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Housing Technology Series

Evaluation of Residential Furnace Filters

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EVALUATION OF RESIDENTIAL FURNACE FILTERS

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EXECUTIVE SUMMARY

Forced air furnaces are a common Canadian heating system. Traditionally, filters placed in the circulating air ductwork were designed to protect the furnace and fans. Over the last several years, there has been increased emphasis on improving the filtration efficiency with the goal of reducing occupant exposure to respirable particulate.

This research project rotated several filters through six houses in southern Ontario during the heating season. Particulate levels were continuously monitored in the outside air, before and after the filter in the ducting system, and in the air in two rooms of each house.

The results show that air passing through the filters was cleaned generally in accordance with rated filtration efficiency. The integrated breathing zone exposure, however, reflects both dust generation and dust removal mechanisms. Breathing zone exposure reductions were, therefore, not as significant as reductions seen in the ducting systems.

A limited study of an in-room filter was also carried out and showed that such a filter can have significant effect on the breathing zone exposure in that room.

A study of 15 additional houses with air cleaning by electrostatic precipitation looked at the levels of ozone found in these houses.

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1 OVERVIEW, DISCUSSION OF OBJECTIVES

Introduction

The primary purpose of this project is to provide a basis for formulating advice to the public on filter selection.

Over 60% of Canadian houses have forced air heating (NRCan, 1997) and the usual filtration in the forced air system is an inexpensive fibreglass throwaway filter. The function of these filters is largely to protect the fan and the furnace heat exchanger, and manufacturers make no claim on their efficiency for dust removal.

In recent years, with an increasing consciousness of indoor air quality issues, more efficient filters have appeared. These range from mild upgrades, such as pleated "medium efficiency" disposable filters, up to high-efficiency particulate arresting (HEPA) filters, with a bewildering variety of products being offered. Filter efficiency can be rated by a number of standards, such as arrestance, dust spot and Di-octyl phthalate (DOP) (ASHRAE, 1992; U.S. Dept. of Navy, 1956), but there is no agreement on which rating system is most appropriate for household filters. Many manufacturers do not provide filter performance information to consumers. It is difficult for homeowners to select a filter suitable for their needs and to know what effects can be expected in their house.

This project was undertaken to provide the data necessary for formulating this advice to consumers on filter selection. Essentially the full range of filters were tested in six occupied houses, which represented a variety of occupancies, locations (urban and rural) and dust sources.

Objectives

Specific objectives

The specific objectives for the project were as follows.

- Establish a testing protocol to enable comparison of different types of filters.
- Establish a relationship between particle concentrations measured in duct, at stationary "mid-room" sites, outdoors and at the breathing zone of a person.
- Compare the performance of representative types of filters in several houses.
- Define operating requirements (e.g., fan operating times, high versus low speed) for a forced air system that maximize benefits of various filters.[1]
- Assess enhancement of particulate removal (if any) provided by a portable air cleaner (air purifier) in a bedroom.
- Survey ambient concentrations of ozone in a variety of installations of electronic air cleaners in several houses to understand possible causes and mitigation.[2]
- Present the data, findings and conclusion so they are readily transferable to a consumer publication.
- Assess the role of in-duct filters in controlling airborne particulate in the breathing zone in houses.

Answers to questions

In achieving the goals set out above, the project would have to answer the following questions.

- To what extent can in-duct filters reduce in-home airborne particulates?
- What benefits do the different types of filters provide?
- What is the relative performance of the tested filters?
- What are the limitations of the tested filters?
- What can householders realistically expect from the tested filters?
- What selection criteria are appropriate for consumers?
- Do room-size air cleaners produce a measurable benefit?
- What operating and maintenance procedures should be followed to maximize or preserve the benefit of in-duct filters?
- Are some installation practices better than others?

With respect to ozone generation and plate and wire type electronic air cleaners:

- Does this issue appear to be important for these devices?
- Does ozone generation appear to be linked to specific maintenance or installation faults?

Limitations

Limited testing time per filter, per house

Each filter was in use in each house only for a matter of days. Questions about the effects of:

- filter loading;
- particle storage levels in the home; or
- influence of longer-term outdoor particulate trends
- cannot be answered by the data generated in this study.

Winter testing only

Testing was conducted in the winter, with doors and windows closed. The results are not necessarily transferable to summer conditions where doors or windows may be open. Some extrapolation of the results can be made concerning homes where air conditioning is operated in the summer with doors and windows closed.

Testing method not optimized for bypass filters

The original study design intended to test systems operating in intermittent, high/low and continuous modes. Unfortunately, it was not possible to modify all the bypass filter installations to allow intermittent or high/low operation with these filters. Refer to Appendix A.3 for more detailed information.

Testing periods too short to account for variability of outdoor particles

The testing period for each filter in each house covered a span of about 24 to 48 hours. Outdoor PM_{10} levels, on the other hand, can undergo significant short-term variation over that time period. For example, the electrostatic precipitator (ESP) filter testing period in House #2 showed an average outdoor PM_{10} level of 3.1 $\mu g/m^3$ over the period of the test. During the test of the 1"MED filter in House #3, the outdoor PM_{10} level averaged 23.1 $\mu g/m^3$. Refer to Appendix I.3 for a more detailed discussion.

Particle Sizes

The objective of this study is to evaluate household filtration products and methods insofar as they affect indoor air quality. In keeping with this objective, the study methods are confined to particles less than 10 microns in aerodynamic diameter. This set of particles is common referred to as PM_{10} or as inhalable suspended particulate[3] (ISP).

Other sets of smaller particles are also studied:

PM_5 Particulate matter below 5 μm
$PM_{2.5}$ Particulate matter below 2.5 μm (also referred to as respirable suspended particulate (RSP))
PM_1 Particulate matter below 1 μm

Respirable suspended particulate, ($PM_{2.5}$) are those which will travel deeply into the respiratory tract. Some of these particles may enter directly into the bloodstream. Particles between 2.5 and 10 μm diameter do not usually penetrate so deeply into the respiratory tract and tend to lodge in the upper respiratory tract and upper air passageways. Particles larger than the PM_{10} cut point are not generally breathed in by persons during ordinary activities.

With regards to the tendency of a particle to settle out from the air, particles larger than 5 μm diameter are primarily influenced by gravity. Particles smaller than 1 μm (PM_1) are largely influenced by electromagnetic forces and particles between 1 and 5 μm are influenced by varying degrees of gravitational and electromagnetic forces.

Rating Methods

Currently, there are four generally accepted measures of filter performance which are applicable to residential-type filters:

- arrestance;
- dust spot efficiency;
- DOP efficiency; and
- clean air delivery.

Arrestance is a result of the arrestance test cycle carried out according to the ASHRAE Standard 52.1 (ASHRAE, 1992). This test is useful for rating filters for their ability to filter particles in the coarse, visible range, but is not useful for rating filters for their ability to remove respirable or inhalable particles from the airstream. The arrestance value can be quite high (90%) for a filter which has only mediocre performance (10% to 20%) in removing inspirable and respirable dust. Arrestance is often quoted by suppliers of filtration products as "efficiency" because it is expressed as a percentage removal value. This practice is misleading, tending to grossly overrepresent the ability of the filter to remove particles in the inhalable/respirable range.

Dust spot efficiency is the result of the atmospheric dust spot test method carried out according to ASHRAE Standard 52.1 (ASHRAE, 1992). This test is useful for rating filters in inhalable/respirable dust range. Dust spot efficiency is often referred to as "efficiency" but, in fact, there are two commonly reported dust spot efficiencies from the test:

Initial efficiency-clean filter
Average efficiency-average of initial and ending results

For this study, average dust spot efficiency is used as the default value.

DOP efficiency (U.S. Dept. of Navy, 1956) is the result of a specific test which measures the ability of the filter to remove particles of 0.3 and larger. The test is relevant for high-efficiency particle arrestance (HEPA) filters which must achieve a value of 99.97% removal effectiveness according to this test in order to be classified as HEPA filters.

Clean air delivery rate is a general term which has been used in product testing reports (*Consumer Reports Magazine*, 1992) by researchers (Leventin, 1992) and as a tested parameter for portable air cleaners (AHAM, 1998). A similar term is used by some researchers (Offermann et al., 1992) and is called the effective cleaning rate or ECR. Conceptually, the clean air delivery rate (CADR) is the flow rate of perfectly clean air which would be required to produce the equivalent effect of the air cleaning device in question. In practice, the CADR is imputed from either:

the measured efficiency and air handling flow rate of the subject air cleaning device[4]:

$$[\text{Air Flow rate}] \times [\%\ \text{Particle Removal Efficiency}] = CADR_{AH}$$

or

the measured decay of suspended particles in a test chamber[5]:

$$CADR_D = V^*(k_e - k_n)$$

where:

V = volume of test chamber
k_e = measured decay rate, 1/time
k_n = natural decay rate, 1/time

It is notable that the CADR can be expressed in any convenient flow rate unit, and for a variety of particle sizes. The American Home Appliance Manufactures Test Standard for Portable Air Cleaners (AHAM, 1998) for example, reports CADR values for each of three types of dust being:

Cigarette smoke	0.09 to 1.0 µm diameter (using cigarette smoke forced through cigarette's filter)
Air cleaner fine fraction dust	0.5 to 3.0 µm diameter (Arizona road dust)
Pollen	0.5 to 11 µm diameter (Paper mulberry pollen)

For this study, CADR is reported as one of $CADR_{10}$, $CADR_5$ or $CADR_1$ being the CADR for particle sizes of 10, 5 and 1 µm respectively.

CADR is a necessary value for comparison of filters of varying airflow on systems for which the airflow varies over time, and systems in which part of the air is filtered and part is not (bypass systems).

It is also useful to recognize that $CADR_{AH}$ reflects only the theoretical value of the air handler and is limited by the upstream/downstream efficiency value on which it is primarily based. On the other hand, $CADR_D$ will reflect system efficiencies and effects which may enhance or reduce the action of the filter in the space. These effects may involve system factors such as the entrainment or re-suspension of unwanted particles after the filter, or the agglomeration and accelerated settling of particles due to electrical effects which are not apparent from the upstream/downstream efficiency.

Manufacturers/Supplier's Information

A consumer may purchase a filter at a walk-in retail location, from mail order or from an in-home sales representative or HVAC contractor. In-home sales representatives may be selling "health-type" products, duct cleaning and HVAC services. The objective of this study was not to investigate specific sales practices and claims, but rather to document the following information:

- range of filters available in Canada;
- supplier's claims to the consumer with respect to performance;
- supplier's claims with respect to performance in technical literature;
- test results from independent labs supplied on request;
- capital, installation and annual service cost; and
- special aspects of service/maintenance or performance.

How Do Filters Affect a Person's Exposure?

An individual's particle-breathing experience indoors is a complex composite of sources such as:

- re-suspended surface and house dust;
- dust generated by an activity such as cooking;
- dander generated by a pet or another individual; and
- particles contained in outside air which infiltrates the house.

Particle concentrations when the home is not occupied and when there is little activity (i.e., sleeping) can drop to very low levels. During activity by the occupants of the house, particle levels can be raised through re-suspension to levels of up to 10 or 20 times the "at rest" values. Peak particle levels during some cooking activities can be raised to 100 times the "at rest" values.

The particle concentration in outdoor air may be greater or lesser than indoor air and can experience significant variations over periods as short as several hours. Some houses may allow greater or lesser rates of air change, and this variable can have significant short-term variation. The entry path of outdoor air may also influence the quantity of particles allowed to enter the home. Some entry paths act as effective filters while others do not.

While a filter may be better or worse at removing particles from an airstream, the actual benefit to an individual will not be a direct relationship to that filter's measured performance. In other words, a filter with 95% effectiveness at removing 2.5 μm particles will not result in the house air seeing the same 95% reduction. Only in a house with very low outdoor air infiltration and little or no occupant activity will the house air particulate reduction approach the rated efficiency of the filter.

In-Room Filtration versus Central

Many Canadian houses are not equipped with forced air systems and, in some houses with central, forced air systems, continuous operation of the forced air system may not be desirable from a noise, comfort or energy cost point of view. In these situations, an in-room filter may be the preferable option. A secondary objective of this study was to verify whether or not these types of devices are effective.

Electronic Air Cleaners and Ozone

Electronic air cleaners (also called electrostatic precipitators or ESPs) are a popular type of forced air system air cleaner and have been installed in Canadian homes for at lest 20 years. It is known that these units produce ozone under certain usage conditions which may or may not be related to maintenance and state of repair. Ozone is a known respiratory irritant, and one of the primary outdoor air pollution components in Southern Ontario. Numerous research papers have identified respiratory symptoms beginning at 80 parts per billion (ppb), and decrements in lung function in healthy children have been suggested for concentrations as low as 60 ppb (Spector et al., 1988).

Recently, there have been published reports of studies by Canadian federal agencies on the respiratory effects of ozone (*The Expositor*, 1999) which state that a level as low as 15 ppb may provoke health effects, and an increment of 10 ppb in environmental ozone will have an effect on a population.

The primary source of ozone is the outdoor air on days when photochemical smog conditions exist. During these conditions, when outdoor levels are 80 ppb or higher, individuals who have sensitive respiratory tracts (suffering from asthma or other respiratory condition) are usually advised to stay indoors where ozone levels are expected to be lower. The significant addition of ozone to the indoor air by an ESP device could unexpectedly remove the benefit of this advice.

This study tested 15 homes with ESP devices installed. Measurements of ozone, airflow and particle concentrations were taken before and after the filter was cleaned and checked for correct operation.

Previous Research

The following is a synopsis of some existing, relevant research. Refer to Appendix J for a more detailed discussion of the differences between these studies and the current project.

Raab - CMHC

In 1982, CMHC published a study by K.H. Raab which reported on the types of filtration products available in Canada for use in residential situations. This study did not involve actual testing and relied on information gathered from manufacturers and independent test reports when available.

McCuaig and Robinson - CMHC

In 1986, CMHC published a study by McCuaig and Robinson (OBOE Engineering Ltd) which reported on the tested characteristics of ordinary, medium-efficiency pleated and electrostatic filters used in residential forced air systems. The study concluded that filter efficiency changes with velocity especially for medium-efficiency filters and that the system airflow reduction for medium-efficiency retrofits was generally less than 20%. It was found that tobacco smoke was not effectively removed by medium-efficiency filters except at low velocity. The study recommended medium-efficiency filtration as a low/no cost retrofit, requiring only a simple adjustment to the air handler, if any.

Offermann et al.

Offermann et al. (1992) studied the effect of residential-type filters on particle removal in an unoccupied test chamber which approximated apartment-sized living quarters. The filters tested covered about the same range as this project except that bypass configurations were not tested. Particles in the range of 0.01 to 1.75 μm were monitored as being representative of the tobacco smoke pollutant which was the focus of the study. Offermann et al. reported results expressed as effective cleaning rate (ECR) defined as the apparent particle removal in the space (decay curve regression) with filtration, less the apparent particle removal without filtration. This is essentially equivalent to the AHAM definition of $CADR_D$ and the usage of $CADR_{D10}$*-Improvement* as described in Figure 18 of this report.

Offermann et al. found that the no filter, viscous impingement, passive electrostatic and foam-pad electrostatic filters had very low ECR values in comparison to the system airflow. The HEPA, ESP and 95% dust spot filters tested by Offermann et al. showed higher ECR values in relation to the system airflow. Based on the experimental results, they predicted that these filters would produce reductions in steady-state residential indoor particle levels of between 9% (no filter) and 80% (95% dust spot filters). The costs of purchase, operation and maintenance were also calculated and compared to the probable quality of clean air which would be supplied by the tested units. A projected annual cost per unit of clean air was predicted.

Burroughs et al.

Burroughs et al. (1998) tested several filters in three homes in Atlanta, Georgia. Particle measurements were made upstream, downstream and in the basement area. Ordinary fibreglass, 95% dust spot and 25 mm pleated media-type filters were tested and a no-filter condition was evaluated as a baseline. Particle sizes between 0.3 and 10 μm were measured.

The filters were not found to reduce the existing system air flows to a significant degree. System efficiencies based on indoor and outdoor air monitoring were calculated for each filter and a no-filter condition. The ordinary fibreglass filter was found to be very similar to the no-filter condition, and the 95% dust spot and 25 mm pleated filter were found to produce distinct improvements in indoor air particle levels. Median system efficiency values varied from 30% to 58% for the no-filter condition and from 73% to 89% for the 95% dust spot filter. The system efficiency values calculated by Burroughs et al. appear similar to the $CADR_D$ value reported in Chapter 3 of this study.

2. DISCUSSION OF METHODS

Manufacturer/Supplier Information

A search of available information was conducted, and 27 manufacturers/suppliers of air filters were identified as supplying filters for household use in Canada. These suppliers typically offered from one to five models.

From this listing, 10 filter models were selected as being representative of the type of filters currently being applied in Canadian homes. Table 1 lists the 10 filters together with their generic description.

Table 1: Selected filters

Code	Generic Description	Full Flow/ Bypass
ORD	Ordinary Furnace filter	Full flow
1"PLT	25 mm pleated media filter	Full flow
1"MED	25 mm pleated media high quality	Full flow
PAS.E	25 mm passive electrostatic	Full flow
E.PAD	Electronic charged pad	Full flow
4"MED	100 mm pleated media	Full flow
95MED	95% dust spot pleated media	Full flow
ESP	Electronic plate and wire type	Full flow
TFP	Turbulent flow precipitator	Bypass
HEPA	HEPA	Bypass

The following information was identified with respect to each filter:

- supplier's claim to the consumer with respect to performance;
- supplier's claims with respect to performance in technical literature;
- test results from independent labs supplied on request; and
- capital, installation and annual service costs.

A complete listing of the characteristics of each of these filters appears in Table 12 in the Appendix.

Particle Counting versus Gravimetric

Particle count data were converted to a gravimetric concentration value expressed in micrograms per cubic metre ($\mu g/m^3$) of air using assumptions of average size and density as set out in Appendix H.1. Gravimetric estimates were verified using collocation tests[6] with conventional gravimetric sampling techniques using impact separators with 10 micrometre and 2.5 micrometre cut sizes. Refer to Appendix G.7 for a detailed description of the methods used.

Preliminary Testing of 10 Filters

The 10 filters listed in Table 1 were tested in House #1[7] using a common testing arrangement. The tests carried out included:

- particle removal efficiency, (upstream/downstream);
- $CADR_{AH}$, (clean air delivery rate air handler);
- power consumption; and
- airflow characteristics.

Each filter was tested for a minimum of 10 hours in the first house, using a blend of active and non-active periods in the house. Each filter was mounted in a specially prepared duct section equipped with stations for measuring particles directly upstream and downstream of the filter as well as airflow and pressure drop across the filter. Particle measurements were made using the particle-counting rig described in Appendix G.1. See Appendix B for more detailed descriptions of the specific methods used and test protocols.

During this time, the protocol for testing in the five other houses was developed.

Whole-House Testing

To evaluate the effect of filtration on persons living in a typical Canadian home, five filters were tested in six homes[8] over a period of two weeks for each house. The houses are representative of typical Canadian homes and occupancies, and the testing occurred during winter (closed window) home operation. A table describing the home characteristics and occupants can be found in Appendix A.

The five filters (listed in Table 2) were selected out of the original 10 filters tested in House #1 as being most representative of the range of filters available and currently being installed in Canada.

Table 2: Filters used in whole-house testing

Code	Generic Description	Full Flow/ Bypass
ORD	Ordinary Furnace filter	Full flow
1"MED	25 mm pleated media high quality	Full flow
E.PAD	Electronic charged pad	Full flow
4"MED	100 mm pleated media	Full flow
ESP	Electronic plate and wire type	Full flow
BYPASS	TFP filter tested in House #2, HEPA tested in houses #1,3,4,5 and 6	Bypass

The study method used real-time measurements of particle levels, furnace status, temperature and wind speed data. These were combined with the known values of furnace airflow and house air tightness to create 24 to 48 hour continuous records of indoor and outdoor particle level, system particle removal and air change. These records were obtained for of each of the five filters and for a no-filter condition for each of the six houses.

In addition to the measured parameters, a record of activity was kept with identification of at least sleeping versus waking, cooking and vacuuming. The detail of activity record varied considerably among houses.

The following parameters were measured in real time:

- particle levels in the air systems ducts before and after the filter[9];
- particle levels in one bedroom;
- particle levels in the principal family/living area;
- outdoor particle levels;
- furnace on/off, high/low airflow status; and
- outside inside temperature and wind speed.

Airflow and power consumption were measured for each fan speed and filter combination. House air tightness was measured using the CGSB 149.1 Test Procedure[10] (CGSB, 1986).

Refer to Appendix C for a detailed description of the test methods and protocol.

Personal Sampling Methods

Some personal sampling was carried out using a particle counter with a pick-up tube located in the wearer's breathing zone. This apparatus was contained in a body pack which allowed the wearer to move freely. Some wearers reported discomfort due to the weight of the pack (2 kg). Data periods for which personal samples are available are over a range of 15 minutes to 2.5 hours. Where the location of the wearer was not known, the breathing zone samples were compared to house average values, that is, the average of the bedroom, family and return air particle values. When the location of the wearer was known to be in a room which had a fixed-location sample, the personal values were compared to the in-room samples without averaging with other locations.

Refer to Appendix D for more detailed information on the sampling methods used.

Infiltration/Removal/Re-suspension Model

Removal/generation effects

The suspended particle level in an interior space is, at any point in time, a function of several variables.

Removal:

- Settling rate of the suspended particles (collection by the surfaces in the house); and
- removal of particles due to operation of mechanical system and filter.

Addition:

- Re-suspension due to activity of persons or animals in the house;
- entry of particles from the outside due to infiltration; and
- generation of particles by an activity such as cooking (or use of candle).

Air change prediction

Air change rates were predicted based on real-time weather data gathered at each house using a weather station located adjacent to the house being tested. The air tightness of each house was tested using the blower-door air tightness method (CGSB, 1986) and the resulting value combined with the weather station data using the AIM-2 calculation method (Walker and Wilson, 1990) to produce a real-time prediction of the air change rate for the house.

Additional details concerning the weather station set-up can be found in Appendix G.3. Details concerning the air change rate calculations can be found in Appendix H.7.

Steady-state analysis

In order to account for the effect re-suspension due to activity, data were separated into three classes.

- *Non-active* data comprise only those periods where there is no activity in the house (house is empty or all sleeping) and after the particle levels appear to have reached a steady state.
- *Active* data comprise only those periods where there is known activity in the house, and there is active re-suspension or generation of particles as shown on the real-time data charts.
- *All data* including *active, non-active* and *transition*[11] data.

Dynamic analysis

Dynamic analysis was undertaken by analyzing the regression constant of the decay curve between active and non-active periods. The model used is described in Appendix H.6 and is based on the house average particle mass concentration parameter which is the average of the bedroom and living area sampling points. The model used accounts for the effect of outside air change by assuming the house air volume is evenly mixed and the infiltrating air is uniformly injected at 50%[12] of the particle mass concentration which was measured at the outdoor sampling point.

Overall particle removal

Other studies (Offermann et al., 1992) and the AHAM filter standard (AHAM, 1998) deduct the natural removal rate of the space from the measured decay rate to obtain a $CADR_D$ which is attributable to the action of the filter. This study presents the results both as overall removal rate and as the improvement in removal rate over the no-filter base case.

Airflow, Fan Operation and Fan Power

The furnace system airflow and power consumption were measured for each of the following conditions:

- no filter;
- each of the five filters (10 filters in House #1);
- at high and low speeds for each filter if the furnace operates at two speeds; and
- via the bypass filter when a bypass filter was in place.

During testing, furnace fan off, low speed and high speed "statues" were monitored using a data logger. By combining the measurements of airflow and power consumption according to the filter being used and the status of the blower, a real-time track of furnace airflow and power consumption was generated and matched to the particle count and infiltration data. Refer to Appendix G, sections G.4 and G.5 for more detailed information on the measurement and logging systems used.

Electronic Air Cleaner Field Survey

Data collection

Twenty households equipped with electronic air cleaners (EAC) were located and surveyed for ozone concentration and cleaning operation. Householders were offered a complete electronic air cleaner tune-up as an incentive. Due to difficulties with the first ozone measuring instrument used, valid ozone data were obtained from only 15 homes.

Parameters measured and data gathered included:

- outdoor and indoor ozone level;
- in-duct ozone level, before and after filter, and at the discharge from furnace;
- furnace airflow and static pressures;
- particle levels (in all ozone reading locations);
- filter cell and pre-filter weight before and after cleaning;
- home air tightness;
- indoor/outdoor temperature and wind speed; and
- operating/cleaning practices of the householder.

Refer to Appendix E for a detailed explanation of the test methods used.

Ozone data analysis

Outdoor and indoor ozone levels (concentration) are reported in ppb. Ozone contribution to the indoor air from the ESP is expressed as source strength in microlitre/sec (μL/s).

Particle removal data analysis

Although data were collected which would allow some analysis of particle removal efficiency and the effect of cleaning on particle removal efficiency, these data were not analyzed.

Portable Air Cleaners

A single, portable in-room filtration unit[13] was tested in a bedroom and a home office environment. The bedroom environment is one in which there is activity for only short periods during the day. With a home office, there is more or less continuous low-level activity throughout the day. Refer to Appendix F for a detailed explanation of the test methods used.

3. DISCUSSION/RESULTS

Upstream/Downstream Efficiency

Preliminary testing of 10 filters

Figure 1 shows the results of testing for the PM_{10}, PM_5 and PM_1 particle categories. The data cover a total of 252 hours, averaging 15 hours per filter (minimum nine hours). Both active and non-active periods are included.

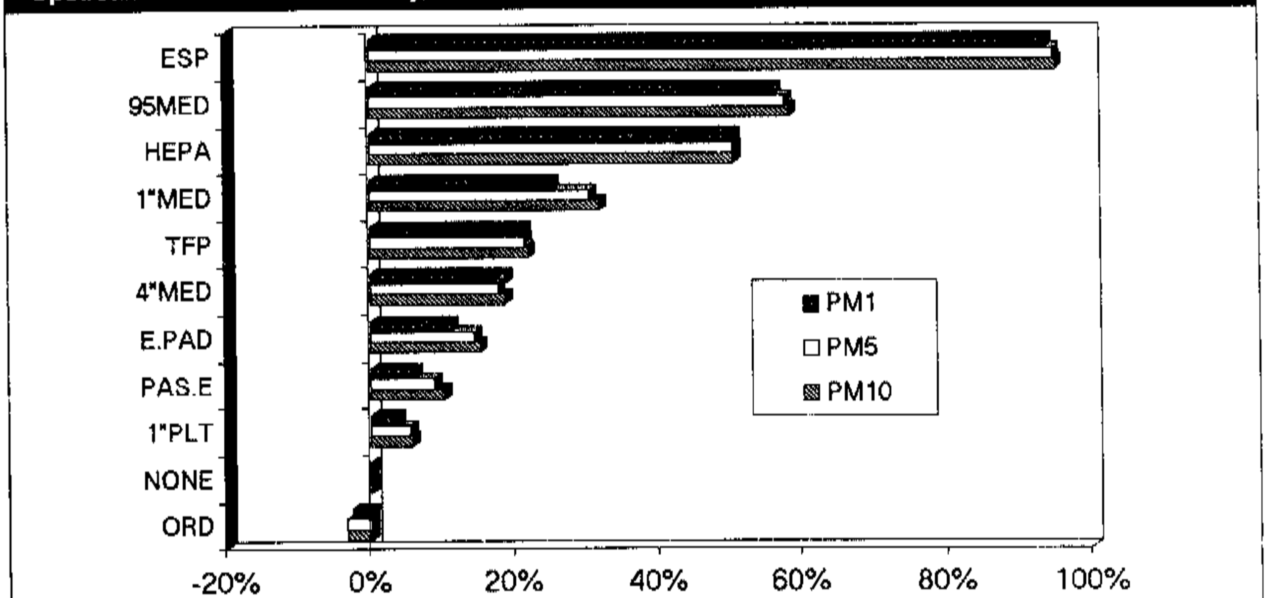
As can be seen, there is very little difference between the measured efficiencies in the different particle classes.[14] For this reason, the balance of this study reports primarily PM_{10} values for upstream/downstream efficiency and PM_1 values only where they are of interest. PM_5 values are not reported as they are, in general, very similar to the PM_{10} values.

In general, the measured upstream/downstream efficiencies range from slightly negative for the ORD filter to over 90% for the ESP. The 1"MED premium 25 mm thick media filter outperformed its look-alike 1"PLT by a wide margin. Although the TFP and HEPA efficiencies were not measured directly, their removal efficiency through the filter itself appeared to approach 100% for both filters. As the HEPA filtered about 50% of the total airflow, it therefore recorded an efficiency of approximately 50%.

Testing five filters in six homes

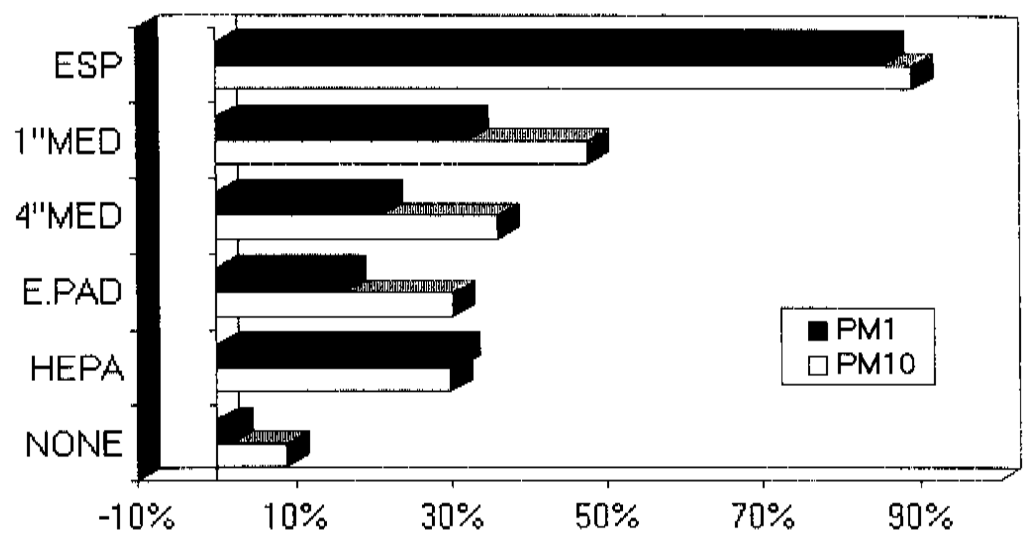
Figure 2 shows the results of testing for PM_{10} and PM_1 upstream/downstream efficiency for the five filters in six homes. These mean values represent a total of 1,040 hours of data averaging 173 hours per house. The data include active, non-active and transition periods. Similar analysis of active and non-active periods did not show significant differences in upstream/downstream efficiency than were obtained for the entire data set.

Figure 1:
Upstream/downstream efficiency, 10 filters tested in House #1[1]



Note:
1 The TFP and HEPA filters are bypass-type filters handling 22% and 51% of the system airflow respectively. However, the efficiencies in Figure 1 are measured in the total airflow, so the implied efficiency directly through the bypass filter approaches 100% for both types.

Figure 2:
Upstream/downstream efficiency, average of all houses[1]



Note:
[1] Auto fan data from House #4 excluded and data from House #5 excluded.

In general, the filters are divided into two groups, the very high-efficiency group represented by the ESP filter at approximately 90%, and a large middle-range group between approximately 25% and 50%. The bypass and ESP filters exhibit very similar performance for PM_{10} and PM_1 size ranges whereas the other filters show a distinctly lower ability to collect the finer particles.

Comparison to manufacturer's claims
Table 3 shows the particle removal efficiency measured for each of the 10 filters tested in House #1 compared to that claimed by the manufacturer.

In general, the claims of the manufacturers/suppliers can be broken down into several types:

- eliminates XX% of airborne particles (or some similar implication);
- XX times more efficient than "________"(usually "ordinary") type of filter;
- XX% arrestance (usually average arrestance);
- XX% dust spot efficiency (usually average dust spot efficiency); and
- removes XX% of particles on multi-pass basis (usually with size range).

The trend appears to be for suppliers of higher-performance filters to supply accurate information. The information for the ESP, TFP and HEPA filters appeared to be substantially accurate when the suppliers were referring to test results or specific performance with respect to particle removal. All these suppliers provided independent test data on request.

For the 95MED filter and the 4"MED, the results, according to our test method, showed lower values than the average dust spot efficiency values provided by the filter suppliers. Our test values exceeded the average dust spot efficiency values claimed for the ESP filter. These differences are more than likely due to specific differences in test method as well as the fact that the tests in this study are essentially "clean device" tests and, in the case of the media-type filters, would tend to underrepresent the average performance.

The PAS.E filter claimed 93% average arrestance and supported this with an independent lab test. The same lab test reported the average dust spot efficiency as being "less than 20%" which agrees with our test result. The suppliers of the 1"PLT and 1"MED filters do not state any specific

Table 3: Manufacturer claimed performance versus tested

Code	Generic Description	Manufacturer Claimed Performance	Test Results Upstream/Downstream Efficiency	
			E% PM1 %	E% PM10 %
ORD	Ordinary Furnace	• Change monthly; made from recycled material	-2	-3
1"PLT	25 mm pleated media filter	• Eliminates 92% of airborne allergens, • 2-3 times more efficient than standard filters	4	6
1"MED	25 mm pleated media high quality	• 99% of particles in your air consist of micro-particles, • 20 times better than ordinary filters, 7 times better than ordinary pleated filters	25	32
PAS.E	25 mm passive electrostatic	• 93% average arrestance	6	10
E.PAD	Electronic charged pad	• Removes 98% of sub-micron particles on multi-pass basis • Single pass @ 0.3-0.5 µm = 33-75%; @ 0.5 - 1.0 µm 75-95% • Multiple pass @0.3-0.5 µm = 97%; @ 0.5 - 1.0 µm 98.6%	11	15
4"MED	100 mm pleated media	• 32% average dust spot efficiency • 92% average arrestance	19	19
95MED	95% dust-spot pleated media	• 95% average dust spot efficiency • 99% average arrestance	56	58
ESP	Electronic plate and wire type	• 75% average dust spot efficiency • 98% average arrestance	94	95
TFP	Turbulent flow precipitator	• 0.5 µm- 84% • 0.7-0.9 µm 87% • 1 µm 92% • 2-3 µm 95% • 5+ µm 99% (according to ASHRAE 52.1)	21[1]	22[1]
HEPA	HEPA	• 99.97% DOP	51%[1]	51%[1]

Note:
[1] The TFP and HEPA filters are bypass-type filters handling 22% and 51% of the system airflow respectively. Efficiencies are measured in the total airflow, so the implied efficiency directly through the bypass filter approaches 100% for both types.

performance parameter. Rather, their claims refer obliquely to other filters, stating that the filters are X times more efficient. The supplier of the ordinary furnace filter made no claims with respect to performance. In general, there is no consistent method of performance reporting used by suppliers to prospective consumers.

Airflow Performance

There is apparently a wide variation in airflow versus pressure characteristics between the filters, when expressed as an airflow at a fixed static pressure. Table 4[15] shows the airflow in L/s[16] for the eight full-flow filters tested in House #1 at fixed static pressures of 25 Pa and 50 Pa. Figure 3 shows the airflow versus pressure curves[17] for these filters.

Table 4:
Airflow at fixed static pressure drop for eight full-flow filters tested in House #1

Code	Airflow @ 25 Pa, L/s	Airflow @ 50 Pa, L/s
ORD	576	875
ESP	548	777
4"MED	475	775
PAS.E	329	507
1"MED	264	412
E.PAD	257	405
1"PLT	243	387
95MED	137	231

The ordinary filter (ORD), electrostatic precipitator (ESP) and 100 mm media filter (4"MED) appear to have the least resistance to flow. The passive electrostatic (PAS.E), 25 mm media (1"MED), charged pad (E.PAD) and 25 mm pleated (1"PLT) form a group in the mid-range, having moderate resistance to airflow. The 95% dust spot (95MED) cartridge appears to present the highest resistance to airflow.

Figure 4 shows the fan high speed airflow rate in House #1 for the eight full-flow filters and the TFP bypass filter. The variation between the base case "ordinary" filter and the worst filter is less than 18%. However, when the 95MED filter is not considered, the maximum airflow reduction is 9% or less. The TFP filter results in an increase in overall airflow for the system, as its "bypass" configuration tends to reduce the velocity through a certain portion of the return air duct. Although the data are not presented here, the HEPA filter exhibited the same general effect.

Change in airflow induced by installing a new filter

While there is a wide variation in airflow at a fixed static pressure drop, the actual change in airflow when exchanging one filter for another in a particular system tends to be less significant.

Figure 5 shows the change in overall system pressure due to a change in filter. As for the airflow, the actual change due to a particular filter other than the "ordinary" filter is quite small. The most restrictive filter resulted in an overall system pressure increase of 17 Pa, or about 13%. The next most restrictive filter resulted in a system pressure change of only 7 Pa or 5%. The bypass TFP filter actually decreased overall system pressure by 7 Pa. The bypass HEPA filter showed similar results to the TFP.

Figure 3:
Airflow versus static pressure drop, eight full-flow filters tested in House #1

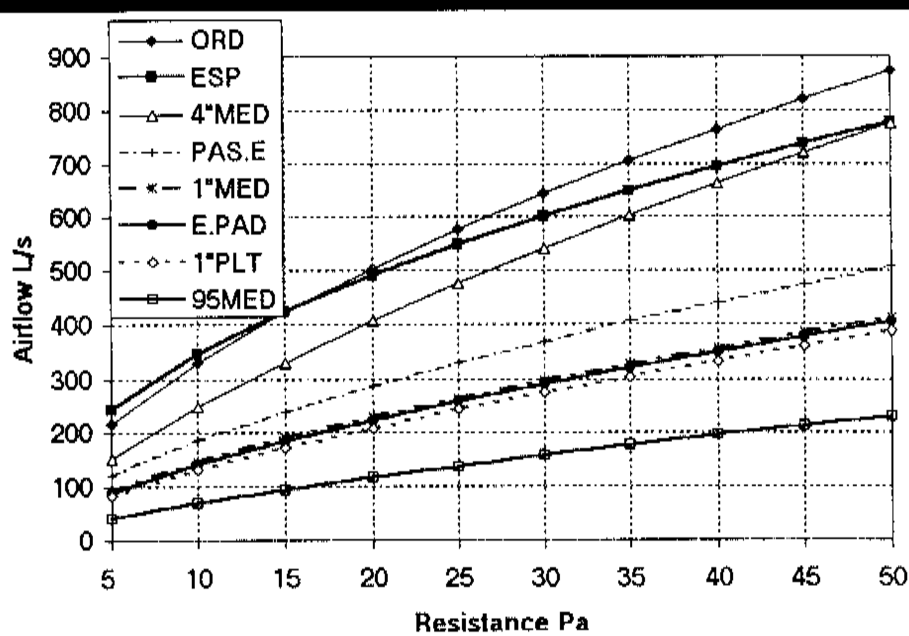


Figure 4:
High-speed airflow, House #1

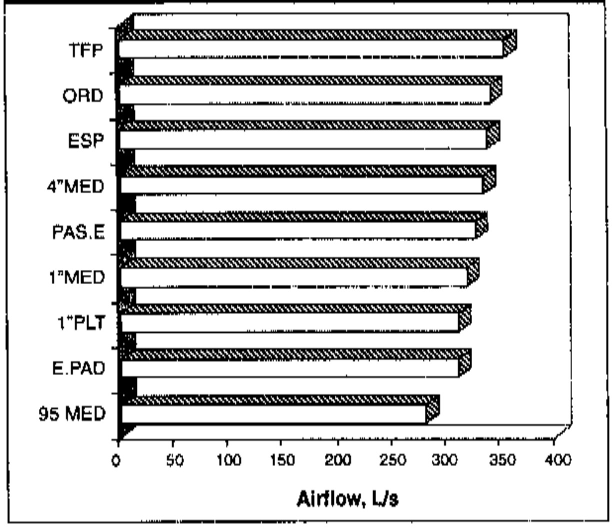
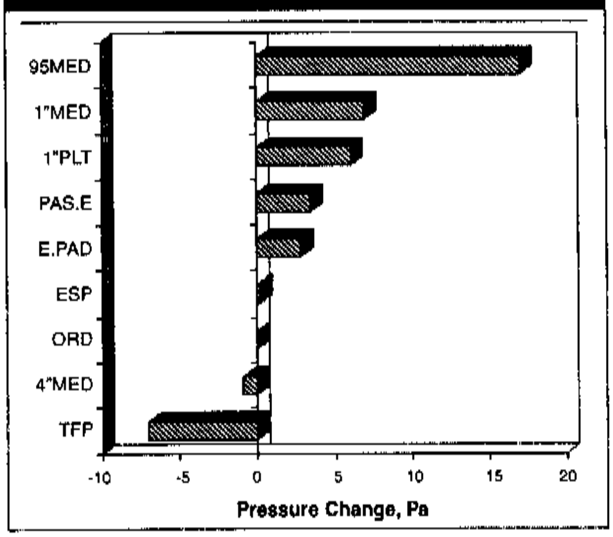


Figure 5:
Change in system external static pressure, House #1



Although not shown here, the results for testing at medium and low speeds for this system were similar. That is to say, the most restrictive filter resulted in airflow reductions of less than 20% when compared to the "ordinary" filter, and the next most restrictive filter resulted in airflow reductions of less than 10%. It should be noted that these results are valid for filters applied at relatively low velocities, that is, approximately 3 m/s (600 fpm) or less.

Discussion

Although it would appear that there is a large variation in resistance to airflow at a fixed static pressure, in fact, there is little significant effect on the air-moving capacity of a normal furnace or air handler for most improved filters when they are clean and properly sized.

The worst filter with respect to airflow is the 95% dust spot media type (95MED). This filter is a commercial filter and not in common use for residential systems. Filters of this type would probably require the intervention of a reasonably knowledgeable air-handling systems mechanic in order to allow proper system functioning and should not be installed by a householder.

The best filters result in virtually no change to airflow at any operating speed. Bypass filters usually result in an overall increase in airflow at all operating speeds.

Intermittent versus Continuous Fan/Blower Operation

Fan operation and clean air delivery

In House #4, the testing program was modified so furnace fan operation varied between auto (intermittent, only on a call for heating) and continuous on alternate days. Two complete data sets were assembled consisting of operation in auto mode versus operation in continuous mode.

Figure 6[18] shows that the average airflow provided by the forced air system in the auto mode for this house is quite small. In fact, the average furnace fan operating time during this mode was 20%, average airflow was 111 L/s and the average $CADR_{AH10}$ was 20L/s. As the system $CADR_{AH}$ depends on airflow, it is proportionally less than it would have been if the furnace fan had provided more airflow.

Figure 7 shows the same house in continuous mode. Airflow and, consequently, CADR rates are substantially increased. Fan operation was 100%, average airflow for the system was 507 L/s and average $CADR_{10}$ was 207 L/s.

Figure 6:
$CADR_{AH10}$ and total airflow L/s intermittent fan operation, House #4

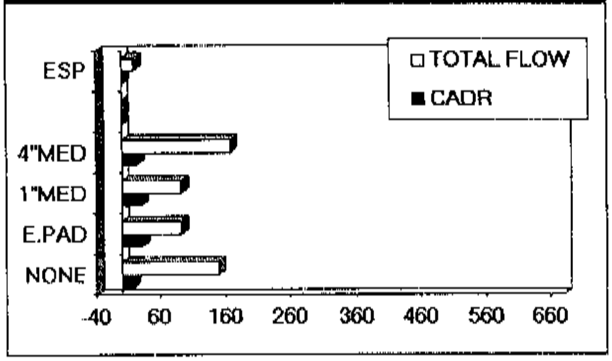


Figure 8:
$CADR_{RMS}$ and total airflow - L/s continuous fan operation: House #4

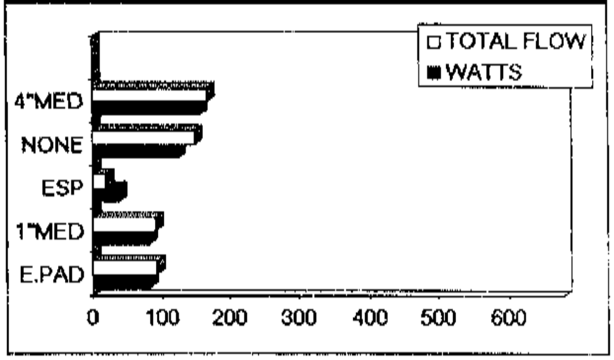


Figure 7:
$CADR_{AH10}$ and total airflow L/s continuous fan operation, House #4

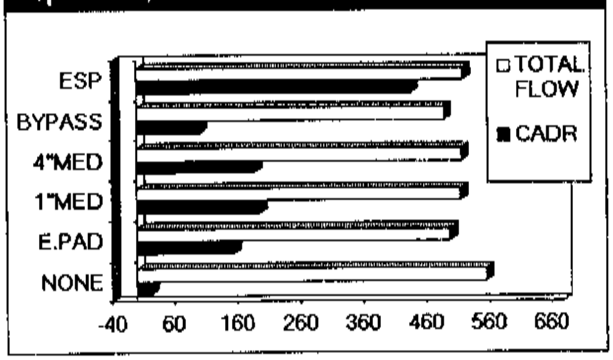
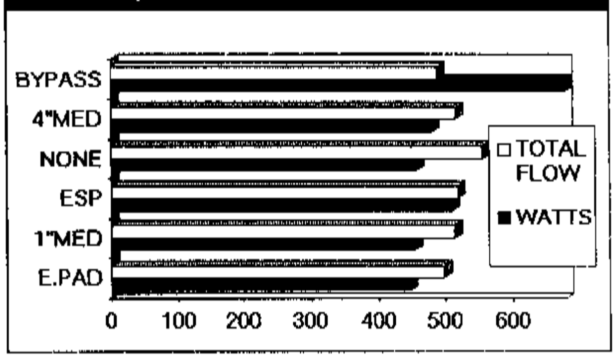


Figure 9:
$Watts_{RMS}$ and total airflow - L/s continuous blower operation: House #4



Fan operation and power consumption
Figure 8 shows the same time period as Figure 6. The power consumption averages 101 watts over this period. Figure 9 shows the same time period as Figure 7. The power consumption increases approximately in proportion with the airflow (average 521 watts). Power consumption for the bypass filter is higher than the full-flow filters due to the added power consumption of the bypass blower motor.

Effectiveness of Reducing Respirable Particles in the Occupied Space

Effect of activity on indoor particle concentrations
Figure 10 shows a typical 24-hour monitoring period in a house. PM10 and PM1 concentrations are shown in a house with the ESP filter in operation. The concentrations are the average of the two interior collection sites, the bedroom and the living room. Note that during activity periods, concentrations go as high as 30 micrograms per cubic metre.

Figure 11 shows the same data period for PM_1 only, with lower amplitude, but a similar pattern. The peaks shown emerge no matter what filter type was in use, and were observed as well with personal monitors. In essence, activity creates a dust cloud that overwhelms background concentrations and will determine the bulk of respiratory exposure. Note that during resting periods (sleeping and absence from the house) the PM_1 concentrations drop to near zero in this house.

Figure 12 shows the same house with no filter in place. The patterns are similar but, during the rest period, baseline concentrations are significantly above zero. It appears that a good filter will significantly reduce the house concentrations during rest periods. However,

Figure 10:
PM_{10} and PM_1 house average, 24 hours, ESP filter, House #3

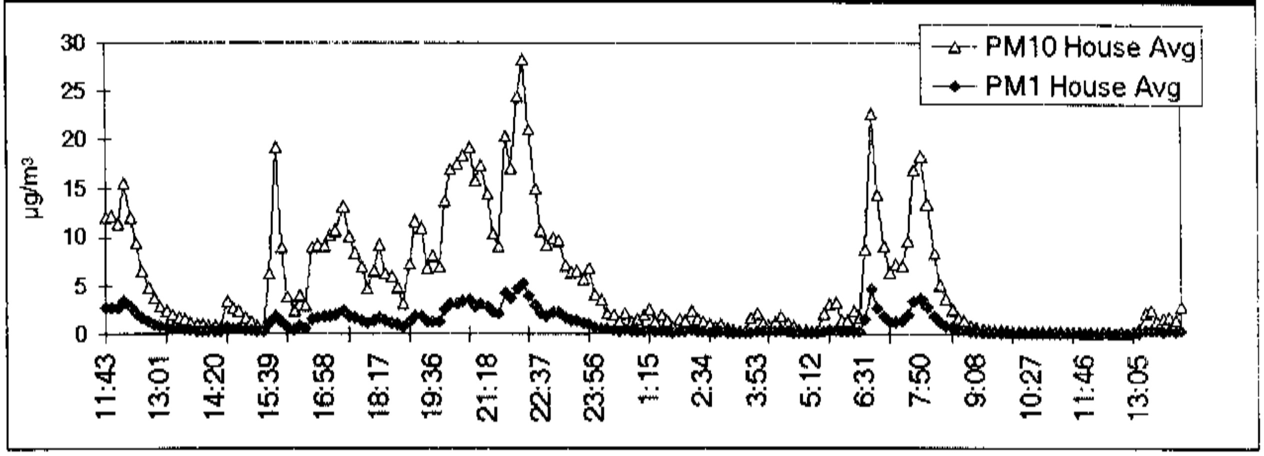


Figure 11:
PM_1, House average, 24 hours, ESP filter, House #3

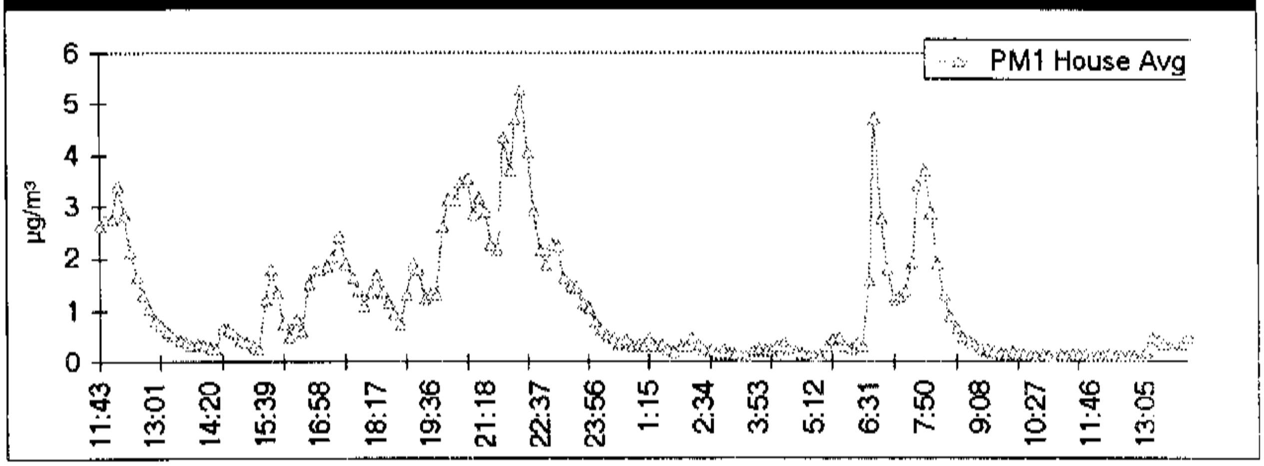


Figure 12:
PM10 and PM1, house average, 24 hours, no filter, House #3

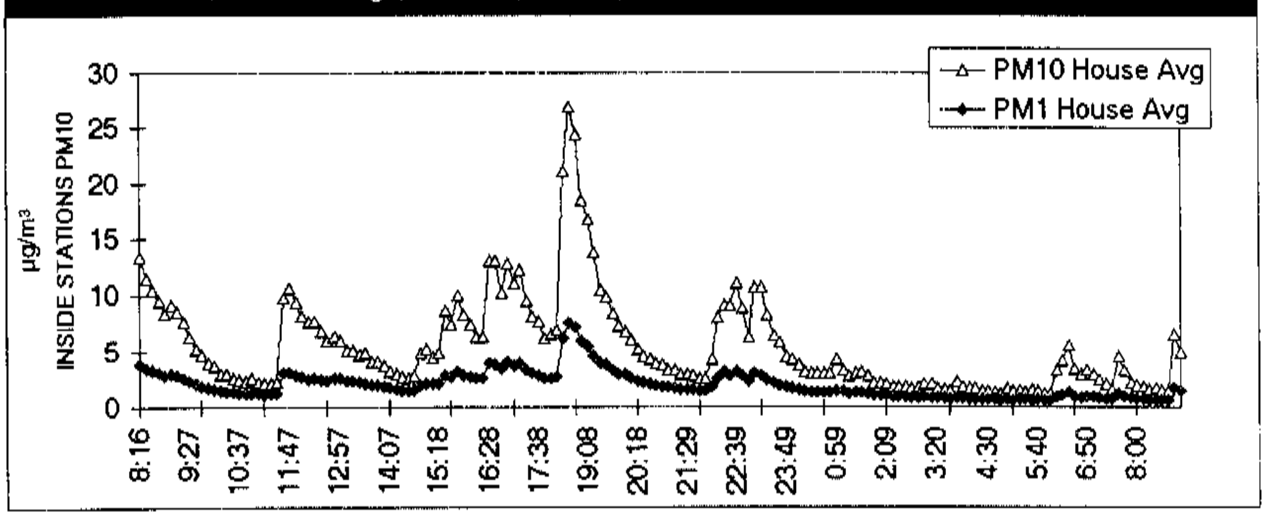


Figure 13:
PM_{10}, house average, PM10 outside, L/s air change, 24 hours no filter, House #3

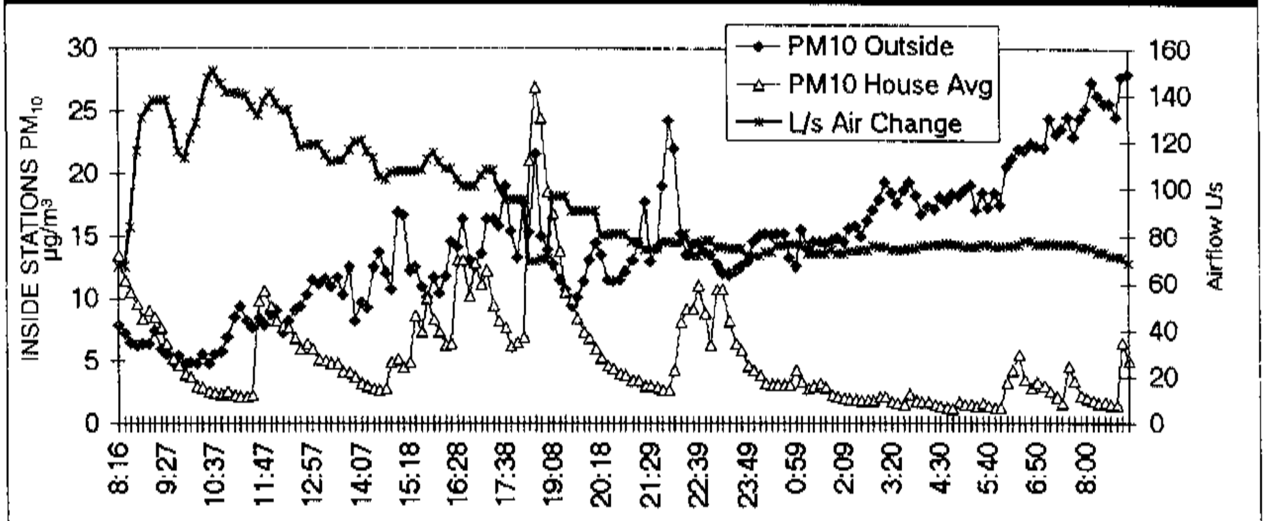
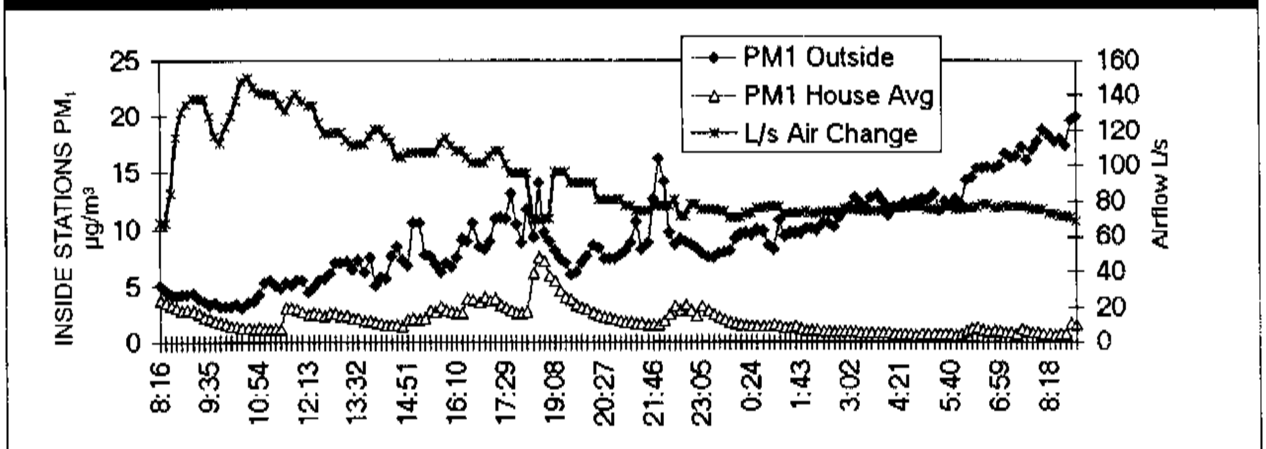


Figure 14:
PM_1 house average, PM_1 outside, L/s air change, 24 hours, no filter, House #3



for most people in most houses, this rest period exposure will be only a small part of the total particulate exposure, dwarfed by particulate exposure during the activity periods.

The effect of outdoor particle concentrations[19]
Figure 13 shows the indoor PM_{10} concentration, outdoor PM_{10} concentration and air change rate over the same 24-hour period as in Figure 12. Indoor PM_{10} concentrations are essentially independent of outdoor levels, which vary from less than 5 µg/m³ to more than 25 µg/m³ over the 24-hour period. In general, outdoor PM_{10} levels are similar to indoor levels during active periods, but higher than indoors during non-active periods. Air change rates may also vary substantially, in this case by approximately +/- 30% from the mean value over the 24-hour period.

Figure 14 shows the indoor PM1 concentration, outdoor PM_1 concentration and air change rate over the same 24-hour period shown in Figure 13. Indoor PM_1 concentrations appear to be independent of outdoor levels, varying from less than 5 µg/m³ to more than 20 µg/m³ over the 24-hour period. In general, outdoor PM_1 levels are higher than indoor levels, even during active periods.

Outdoor particle penetration rate
As part of the dynamic analysis, some investigation of the penetration rate of outdoor particles was undertaken. It was found that the PM_{10} and PM_5 decay constants were not sensitive to penetration rate assumptions varying between 1 and 0, but that PM_1 decay constants were quite susceptible to variations in the penetration rate assumption. Further analysis showed that the best sum of squares results were obtained for penetration rate assumptions 0.5 or less. Refer to Appendix H.6.6 for more information on this subject.

Active versus non-active periods
Figures 15 and 16 show the indoor and outdoor PM_{10} mean levels for active and non-active periods[20] respectively. The outdoor levels are shown to demonstrate that the improvement of certain filters over the no-filter base case may not be attributable entirely to the action of the filter. Substantial day-to-day variations in outdoor particle levels were observed between tests for individual filters, and the length of testing for each filter was too short to remove the potential effect of this variability. Refer to Appendix I.3 for a more detailed discussion of this subject.

Table 5 lists the mean reduction in indoor PM_{10} levels achieved by each filter over the duration of the testing. Absolute reductions versus the no-filter base case are similar whether there is activity in the house or not; however, the percentage of reduction during non-active periods is larger, owing principally to the reduced overall particulate levels during non-active periods.

Figure 15:
Indoor versus outdoor PM_{10}, active data, all houses

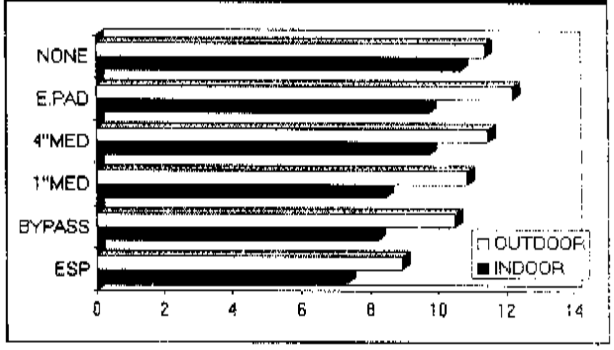


Figure 16:
Indoor versus outdoor PM_{10}, non-active data, houses #1, #2, #3, #4 and #6

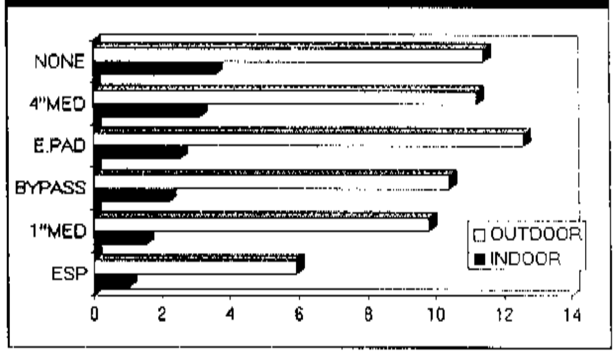


Table 5:
Mean reduction of indoor PM_{10} level below no-filter case

FILTER	Active		Non- Active	
	µg/m³	% Improvement	µg/m³	% Improvement
4"MED	1	9	0.5	13
E.PAS	1	9	1.1	29
BYPASS	2.5	23	1.4	38
1"MED	2.3	21	2	57
ESP	3.4	31	2.6	71

Dynamic analysis

Dynamic analysis was undertaken to identify system effects and effects of particles being carried into the house by air change. Figure 17 shows the $CADR_{AH10}$ for the non-active periods charted against the $CADR_{D10}$ derived from the measurements of indoor particle level, outdoor particle level and air change rate. House #3 is not included due to intermittent fan operation which was significantly variable during the transition periods. House #5 is not included because the $CADR_{AH}$ may be significantly affected by particle entry into the blower cabinet downstream of the filter (see Appendix H.4). Only the continuous fan data are used from House #4.

Overall particle removal

If one assumes that the no-filter case is the base line, then the filters could be expected to provide the incremental CADR, and this would be approximately equal to the $CADR_{AH}$. Figure 18 compares the incremental CADRD10 to the calculated $CADR_{AH10}$ for each filter. Table 6 shows the same information, adding the percentage of each filter's $CADR_{AH10}$ which can be identified as an improvement in $CADR_{D10}$. It appears that $CADR_{AH}$ overestimates the actual effect of a filtering system in some cases and underestimates in others. This disagreement is quite pronounced for some filters but not for others.

Figure 17:
$CADR_{AH10}$ versus $CADR_{D10}$, L/s, non-active data, houses #1, #2, #4c and #6

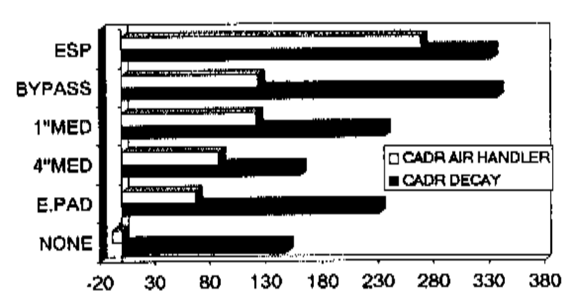


Figure 18:
$CADR_{D10}$ improvement versus $CADR_{AH10}$, L/s non-active data, houses #1, #2, #4c and #6

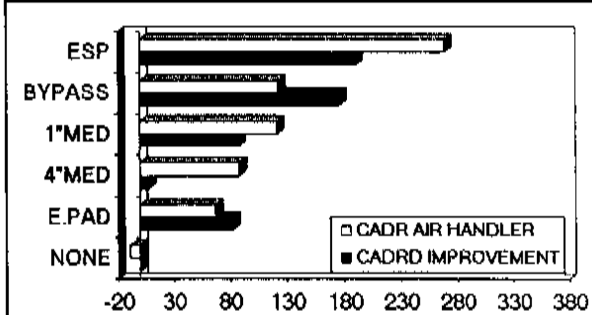


Table 6:
$CADR_{D10}$, $CADR_{AH10}$ and $CADR_{AH10}$ improvement, houses #1, #2, #4c and #6

Filter	$CADR_{D10}$ L/s	$CADR_{AH10}$ L/s	Improvement in $CADR_{D10}$	
			L/s	% of $CADR_{AH10}$
NONE	148	-9	0	0
E.PAD	230	67	82	122
4"MED	160	88	12	14
1"MED	235	122	87	71
BYPASS	338	123	190	154
ESP	332	269	184	68

System effects
The influence of system effects is not clear when it comes to the reasons for the shortfall or lack of shortfall when comparing the $CADR_{AH}$ to the $CADR_D$. For House #5, $CADR_{AH}$ values appeared to be severely influenced by the entry of particles into the blower cabinet downstream of the filter. This effect was sufficiently pronounced to produce a calculated negative $CADRA_H$ during non-active periods. Examination of the $CADR_D$ for this house over that same period showed that particle removal in the living area continued to occur, and appeared to be influenced by the quality of the filter, much in the same manner as the other houses (see Figure 19). While this house was excluded from the analysis due to the pronounced degree of this effect, the other houses with the exception of House #1 exhibited some influence due to this effect. Refer to Appendix H.4 for more information on this topic.

Figure 19:
$CADR_{AH10}$ versus $CADR_{D10}$, non-active data, House #5

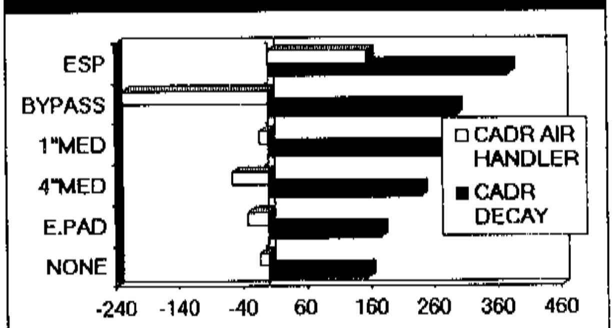
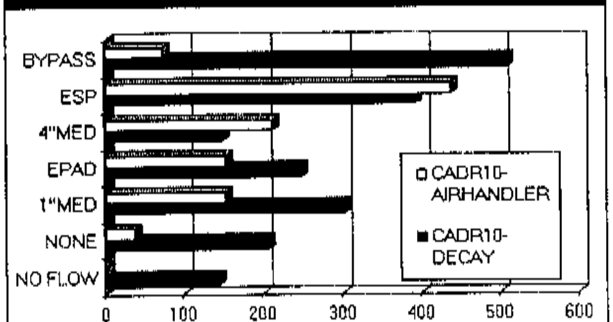


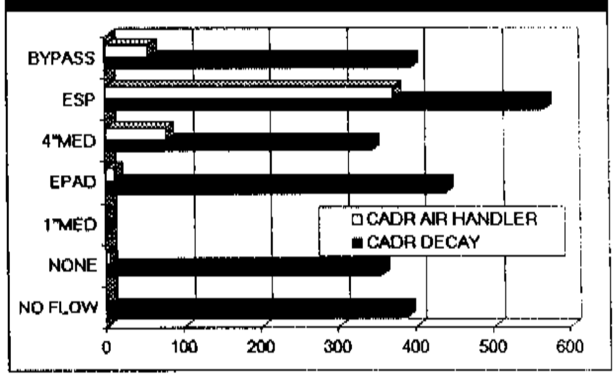
Figure 20:
$CADR_{D10}$ versus $CADR_{AH10}$, non-active data, House #4



At the same time, comparison of the intermittent and continuous fan operating modes in House #4 showed that simply operating the air-handling system may enhance the removal of particles from the living space (see Figure 20).

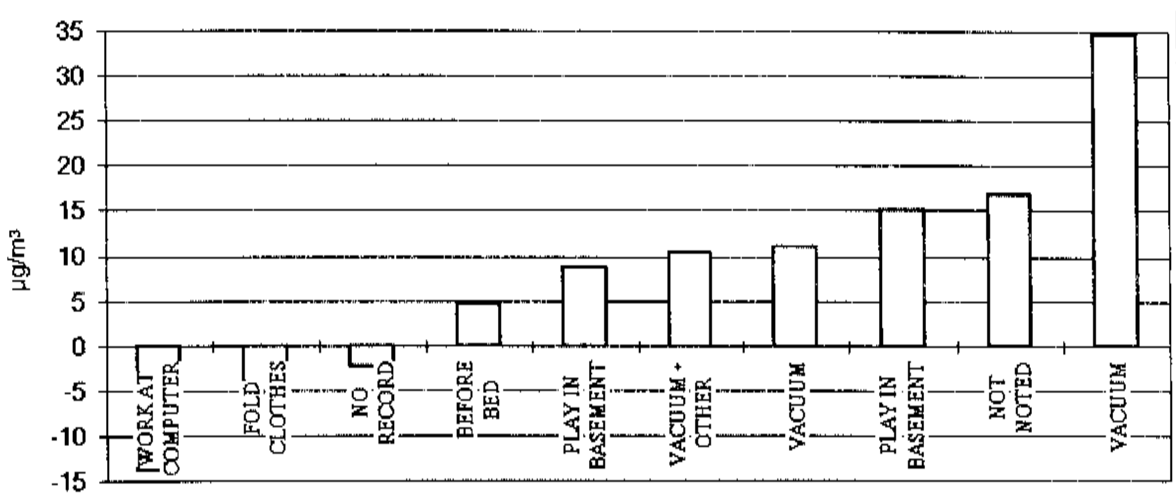
House #3 was not included in the above analysis because the furnace blower was operated in intermittent mode during all the testing. In particular, the furnace blower operation was quite variable during the decay curves which were analyzed to obtain the $CADR_D$ values. Figure 21 shows the analysis for House #3. Due to significant "blower off" times, only the ESP provided significant $CADR_{AH}$ rates. Even so, the 371 L/s $CADR_{AH}$ provided by the ESP appeared to increase the overall CADR by 196 L/s over the apparent house baseline of approximately 370 L/s.

Figure 21:
$CADR_{D10}$ versus $CADR_{AH10}$, transition data, House #3



The complexity of the systemic effects was confirmed by comparing the no-filter $CADR_D$ to the settling rate which would be predicted by Stoke's law. If the floor area of the home is assumed to be the area available for settling, the no-filter settling rate was found to be about twice that predicted by Stoke's law for all the houses. This difference may be due to other collection methods that were not taken into account, that is, Brownian diffusion or electrostatic forces.
The true deposition area, including furniture and vertical surfaces, may be larger than the floor area. Operation of the air handler even without a filter may also enhance the deposition rate over that predicted by Stoke's law. See Appendix H.6.8 for more detailed information on this item.

Figure 22:
Excess of personal over house average, PM_{10} for various activities, House #3



Personal versus In-Room Sampling Results

Figure 22 shows the excess or deficiency of the personal PM_{10} levels compared to the house average PM_{10} level for the index person on House #3. The data are described by principal activity and sorted.

In general, the personal samples show that when activities are sedentary (e.g., reading, working on a computer), the breathing zone levels are not significantly above those obtained with a fixed-location sample. When the wearer is active or engaged in an activity which is likely to result in production of, or re-suspension of, particles the personal samples exceeded the fixed-sample values by large margins.

When the activity was vigorous (e.g., vigorous play), the large particle values rose significantly over the background levels, and the fine particle values did not show significant change. An exception to this is vacuuming which showed an increase of particle levels in all ranges during the activity.

From the results for this study, it can be inferred that where a filter reduces the particulate levels in a space, personal exposure is reduced to the extent that the person is not engaged in vigorous activities which re-suspend local particles or do not generate particles (e.g., cooking).

Electrical Operating Costs

Air movement efficiency

Figure 23 shows the air-moving efficiency of each of the five filter types and the no-filter condition expressed as watts per L/s of airflow. The bypass filter type exhibits a low air-moving efficiency, (1.3 watts per L/s) due to the additional power consumption of the bypass fan and the characteristically high airflow resistance of the bypass filter element. For a system moving 350 L/s, this could represent an annual electrical expense of approximately $92 per year if operated continuously.

The full-flow filters tend to follow the expected pattern, that is, as resistance to airflow is added, power consumption relative to the airflow achieved is increased. The ESP filter also has a small parasitic power consumption of 20 watts associated with the electrical charging circuits. The range is of efficiency for full-flow filters at 0.87 (no filter) and 0.98 watts per L/s (ESP).

Figure 23:
Mean air-moving efficiency, watts per L/s, all data according to filter

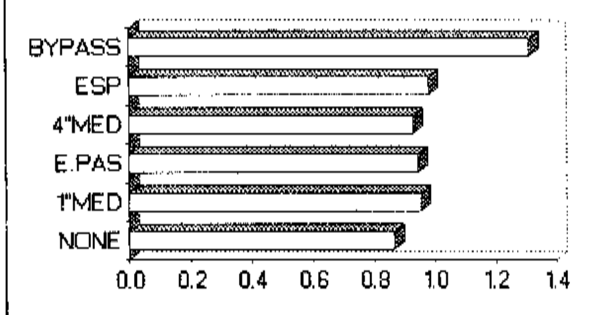
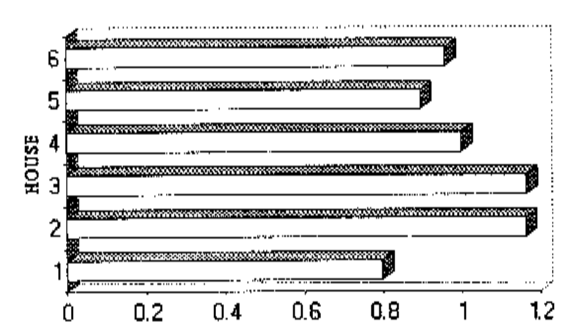


Figure 24 shows the same data organized by house rather than by filter. Efficiency values range from 0.80 watts per L/s to 1.16 watts per L/s. House #1 was equipped with a higher efficiency motor while houses #5 and #6 operated most of the time on a low blower setting.

Figure 24:
Mean air moving efficiency, watts per L/s all data, according to house



Continuous versus intermittent operation
Operation of the furnace fan air handling unit can be a significant electrical load, particularly if the operation is sustained. As discussed above, the benefit of filtration only occurs if the air handler is operating. In an installation where the furnace fan only operates according to the need to heat or cool the building, the additional electrical cost due to the installation of the filter is negligible for a full-flow filter. If the householder makes a decision to operate the furnace fan for longer periods, or continuously, to enhance the effect of the filter, an additional electrical cost will be incurred. If continuous blower operation is selected, the amount of additional run time will vary substantially from house to house.

During the intermittent fan operation monitoring period, the furnace air handler for House #4 operated only 21% of the time, consuming approximately 2.4 kWh per day. If set in the continuous mode, blower energy consumption would have risen to 12 kWh per day. If the electrical energy is valued at $0.05 per kWh,[21] increased fan operation for this house would add $87 over a six-month heating season. If one assumes a similar pattern during the cooling season and that electrical energy consumed during the cooling season has a value of $0.10 per kWh,[22] then the additional cost to operate the furnace blower continuously during the cooling season could be as high as $175.

In the other house (#3) where intermittent fan operation was permitted, the main air handler experienced significant operating times. This house was equipped with a variable output outdoor air heat pump, and the main air handler operated 85% of the time during the data-gathering period, consuming approximately 7.7 kWh per day with the full-flow filters. If the furnace fan had been set on continuous operation, additional consumption of only 1.4 kWh per day would have resulted, representing an incremental cost of only $13 over the course of a six-month heating season. If a similar pattern exists for the cooling season and electrical energy consumed during non-heating periods is valued at $0.10 per kWh, then the additional cost for continuous operation during the non-heating season could be approximately $26.

Two-speed operation
Continuous operation on low speed is often implemented when higher-quality filtration is installed. Although air flows are lower than at high speed, system noise and, in theory, energy consumption are lower. Houses #5 and #6 were operated with continuous low speed, with high speed only on demand for heating. Both houses recorded a high-speed cycle time of only 3% over the data-gathering period. This lower-than-

expected, high-speed operating time seemed to arise from the nature of the fan control on the particular furnaces, which is done by the heat exchanger temperature.[23] Essentially, the fan would only switch from low to high when the discharge air temperature was sufficiently high. Because the low-speed fan was continuously operating, the switch from low to high speed would occur much later in the burner-on cycle than a corresponding switch from off to high speed would on the same control input. In some cases, short-cycle burner operation would occur without inducing a high-speed blower cycle. Detailed examination of fan operation records showed that, for these houses, high-speed blower operation may occur only for a brief period in the morning when the night-setback thermostat called for heating.

Table 7 shows the high-speed versus low-speed power consumption, airflow and airflow efficiency for the systems installed in houses #1,[24] #5 and #6 for the 4"MED full-flow filter. Air moving efficiency improves noticeably on switching to low speed for House # 6, but the improvement for houses #5 and #1 is not so pronounced. Depending on the system set-up however, there can be a 50% or more variation in airflow and absolute power consumption between high and low speed.

It should be noted that the systems for houses #5 and #6 are for belted blowers which are not usually found in new furnaces. The blower motor for House #1 is a pole-shifting PSC direct drive motor which is expected to have a higher low-speed efficiency than a conventional direct drive PSC fan motor. As such, these results may not be representative of the general case when standard, direct-drive, PSC, non-pole-shifting motors are used.

Cost of Clean Air

The economic factors which enter into filter selection include capital, operating and maintenance cost.

An annual operating cost has been derived as follows.

- Capital costs are amortized over 15 years.
- Replacement element costs assume that 25 mm disposable media will be replaced four times per year and 100 mm disposable media will be changed once per year. It is assumed that cleaning activities, such as washing the E.PAD and ESP filters, will be undertaken by the householder at no charge.
- Annual electrical operating costs (energy costs) are considered to be the excess over no-filter power consumption for each filter, as measured in House #1, normalized to a flow of 300 L/s, at an electrical cost of $0.05 per kWh during the heating season and $0.10 during the non-heating season.[25] Continuous furnace fan operation is assumed so this value does not include any cost associated with switching from intermittent to continuous blower operation.

Table 7:
High-speed versus low-speed operation 4"MED filter, houses #1, #5 and #6

House	High			Low		
	Watts	L/s	Watts per L/s	Watts	L/s	Watts per L/s
6	585	650	0.9	323	417	0.77
5	500	525	0.95	210	223	0.94
1	228	318	0.72	106	150	0.7

Table 8:
Capital, maintenance and operating costs of the 10 filters

Code	Amortized 15-year Capital Cost	Annual Maintenance Cost	$CADR_{AH10}$ L/s	Annual Cost of Clean Air (Non-Energy) $ per L/s	Annual Cost of Clean Air (Energy) $ per L/s	Annual Cost of Clean Air $ per L/s
ORD	0	8[2]	-11	N/A	N/A	N/A
1"PLT	0	48[2]	17	2.83	0.53	3.36
1"MED	0	100[2]	97	1.03	0.1	1.13
PAS.E	6.67	0	300	0.23	0.4	0.63
E.PAD	10	33.33[2]	44	0.98	0.27	1.25
4"MED	33.34[6]	60[3]	60	1.55	0.16	1.71
95MED	26.67[1]	200[3]	155	1.46	0.25	1.71
ESP	46.67	20[5]	298	0.22	0.04	0.26
TFP	66.67	36.01[7]	65	1.57	0.72	2.29
HEPA	146.67	93[4]	175	1.37	0.66	2.03

Notes:
1 Installed cost includes cost of custom cabinet/rack.
2 Based on four replacements per year.
3 Based on one replacement per year.
4 Based on $370 element with four-year life.
5 Assumes cleaning by homeowner at no charge.
6 Assumes new installation, cost to replace ESP is $125 list.
7 Based on replacement of two of six elements per year.

Table 8 lists the annual capital, maintenance and operating costs for the 10 filters tested in House #1. Annual costs are summarized as energy and non-energy related. A value called "annual cost of clean air, $ per L/s" is derived by dividing the $CADR_{AH10}$ for each filter into the annual operating cost. This value is similar to the "annual cost per unit of clean air" derived by Offermann et al. (1992). It should be noted that this value includes only the additional energy costs associated with the filter, and not with any additional fan operating times.

When considering overall annual operating costs, the cost for continuous fan operation should be considered if the householder is not already operating it in continuous mode. Consider an existing air-handling system in a hypothetical home which operates at 300 L/s on an intermittent basis. The fan-on fraction on a call for heating or cooling amounts to 25%. Continuous operation of the fan will carry an additional energy purchase price of $133 based on the assumptions set out in Appendix H.10. Use of the 1"MED filter would result in an overall annual operating cost of $243 broken down as follows:

Filter operation, maintenance and energy, 97 L/s CADR x $1.13	$110
Additional energy cost to operate furnace fan continuously	<u>$133</u>
Total	$243

Use of a filter with a higher cost factor and higher clean air delivery rating such as the bypass HEPA would result in an overall annual operating cost of $510, broken down as follows:

Filter operation, maintenance and energy, 175 L/s x $2.03	$355
Additional energy cost to operate furnace fan continuously	<u>$133</u>
Total	$488

Although the HEPA system has a higher overall annual cost, the two systems are not directly comparable as the HEPA filter provides a higher CADR (175 L/s) than the 1"MED (97 L/s).

ESP Ozone Generation, Clean versus Dirty

Figure 25 shows the source strength of ozone generation for each of the filters before and after cleaning. There did not appear to be a specific relationship between the rate of ozone generation and cleaning. For some filters, there was no appreciable change (e.g., House #15). For other filters, there was an increase after cleaning (e.g., House #12) or a decrease (e.g., House#14).

Figure 25:
Ozone source strength (microlitre/sec) ESP before and after cleaning

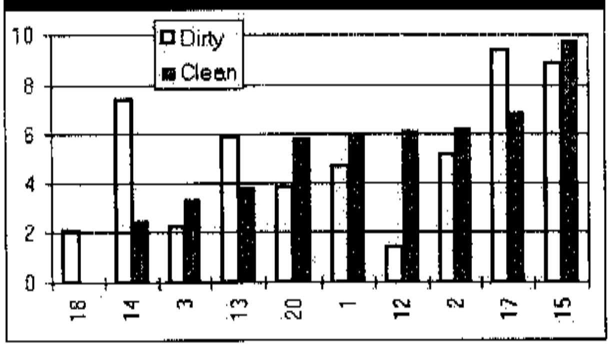


Figure 26:
Change in ozone source strength (microlitre/sec) compared to change in mass on cleaning

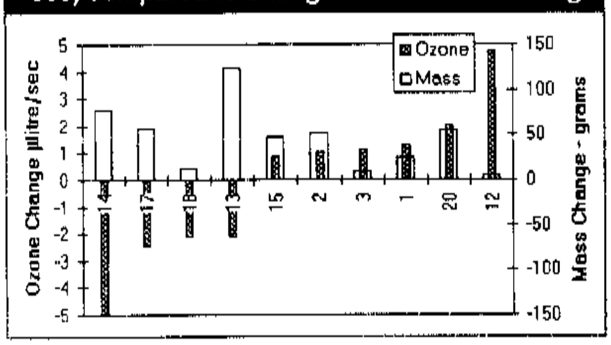


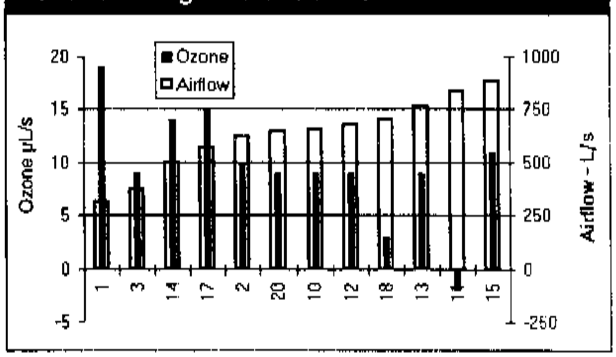
Figure 26 shows the reduction (or increase) of ozone source strength after cleaning compared to the change in cell and screen mass before and after cleaning. In theory, if ozone production is related to the degree of neglect, the air cleaners having the greatest mass change on cleaning should also show the largest change in ozone source strength. There appears to be no specific relationship. Some houses show a substantial decrease in ozone generation with large mass change (e.g., House #14), while others show substantial increases in generation with only slight mass change (e.g., House #12).

ESP Ozone Generation, Variation with Airflow

Figure 27 shows the highest recorded rate of ozone generation for each of the filters tested for which valid data are available. The 12 cases result in an average source strength of 6 µL/s (standard deviation 3). In general, the source strength for the filters is independent of airflow, with some houses recording high source strengths on high airflow (e.g., House #15) and other houses recording low emission rates on high airflow (e.g., houses #18 and #14). Although low- speed airflow was not measured for two-speed systems, the upstream/downstream ozone concentration was measured for those systems equipped for two-speed operation. In general, an increase in the leaving concentration of ozone was recorded when the fan was at low speed.

These observations point to the probability that ozone source strength is not directly related to airflow; rather it is relatively constant, regardless of airflow.

Figure 27:
Ozone strength versus airflow



ESP Ozone Generation, Contribution to House Levels

Figure 28 shows the recorded levels of ozone inside and outside the home at the time of the first visit. The data include cases where the ESP is operating and cases where it is not (malfunction, furnace fan not operating continuously.)

Figure 28:
Ozone level, outside and inside as found before ESP cleaning (ppb)

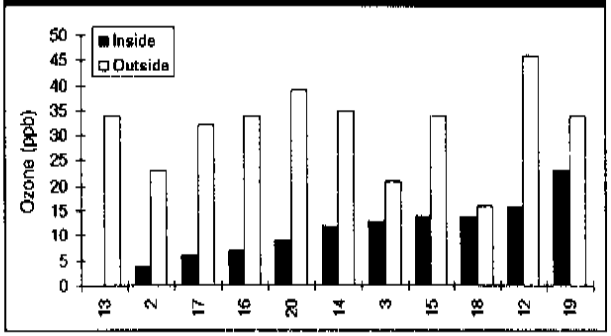
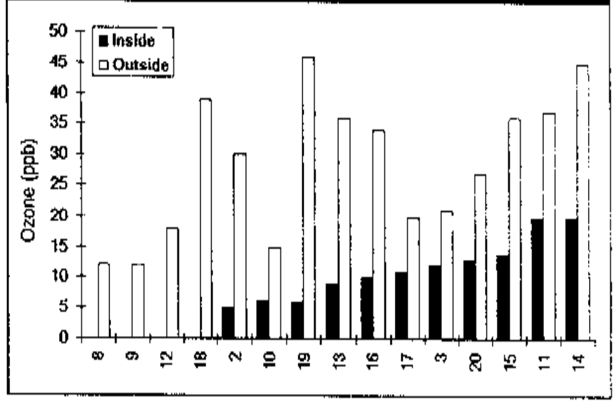


Figure 29 shows the recorded indoor and outdoor levels of ozone at the time of the second visit. At this juncture, the house was operating without the ESP for one or more days, so the ozone level can be taken as a "without ESP" case. The results are very similar to the "as found" case.

Table 9:
Ozone level, outside and inside before and after ESP cleaning (ppb)

	As Found, Before ESP Cleaning		After Cleaning, (ESP not Operating)	
	Indoor Ozone	Outdoor Ozone	Indoor Ozone	Outdoor Ozone
Average	11	32[1]	8	29[1]
Standard deviation	6	9	7	12
Maximum	23	46	20	46
Minimum	0	16	0	12

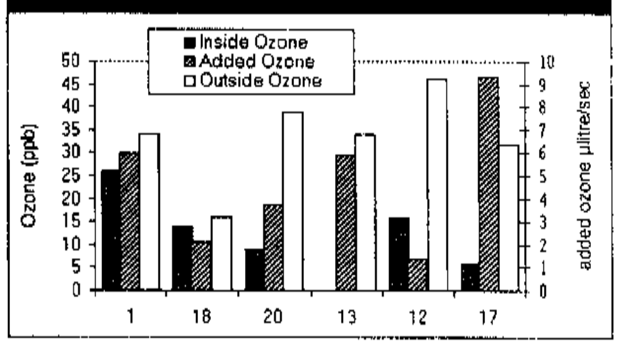
Figure 29:
Ozone levels, outside and inside after cleaning (ESP not operating) (ppb)



In general, the indoor levels are significantly lower than outdoor levels and, in no case, does the indoor level exceed the outdoor level. Of the homes tested, 33% were found to have indoor levels of 15 ppb or higher on at least one of the in-home visits.

To see whether the indoor levels were affected by the operation of the ESP, a group of houses was identified within the data set where it was known that the ESP was in operation for some time on a continuous fan basis before data were collected. Figure 30 shows this group of houses along with ozone source strength. House #1 recorded an unusually high indoor ozone level.[xxvi]

Figure 30:
Indoor ozone levels with house ELA and ozone emission rate



Portable Cleaners

Figure 31 shows the ratio of bedroom particulate levels to house average particulate levels achieved with and without the portable filter in operation. Without the filter, bedroom levels consistently mirror the house average levels. When the filter operates, bedroom levels are consistently reduced to 50% or less of the house average level.

Figure 32 shows the ratio of office particulate levels to house average particulate levels achieved with and without the portable filter in operation. Without the filter, office levels are the same or higher than the house average levels. When the filter operates, office levels are consistently reduced to 75% or less of the house average level.

Figure 31:
Ratio of bedroom PM to house average PM, with and without portable filter in operation

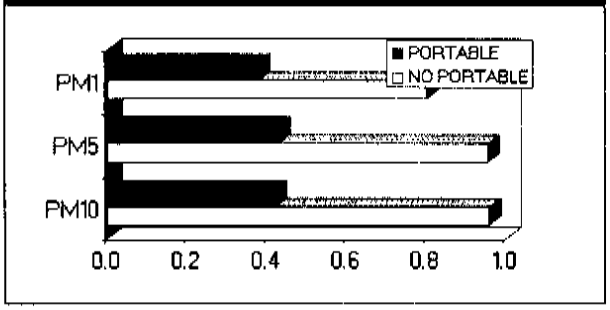
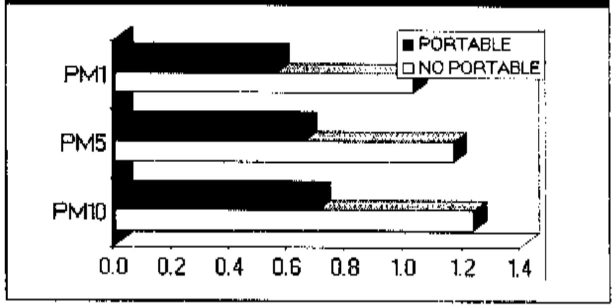


Figure 32:
Ratio of PM office area to PM house average, with and without portable filter operating



4. CONCLUSIONS

Filter Rating Methods

This study found that representative and meaningful rating tests such as the ASHRAE dust spot method exist, but are not often presented to consumers by filter suppliers in a useful manner. With respect to efficiency, an overabundance of potentially confusing terms and references serve to make comparisons between filters difficult or impossible for all but the most expert of consumers. Established, meaningful terms such as "clean air delivery" which would allow comparison between bypass and full-flow filters, for example, tend not to be used by filter suppliers. Central filtration products could benefit by having ratings similar to household exhaust fans, where fans are labelled with simple, uniformly established, independently tested ratings for airflow and noise (HVI, 1998).

Resistance to Airflow

Although this study did not examine the performance of filters over their lifetime, clean filters did not have excessive resistance to airflow.

Exposure to Respirable/Inhalable Particles

Exposure of the house occupants appears to be directly linked to their activities when they are in the home and active. The operation of a central furnace filter appears to have only a moderate effect on the exposure of an individual to respirable particles in the home. While the effect of a central filter is more pronounced when there is no one home, or when the occupants are inactive (sleeping), it is not clear that this has a significant effect on the exposure of the individual occupants to respirable/inhalable particles.

Personal monitoring showed that an individual's exposure to airborne particles was similar to that measured at fixed stations in the house, but that activity played a very strong role in a person's particle exposure.

The effect of a centrally mounted filter does not appear to be directly related to the particle removal rate that would be calculated simply by multiplying the particle removal efficiency by the airflow. Actual particle removal rates varied from 14% to 154% (see Table 6) of the expected particle removal calculated by efficiency times measured airflow.

Assessment of Filter Types

Ordinary furnace filter

- Does not filter respirable/inhalable particles.

25 mm pleated media filter (ordinary type)

- Does not provide good value; $3.36 annual cost per L/s or clean air.

25 mm pleated media high quality

- Provides good value; $1.13 annual cost per L/s of clean air.
- Readily available.
- Does not require special installation, power supply or duct modifications.

25 mm passive electrostatic

- Provides good value; $0.63 annual cost per L/s of clean air.
- Has low overall performance.
- Readily available.
- Does not require special installation, power supply or duct modifications.

Electronic charged pad

- Provides good value; $1.25 annual cost per L/s of clean air.
- Has low overall performance.
- Readily available.
- Does not require special installation, or duct modifications.

- Small power supply may require wiring modification (outlet plug).

100 mm pleated media
- Provides moderate value; $1.71 annual cost per L/s of clean air.
- Moderate overall performance.
- Requires special installation and duct modifications.
- Power supply wiring not required.

95% dust spot pleated media
- Provides moderate value; $1.71 annual cost per L/s of clean air.
- High overall performance.
- Requires special installation and duct modifications.
- Not readily available.
- May restrict airflow if not carefully selected.
- Power supply wiring not required.

Electronic plate and wire type
- Provides good value; $0.26 annual cost per L/s of clean air.
- High overall performance.
- Requires special installation and duct modifications.
- Power supply may require wiring modification (outlet plug).

Turbulent flow precipitator (bypass)
- Provides moderate value $2.29 annual cost per L/s of clean air.
- Moderate overall performance.
- Requires special installation and duct modifications.
- Power supply may require wiring modification (outlet plug).

HEPA (bypass)
- Provides moderate value $2.03 annual cost per L/s of clean air.
- High overall performance.
- Requires special installation and or duct modifications.
- Power supply may require wiring modification (outlet plug).

Electronic Air Cleaners and Ozone Production

Electronic air cleaners (ESPs) were found to produce ozone inside the home when the air-handling system was in operation. No particular relationship between cleanliness and ozone production could be found. As a source strength, the mean value was 6μL/s. It was noted that the source strength was not strongly related to airflow but appeared to be relatively constant.

Measured indoor ozone levels were always lower than outdoor levels. While operation of the ESP adds ozone to the indoor environment, the degree of contribution to indoor levels was not identified.

Filter Operating Costs

Blower operation directly affects the performance of a central filter, in that if the blower does not operate, no filtration occurs. Some data suggest that operation of the blower and central air handler without a filter increases deposition rates over the case when the central airhandler does not operate. Where intermittent blower operation was permitted, "on cycle" fractions varied between 26% and 86%, suggesting that, for some houses, it may be sufficient to permit intermittent fan operation if blower-on cycles are significant. In other situations, it will be necessary to operate the furnace blower continuously to achieve any significant filtration result.

Depending on the baseline fraction of operating time, a change to continuous blower operation to achieve improved filtration could result in an increase of annual energy expenses of up to $250. In addition, costs to own and maintain a filter could range between $7 and $240.

Bypass filters recorded significantly higher electrical energy consumption than full-flow systems. The additional expense for annual operation of a bypass filter could be as high as $120.

Continuous low-speed air handler fan operation appears to be an effective strategy, provided the energy consumption is reduced in appropriate proportions. For the tested systems, low-speed operation appeared to reduce the proportion of high-speed operation that would otherwise have been required for heating purposes.

Portable Air Cleaners

Limited testing of portable air cleaners indicated that, for particulate removal in a single room, they are highly effective.

General

This research showed that upgraded filters installed in a forced-air furnace circulation system reduce the amount of particulate in the duct system, roughly in proportion to their measured effectiveness. The results also show that central filter operation does not result in a corresponding reduction in particulate levels in the inhabited areas of the house. In particular, re-suspension and generation of particulates due to activity appear to be the dominant factor affecting exposure of the individual to particulates inside the home.

The limited amount of testing does not allow conclusions regarding long-term reduction in particulates which might occur in a home if higher effective filters were operated for extended periods. Household particulate and subsequent exposure through re-suspension may also be controlled by approaches such as removing footwear on entry, keeping major dust generators (e.g., smoking) out of the house, vacuuming with an efficient vacuum cleaner and reducing the entry of particulate-laden outdoor air by improving house air tightness and installing an intake filter on the air supply.

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ENDNOTES

[1] One study (McCuaig and Robinson, 1986) found a change in particle removal ability with variation in airstream velocity.

[2] Ozone is a significant respiratory irritant. It is known that plate and wire type electronic air cleaners are capable of generating ozone, particularly if the airflow is too low or if they are incorrectly installed. It is not known however, whether the ozone being created in these situations is significant to the health of the householder.

[3] Particulate matter less than 10 micrometers (lm).

[4] In this study, this form of CADR will be referred to as $CADR_{AH}$ or clean air delivery rate - air handler.

[5] In this study, this form of CADR will be referred to as $CADR_{D}$ or clean air delivery rate - decay.

[6] That is, comparison of the results of the two samplers when testing the same airstream or ambient air location.

[7] See Appendix A for a description of House #1.

[8] House #1 plus five additional houses.

[9] In some cases, sampling immediately downstream of the filter was not practical, so downstream measurements were at the discharge of the furnace or air handler.

[10] Also known as the blower door test.

[11] Transition data refers to the period between when an activity ends and the particle level appears to reach a steady state. Data in these periods are referred to as the decay curve. See Appendix H.6.1 for detailed information on selection of the decay curve.

[12] Penetration rates of 1.0, 0.5 and 0 were applied experimentally to the collected data; it was found that a penetration rate of 0.5 or less was most appropriate. See Appendix H.6.6 for more information on this topic.

[13] A commercially available unit was operated at a low-speed airflow rate with CADR of 59 L/s. The unit is capable of higher airflow rates/CADR values of 118 and 142 L/s at medium and high blower speeds.

[14] Due to the gravimetric calculation method used, the PM_5 values include the weight of PM_1 particles, and PM_{10} values include the weight of PM_5 and PM_1 particles.

[15] The TFP and HEPA filters are bypass types and cannot be evaluated using this method.

[16] The filter size as tested is 400 x 635 mm nominal (16" x 25"). The airflows shown can be converted into velocity values using the factor of L/s * 0.00394 =V m/s, or L/s * 0.76534 = V fpm.

[17] The TFP and HEPA filters are bypass types and cannot be evaluated using this method.

[18] The bypass filter installation required the furnace fan to run continuously so data are not available for this mode.

[19] In general, the outdoor particle concentrations recorded over the course of this study were lower than measured at regional monitoring stations, as well as those recorded in other North American studies of outdoor particulates. Refer to Appendix I, sections I.1 and I.2 for more information.

[20] Active data include all houses. Non-active data do not include House #5 due to possible particle entry at the blower cabinet. See Appendix H.4.

[21] The value of $0.05 per kWh has been selected based on the purchase price of electrical energy and some offset for the value of heating energy provided during the heating season. Refer to Appendix H.10 for a more detailed discussion.

[22] The value of $0.10 per kWh has been selected based on the purchase price of electricity and the non-desirability of incurring additional electrical internal loads during the cooling season. Refer to Appendix H.10 for more detailed discussion.

[23] More modern furnaces which may use control algorithms to control the blower speed directly with a call for heating may not experience the same operating characteristics.

[24] House #1 was operated continuously at a medium blower speed during the filter efficiency tests, but single-point data are available at low blower speed for individual filters.

[25] Refer to Appendix H.10 for a discussion of electrical energy rate selection.

[26] The central exhaust fan ventilation system for the house was turned off.

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