates of the particle size-resolved penetration factor *P* and deposition rate k_d from published studies are summarized in El Orch et al. (2014). Another alternative is to design the field study such that some of the parameters are controlled. This can be accomplished by requiring no window opening during the study period, or by selecting homes that do not usually use their windows. A third option is to select periods of time in the data analysis when it is reasonable to assume certain parameters are negligible. For example, an example of when nucleation of particles may occur indoors is from ozone-terpene reaction during the uses of certain cleaning products. Coagulation of particles may occur when there are high concentrations of freshly generated particles, such as from cooking, cigarette smoke. If there are indications from occupants, such as from survey data, when these activities occur, those time periods can be excluded from the analysis. These short-term events are expected to have limited influence on daily statistics such as average PM concentrations.

It is important to note that some components of outdoor PM2.5, notably ammonium nitrate, may evaporate relatively quickly when they enter the indoor environment (Lunden et al. 2003). The fraction of ammonium nitrate varies by seasons and regions, and the extent to which these particles volatile indoors will depend on indoor temperature and relative humidity, as well as other sources and sinks for the gas phase pollutants. Consequently, careful selection of homes and planning when sampling occurs need to be considered as part of the study design.

Appendix B Removal Efficiency

Apparent Particle Removal Rate

At steady state, and assuming indoor emission and transformation are negligible, the following gives the following apparent particle removal efficiency:

$$k_f f_f \eta_f = \frac{C_{out}\left[k_n P + k_w + k_v(1-\eta_v)\right]}{C_{in}} - \left[(k_n + k_w + k_v) + k_d\right] \quad \text{(B1)}$$

If all the above rate parameters are constants, then the apparent particle removal efficiency shown in Equation (B1) is simply a function of the difference in outdoor-to-indoor ratio when the filtration system is running compare to when it is not:

$$k_f f_f \eta_f = \left[k_n P + k_w + k_v(1-\eta_v)\right]\left(\left.\frac{C_{out}}{C_{in}}\right|_{ON} - \left.\frac{C_{out}}{C_{in}}\right|_{OFF}\right) \quad \text{(B2)}$$

Equation (B2) is one measure of the apparent particle removal efficiency. To further simplify this, the multiplier may be approximated using the air-exchange rate, k. For example, in a case where C_{out} = 10 μg/m^3 and k = 0.5 h^{-1}, a change in C_{in} from 8 μg/m^3 to 6 μg/m^3 with the filtration system running would imply an apparent particle removal rate of 0.2 h^{-1}, if all else held equal.

$$k_f f_f \eta_f = 0.5\text{h}^{-1}\left(\left.\frac{10\,\mu\text{g}/\text{m}^3}{6\,\mu\text{g}/\text{m}^3}\right|_{ON} - \left.\frac{10\,\mu\text{g}/\text{m}^3}{8\,\mu\text{g}/\text{m}^3}\right|_{OFF}\right) = 0.2\text{h}^{-1} \quad \text{(B3)}$$

When estimating the apparent particle removal rate using Equation (B2), the use of longer averaging time will help to ensure that the result is not impacted by short-term variations in PM concentrations. In most cases, the indoor and outdoor concentrations should be averaged for 24 hours or longer when calculating this ratio. If multiple day data is available, the indoor-to-outdoor ratio can be computed at different averaging times to check the sensitivity of the results with respect to this choice.

An underlining assumption in Equation (B2) is that air infiltration (k_n), window use (k_w), outdoor air intake rate through mechanical system (k_v) if any, deposition rate (k_d), and particles removed by furnace fan filter ($k_v f_v \eta_v$), did not change between the two periods being compared. It is important to assess each of these parameters and determine if the assumption holds. For example, a significant change in weather leading to differences in indoor-outdoor temperature difference and wind speed may mean higher air infiltration rates in one period compare to the other. Air sealing to tighten the building envelope is expected to reduce air infiltration, so k_n should not be assumed constant in that case. Air sealing likely reduce particle penetration as well (Stephens and Siegel 2012b).

It is reasonable to assume that physical properties such as deposition rate and penetration factor did not change over a short period of time. However, this may be a poor assumption when comparing before and after major home renovation, and also when comparing between homes. Use of windows and the mechanical system is expected to change by seasons. Information about them should be collected from occupant surveys, or controlled by the study design. Outdoor air intake and the furnace fan runtime will need to be measured or maintained at a reference state, especially if the filtration system effectiveness is being compared between different homes.

In occupied homes where there are indoor sources, the assumption that *E* is zero means that Equation (B2) likely underestimate the apparent particle removal rate. Consider the same example where k = 0.5 h^{-1}, if indoor sources add about 2 μg/m^3 to the indoor air, then the indoor source strength is about 1 μg/h-m^3 (calculated from 2 μg/m^3 divided by 0.5 h^{-1}). For the same values of C_{out} and C_{in}, the apparent particle removal rate would change from 0.2 h^{-1} to 0.25 h^{-1}, i.e. 25% underestimation of the filtration efficiency because of the zero indoor source assumption, relative to Equation (B3).

$$k_f f_f \eta_f = \left.\frac{0.5\mathrm{h}^{-1}\left(10\,\mu\mathrm{g}/\mathrm{m}^3\right)+1\,\mu\mathrm{g}/\mathrm{h}\cdot\mathrm{m}^3}{6\,\mu\mathrm{g}/\mathrm{m}^3}\right|_{ON} - \left.\frac{0.5\mathrm{h}^{-1}\left(10\,\mu\mathrm{g}/\mathrm{m}^3\right)+1\,\mu\mathrm{g}/\mathrm{h}\cdot\mathrm{m}^3}{8\,\mu\mathrm{g}/\mathrm{m}^3}\right|_{OFF} = 0.25\mathrm{h}^{-1} \qquad \text{(B4)}$$

Transient Analysis

A transient analysis using real-time PM indoor concentrations may be appropriate if there are incidences of indoor emissions that are brief in duration but generated a large increase in indoor concentrations. Alternatively, this can be simulated using a standardized source in an unoccupied test house. Following this sudden jump in indoor concentration, the rate of decay can be described using Equation (B5). Here, the two periods are (1) before the large increase in indoor concentrations, and (2) decay in indoor concentrations at some time after the indoor emission has ended, as shown in Figure B1.

$$\begin{aligned} & C_{in,(2)}(t) = C_{in,(1)}\left(1-e^{-kt}\right) + C_{in,(2)}(t_0)e^{-kt} \\ \text{where} \quad & C_{in,(1)} = \frac{C_{out}k_n P + E/V}{k} \qquad \text{(B5)} \\ \text{and} \quad & k = k_n + k_d + k_f \end{aligned}$$

The rate of decay during period (2) gives an estimate of k, which is the sum of the air infiltration rate k_n, deposition rate k_d, and the particle removal rate by filtration, k_f. Equation (B6) shows the linear relationship between the logarithmic of indoor particle concentrations and time, t. The best-fit slope of this linear regression gives an estimate of the value of k.

$$\ln\left[C_{in,(2)}(t)\right] = X - kt \tag{B6}$$

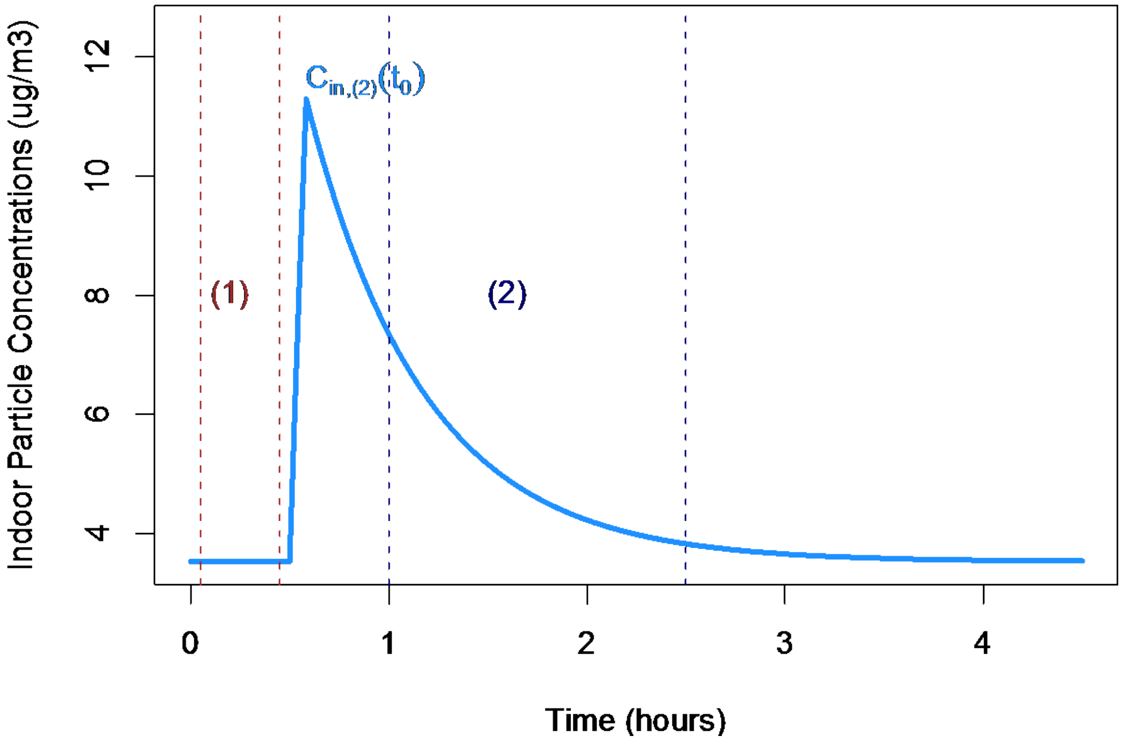

Figure B1. An illustration of indoor particle concentrations (1) before and (2) after a large release of indoor particles, where $C_{in,(2)}(t_0)$ is the peak indoor concentration reached as a result of the release.