RESEARCH REPORT

Penetration of Outdoor Particles into a Residence

Canada

CMHC SCHL
HOME TO CANADIANS

CMHC—HOME TO CANADIANS

Canada Mortgage and Housing Corporation (CMHC) has been Canada's national housing agency for more than 60 years.

Together with other housing stakeholders, we help ensure that Canada maintains one of the best housing systems in the world. We are committed to helping Canadians access a wide choice of quality, affordable homes, while making vibrant, healthy communities and cities a reality across the country.

For more information, visit our website at **www.cmhc.ca**

You can also reach us by phone at 1-800-668-2642
or by fax at 1-800-245-9274.

Outside Canada call 613-748-2003 or fax to 613-748-2016.

Canada Mortgage and Housing Corporation supports the Government of Canada policy on access to information for people with disabilities. If you wish to obtain this publication in alternative formats, call 1-800-668-2642.

Penetration of Outdoor Particles into a Residence

Prepared for:

Research Division
Canada Mortgage and Housing Corporation
700 Montreal Road
Ottawa, Ontario
K1A 0P7

CMHC Project Manager: Don Fugler

Prepared By:

Bowser Technical Inc
222 Memorial Drive
Brantford, Ontario
N3R 5T1

Principal Investigator: Dara Bowser

March 2003

This study was conducted for Canada Mortgage and Housing Corporation (CMHC) under Part IX of the National Housing Act. The analysis, interpretations and recommendations are those of the Consultant and do not necessarily reflect the views of CMHC.

Acknowledgments

The authors would like to thank the following individuals and organizations who contributed to the quality of this project:

Charmaine Roye . . . . Homeowner

The Project Team . . . . Dara Bowser
Will Kwan

EXECUTIVE SUMMARY

Outdoor fine particles (respirable & inhalable) are a significant factor which negatively affect public health. Outdoor exposures to these particles may be estimated by using the time spent outdoors (10% for most North Americans) together with measurements of the outdoor levels of these particles. Indoor exposure estimates usually rely on fixed ratios of indoor to outdoor levels of these particles.

The objectives of this study are to determine how ventilation and operational configurations can affect the indoor-outdoor relationship of fine particle concentrations in a home and to determine the filtration effect of the house envelope for incoming ventilation or infiltrating air.

The study is limited to one, southern Ontario Canadian home with moderate airtightness. The house was operated with normal occupancy of 2 adults and with 5 distinct ventilation modes as follows:

1) Supply Only, No Filtration
2) Exhaust Only, No Filtration
3) Balanced, No Filtration
4) Balanced, with HEPA Intake Filter
5) Supply Only, with HEPA Intake Filter

Ventilation rates ranged between 1.20 and 0.71 ACPH and were selected to ensure that in the Supply Only arrangements, all of the incoming air passed though the ventilation system and in the case of the Exhaust Only arrangement all of the incoming air passed though the building envelope. Continuous real-time measurement of indoor and outdoor particulate levels were made in 5 locations. Air temperature, air pressure, windspeed and ventilation flows were also measured continuously. A total of 428 data-hours were used for data-analysis.

The non-filtered ventilation arrangements resulted in higher indoor-outdoor ratios in both the PM1 (Particulate Matter less than 1μm) and PM10 (Particulate Matter less than 10μm) size ranges. Filtered ventilation arrangements resulted in significantly lower indoor-outdoor ratios. Exhaust only ventilation arrangements (incoming air filtered by the house envelope) resulted in ratios in the mid-range between the filtered and un-filtered ventilation cases.

Comparison of the data with a mass-balance model showed that, for a fixed rate of indoor particle generation/resuspension, there was poor correlation of measured and predicted particle levels for the filtered ventilation modes, but good correlation for the unfiltered ventilation modes. This probably occurs because the indoor particles in the filtered ventilation modes are dominated by indoor generation/re-suspension which is in fact quite variable. In the unfiltered cases however, the improved correlation of measured with predicted levels demonstrates that indoor levels are primarily a function of outdoor levels.

Further analysis of the data using the mass-balance model predicted filtration factors (removal rate of incoming particles) for the building envelope of 0.43 and 0.37 for the PM1 and PM10 size ranges respectively.

In general, it was found that there are substantial benefits to filtering the incoming ventilation air. The benefits of filtering appear to be only slightly reduced for balanced ventilation systems when compared to supply-only ventilation systems. Ventilation air which enters via the building envelope appears to experience a significant degree of filtration.

RÉSUMÉ

PÉNÉTRATION DE PARTICULES EXTÉRIEURES DANS LA MAISON

Les objectifs de la recherche consistaient à déterminer comment la ventilation et le fonctionnement risquent d'influer sur le rapport intérieurs-extérieurs des concentrations de particules fines dans la maison et de déterminer l'effet de filtration que procure l'enveloppe de la maison quant à l'admission d'air de ventilation ou l'infiltration d'air.

L'étude a été limitée à une maison située dans le sud de l'Ontario, modérément étanche à l'air. La maison était occupée par 2 adultés et 5 modes de ventilation distincts ont été utilisés comme suit :

1) Alimentation seulement, sans filtration
2) Extraction seulement, sans filtration
3) Ventilation équilibrée, sans filtration
4) Ventilation équilibrée, avec filtre de prise d'air HEPA
5) Alimentation seulement, avec filtre de prise d'air HEPA

Les taux de ventilation variaient entre 1,20 et 0,71 renouvellement d'air à l'heure et ont été choisis pour qu'en mode alimentation seulement, toute la quantité d'air admise traverse l'installation de ventilation et, qu'en mode extraction seulement, toute la quantité d'air admise traverse l'enveloppe du bâtiment. La mesure continue en temps réel des niveaux de particules intérieures et extérieures a été effectuée à 5 endroits. La température de l'air, la pression de l'air, la vitesse du vent et les débits de ventilation ont également été mesurés continuellement. En tout, 428 heures de données ont été analysées.

Les modes de ventilation sans filtration ont entraîné des ratios intérieurs-extérieurs élevés aussi bien pour la MP1 (matière particulaire inférieure à 1 fm) que pour la matière MP10 (matière particulaire inférieure à 10 fm). Les modes de ventilation avec filtration ont entraîné des ratios intérieurs-extérieurs beaucoup plus faibles. Les modes de ventilation par extraction seulement (air admis filtré par l'enveloppe de la maison) a donné lieu à des ratios se situant au milieu de la gamme entre les cas de ventilation avec filtration et sans filtration.

La comparaison des données au moyen d'un modèle de bilan massique indique que, pour un taux fixe de génération ou de remise en recirculation de particules intérieures, il y avait une corrélation médiocre des niveaux de particules mesurées et prévues pour les modes de ventilation avec filtration, mais une bonne corrélation pour les modes de ventilation sans filtration. Cette situation s'explique probablement par le fait que les particules intérieures soumises aux modes de ventilation avec filtration sont dominées par la production ou remise en circulation de particules intérieures, qui, en fait, varie assez. Dans les modes de ventilation sans filtration, la meilleure corrélation des niveaux mesurés et prévus démontre cependant que les niveaux intérieurs sont surtout fonction des niveaux extérieurs.

Une analyse plus poussée des données à l'aide du modèle de bilan massique a permis de prédire des facteurs de filtration (taux d'enlèvement des particules dans l'air admis) de l'enveloppe du bâtiment de 0,43 pour la MP1 et de 0,37 pour la MP10.

En général, on a découvert que la filtration de l'air de ventilation admis apporte des avantages appréciables. En effet, les avantages de filtrer l'air semblent être seulement réduit légèrement pour les installations de ventilation équilibrée comparativement aux installations de ventilation avec alimentation seulement. L'air de ventilation qui s'infiltre par l'enveloppe du bâtiment semble subir une filtration appréciable.

CMHC SCHL

National Office
700 Montreal Road
Ottawa ON K1A 0P7
Telephone: (613) 748-2000

Bureau national
700 chemin de Montréal
Ottawa ON K1A 0P7
Téléphone : (613) 748-2000

Puisqu'on prévoit une demande restreinte pour ce document de recherche, seul le résumé a été traduit.

La SCHL fera traduire le document si la demande le justifie.

Pour nous aider à déterminer si la demande justifie que ce rapport soit traduit en français, veuillez remplir la partie ci-dessous et la retourner à l'adresse suivante :

Centre canadien de documentation sur l'habitation
Société canadienne d'hypothèques et de logement
700, chemin Montréal, bureau C1-200
Ottawa (Ontario)
K1A 0P7

Titre du rapport: ______________________________

____

Je préférerais que ce rapport soit disponible en français.

NOM ______________________________

ADRESSE______________________________
rue App.

____
ville province Code postal

No de téléphone ( ) ____________

CONTENTS

1 OVERVIEW, DISCUSSION OF OBJECTIVES . . . . . -1-
- 1.1 Introduction . . . . . -1-
- 1.2 Objectives . . . . . -1-
- 1.3 Limitations . . . . . -1-
- 1.4 Outdoor Particle Penetration into Homes . . . . . -2-
- 1.5 Influences on Indoor Fine Particle Levels . . . . . -2-

2 DISCUSSION OF METHODS . . . . . -4-
- 2.1 Description of Experiment . . . . . -4-
- 2.2 Sampling . . . . . -5-
- 2.3 Data Organization . . . . . -5-

3 DISCUSSION/RESULTS . . . . . -7-
- 3.1 Indoor Particulate Levels . . . . . -7-
- 3.2 Filtration of Incoming Outdoor Air by The Building Envelope . . . . . -10-

4 CONCLUSIONS . . . . . -13-
- 4.1 Direct Entry of Unfiltered Air . . . . . -13-
- 4.2 Exhaust Only Ventilation Systems . . . . . -13-
- 4.3 Supply Ventilation with Filtration . . . . . -13-
- 4.4 Balanced Ventilation with Filtration . . . . . -13-

REFERENCES . . . . . -14-

1 OVERVIEW, DISCUSSION OF OBJECTIVES

1.1 Introduction

Outdoor fine particles (respirable & inhalable) are a significant factor which negatively affect public health. Outdoor exposures to these particles may be estimated by using the time spent outdoors (10% for most North Americans) together with measurements of the levels of these particles at outdoor atmospheric sampling stations.

Given that the portion of time spent indoors is 90% of most individuals, indoor exposures to fine particles may be more important from a total dose point of view than outdoor exposures. Estimation of indoor exposure relies on the extrapolation of outdoor particle concentration data by using relatively uncertain estimates of the penetration rate of these particles into the home.

Currently, these penetration rates are based on data collected from indoor-outdoor sampling studies without detailed examination of the factors which affect the observed relationships. Consequently there is little or no information on how specific modes of house operation or ventilation system configuration affect penetration rates.

1.2 Objectives

a) To determine how ventilation operational and filtration arrangements affect the indoor/outdoor ratio of fine particles in a house, and

b) to determine the filtration effect of the house envelope for incoming ventilation or infiltrating air.

1.3 Limitations

All of the experiments are based on one home in Brantford Ontario Canada. From a regional outdoor air pollution perspective, the location is considered to be in the "Great Lakes Basin" area.

The test conditions replicate typical southern Ontario Canadian spring and summer conditions.

This study applies only to homes with continuously operating air handling and ventilation systems operated with all of doors and windows closed. Operation of the home in this manner is a discretionary decision of the house occupant, however it is often recommended by public health officials for persons who have respiratory challenges arising from outdoor air sources. Continuous operation of the ventilation system in particular is increasing in popularity due to increased airtightness in the housing stock and awareness of indoor air quality concerns.

In the context of Canadian housing stock, the range of air-change rates used in this study (1.20 to 0.71 ACPH[1]) is significantly higher than would be expected during normal operating conditions, and were chosen to maintain the integrity of the experiments based on the airtightness of the house. The experimental results may be extrapolated to houses with lower ventilation rates.

---

1 Air Changes Per Hour

1.4 Outdoor Particle Penetration into Homes

Outdoor particles usually penetrate by one of two paths:

1) Via the building envelope, or
2) Via an intentional air inlet.

Particles penetrating the building envelope are carried by infiltrating airstreams that may pass through both above and below-grade building assemblies. The paths range from the relatively large and direct (an air leak beside building service penetration), to the lengthy and convoluted (via the wall assembly, through batt insualtion). The aerodynamic pressure causing the air movement may be due to naturally occurring forces such as wind and indoor-outdoor temperature difference, or they may be caused by the operation of mechanical equipment within the home. Some of the mechanical equipment serves primarily a ventilation function (e.g. outdoor air supply connection to a central air handler, or an exhaust only ventilation system), while other devices may not be closely associated with the ventilation system (e.g. clothes dryer).

Independent air inlets may be non-powered (e.g. a passive combustion air inlet which is a duct through the wall) or may be part of an independent mechanical ventilation system. In Canada, independent ventilation systems are normally based on a central Heat Recovery Ventilator (HRV). HRV's are normally equipped with filters which are capable of removing large particles which would block the heat exchange passages, but these filters are not usually effective for removing fine particles from the airstream. Fine particle filtration is often available as an optional feature or as a add-on accessory.

Inlets associated with a central forced air heating systems may be non-powered, that is to say they are connected to the suction side of the main recirculation air-handler and the rate of airflow is directly influenced by the suction pressure of the air handler. A second type consists of an HRV which has it's outdoor air supply connected to the return air duct of the central forced air system. The flow rate of the HRV is controlled by the internal fans and controls of the HRV. In both of these systems, the incoming outdoor air is passed through the central forced air system's main filter before being delivered into the occupied spaces of the home. The filter in the central forced air system may have fine particle removal capabilities ranging from 0 to over 90%.

1.5 Influences on Indoor Fine Particle Levels

The level of indoor fine particles at any given moment in time is influenced by:

1.5.1 **Internal Generation**

Internal generation arises primarily from cooking and combustion (candle burning, smoking) activities. Particles arise from human & pet dander are also generated. Cat dander has been noted to have both high generation rates and slow settling times. Generation usually occurs when the house is occupied and the occupants are active.

1.5.2 **Resuspension**

Resuspension arises from the movement of the occupants in the home during periods of activity. The re-suspended particles are those which are stored on surfaces and materials, are easily re-suspended and which have low settling rates. These particles may include the afore-mentioned internally generated particles , particles of outdoor origin which have entered by being tracked in by the occupants, or particles which enter as part of an infiltration or ventilation airstream. It is theorized that if particle entry and generation can be minimized then resuspension will also be reduced over time, due to the removal of particles from the house by cleaning activities.

1.5.3 **Entry via House Envelope**

Airstreams entering the occupied zone via the house envelope may contain more or less fine particles depending on the level of outdoor fine particles and the removal of particles by the building components as the air passes though them.. Some authors (refs 8 and 9) have estimated the filtration effect to be negligible, while others (ref 7) have estimated the filtration rate to vary between 6 and 88%, depending on particle size. Outdoor particle levels may vary by a factor of 10 or more from day to day and from hour to hour.

1.5.4 **Entry Via Intentional Inlet**

An airstream entering the house from outside via an intentional inlet will contribute particles to the occupied space depending on the concentration of particles in the outdoor air and the efficiency of the filter placed in the airstream. Filters are available with fine particle removal efficiencies between 0 and 99.5%.

1.5.5 **Removal by Settling**

Particles are removed by settlement on the available surfaces in the house. The rate of removal depends on the available surfaces and the settling rate of the individual particles. The operation of an air-handling system will influence particle settling by increasing turbulent surface effect settlement.

1.5.6 **Removal by Filtration**

A central air handling system equipped with a fine-particle air filter, or a local (in-room) fine particle air-filter may be used to remove particles.

1.5.7 **Removal by Exhaust/exfiltration**

Particles are also removed from a space by air which leaves from the space by exfiltration through the building envelope or via an intentional device such as an exhaust fan. It should be understood that this only results in a net reduction of indoor particles when the air replacing the removed air contains less particles. In many cases the outdoor level of fine particles is higher than the indoor level so that the exchange of air may actually increase the indoor particle level.

2 DISCUSSION OF METHODS

2.1 Description of Experiment

A controlled outdoor air inlet was added to the Bowser Technical Inc filter test facility (see appendix B.1). The air inlet was connected directly to the central, recirculation air handler.

The laboratory and instrument room was located in the furnace/utility/laundry/mechanical room of a 2-level (basement and upper floor) home located in Branford, Ontario, Canada. The upper floor of the house contains the normal sleeping, living and food preparation rooms and the lower lever contains the furnace/utility/laundry/mechanical room and a home office. The home was normally occupied by one person during the day (mostly in the basement) and 2 persons (mostly on the upper floor) during the evening and overnight. Additional details concerning the home are given in appendix A.

The system was arranged to operate in 5 distinct modes as follows:

Table 1

Set-Up	Air Change Rate (Air Changes per Hour)	Indoor-Outdoor Pressure
Supply Only with No Filtration (Supply No Filter)	1.07 ACPH	+4.9 pa
Exhaust Only with No Filtration (Exhaust No Filter)	0.72 ACPH	-2.2 Pa
Balanced with No Filtration (Balanced No Filter)	0.77 ACPH	-0.2 Pa
Balanced with HEPA Intake Filter (Balanced HEPA)	0.71 ACPH	+0.2 Pa
Supply Only with HEPA Filter (Supply HEPA)	1.20 ACPH	+5.3 Pa

A total of 543 hours of data were obtained with the data-hours ranging from between 53 to over 160 hours per arrangement. Sampling occurred at all times of the day and night, and where possible, an effort was made to obtain both daytime, night-time, active and non-active data for each particular experiment.

With respect to the ventilation rates, the weather variables were measured continuously during the experimental period and a natural infiltration value was predicted using the AIM2 model (see appendix D.2). the combined effect of natural and exhaust ventilation was predicted using a modification of the Keil-Wilson [Ref 6] relationship. (See appendix D.2) The predictive model was verified using $C0_2$ decay experiments for each of the experimental conditions. (See appendix D.2)

All experiments occurred between April and September 2001. The central air handling system was operated continuously during all of the experiments, with the main filter removed. All of the central system ductwork is located within the building envelope. All of the windows were kept closed during the experiments.

The house is considered to be moderately air-tight by Canadian standards, having an ELA_{10}[2] of 733 cm^2 and ACPH@50[3] of 5.33.

[2] Equivalent Leakage Area at 10 pa according to the CGSB 149.1 Test Procedure (Ref 2)

[3] Air Changes Per Hour at 50 pa according to the CGSB 149.1 Test Procedure (Ref 2)

2.2 Sampling

Fine particulate samples were obtained using the Bowser Technical Inc real-time air sampling rig (see appendix C.1) arranged so that samples were obtained from the following stations:

1) Outside
2) Air Intake from Outside
3) Office Area (Basement)
4) Central Air Handling System (Mixed Return & Outside Air)
5) Bedroom (Upstairs)

The outside sampling point was located under an over-hanging roof area (covered patio) approximately 2.5 metres from the house and 1 metre from the roof edge. Height above grade was 3 metres.

The office sampling point was located in a "Home Office" area in the basement of the house. There is one computer, a laser printer and a computer monitor in continuous operation within 1.5 metre radius of the pick-up location. The height above floor level is 1.6 metres. Occupancy of the office area was variable during the testing periods.

The bedroom sampling point is located at 2 metres above the floor, and approximately 4 metres from the supply air inlet to the room and 1.5 metres from a supply air inlet located in an adjacent bathroom. There is no return air inlet in the room. The bedroom was normally occupied by two persons from midnight until 7:00 a.m. and not during the daytime hours.

Sampling interval for particle measurements was 1.50 minutes with a 0.25 minute hold period between samples so that the time for a each complete set of 5 samples was 8.75 minutes.

In addition to the above, airflows were measured at the following locations:
1) Main re-circulation air handling system
2) Central exhaust flow.
3) Central intake flow
4) Dryer exhaust flow

Carbon dioxide level was measured:
1) Outdoors
2) At the air handling system main return, prior to mixing

Air pressure was measured from the lower to level of the house to a point 2 metres above grade approximately 12 metres away from the house in a open area. The outdoor pressure station was equipped with an apparatus to minimize the effect of the wind on the pressure reading.

Airflow, air pressure and CO_2 measurements were recorded continuously at 20 second intervals during all experiments.

2.3 Data Organization

Where a "House average" value is used, it has been calculated using the average of the office and bedroom values.

Interior particulate levels are reported as absolute values of PM1 (particulate matter less than 1 micron) and PM10 (particle matter less than 10 microns). Indoor/outdoor ratios are also reported. An indoor/outdoor ratio of 0.5 would indicate for example, that the inside measurements were 50% of the outdoor levels. A ratio of 1.5 would indicate that indoor levels were 150% of outdoors

The outside average particulate level varied significantly between individual experiments. For example, when all data was assembled the range of outdoor PM10 was from 37.4 (+/- 34.7) μg/m^3 to 4.4 (+/-2.6) μg/m^3. In order to reduce the effect of this variability on the results, individual daily-groups with average PM10 levels of greater than 60 μg/m^3.were removed from the total data set. This reduced the variability between individual data-sets to outdoor PM10 values of between 10.2 (+/-9.5) μg/m^3 and 4.4 (+/-2.6) μg/m3. Total data-hours were reduced to 428 with individual arrangements ranging between 117 and 53 hours.

3 DISCUSSION/RESULTS

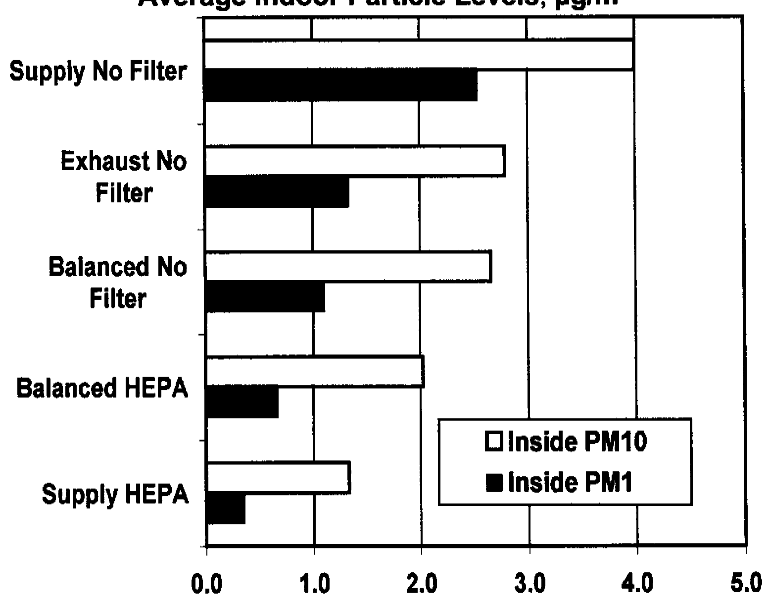
3.1 Indoor Particulate Levels

Table 2

Set-Up	Indoor Particle Level PM1 (Average)	Indoor Particle Level PM10 (Average)
Supply Only with No Filtration (Supply No Filter)	2.5 μg/m³	4.0 μg/m³
Exhaust Only with No Filtration (Exhaust No Filter)	1.3 μg/m³	2.8 μg/m³
Balanced with No Filtration (Balanced No Filter)	1.1 μg/m³	2.7 μg/m³
Balanced with HEPA Intake Filter (Balanced HEPA)	0.7 μg/m³	2.0 μg/m³
Supply Only with HEPA Filter (Supply HEPA)	0.4 μg/m³	1.3 μg/m³

Indoor particulate levels (see Table 2 and Figure 1) were substantially higher for the Supply No Filter condition than all of the other arrangements. This was true for both PM1 and PM10 size ranges.

Figure 1
Average Indoor Particle Levels, μg/m³

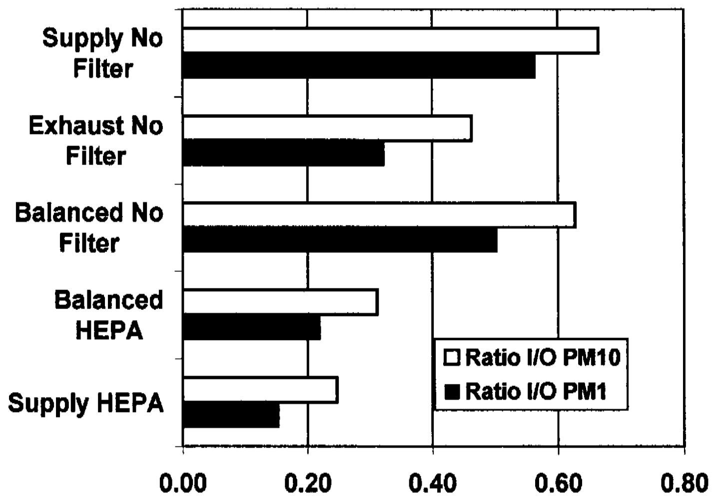


When the data is expressed in terms of the indoor-outdoor particle ratio (see Table 3 and Figure 2), it can be seen that there are distinct differences between the Balanced No Filter condition and the Exhaust No Filter condition that are not evident when observing indoor particle level alone. This occurs due to the high level of variability in outdoor particle level from experiment to experiment.

Table 3

Set-Up	Indoor/Outdoor Ratio PM1 (Average)	Indoor/Outdoor Ratio PM10 (Average)
Supply Only with No Filtration (Supply No Filter)	0.56	0.66
Exhaust Only with No Filtration (Exhaust No Filter)	0.32	0.46
Balanced with No Filtration (Balanced No Filter)	0.50	0.63
Balanced with HEPA Intake Filter (Balanced HEPA)	0.22	0.31
Supply Only with HEPA Filter (Supply HEPA)	0.15	0.25

Figure 2
Average Indoor/Outdoor Particle Ratio



In general, the systems with HEPA filtration of outdoor air provided superior control of indoor particles relative to outdoors. The systems which supplied outdoor air directly to the space without filtration did not control particle levels well with respect to outdoors.

The exhaust only system, which relies on filtration of incoming particles by the building envelope demonstrated performance in the middle ground between the filtering systems and the systems without filtration.

The dynamic functioning of the systems can be seen in the following series of sample data-sets.

Figures 3 and 4 show the Supply HEPA and Balanced HEPA conditions respectively. There is only minor trend-following of the indoor particle levels compared to outside. The indoor particle levels appear to be related principally to occupant activity rather than outdoor levels.

Figure 5 shows the Exhaust Only condition. There is distinct trend following of indoor particle levels with respect to outdoor particle levels, but there is a significant offset and the effects of occupant activity remain apparent.

Figure 6 shows the Supply No filter condition. Indoor particle levels are essentially a mirror of outdoor particle levels with an offset that is attributable to the settlement rate of indoor particles. The effect of occupant activity is not distinct from the much greater effect of outdoor particle penetration.

Figure 3
Sample Data, Supply Only with HEPA Filter
PM1, µg/m³ vs time

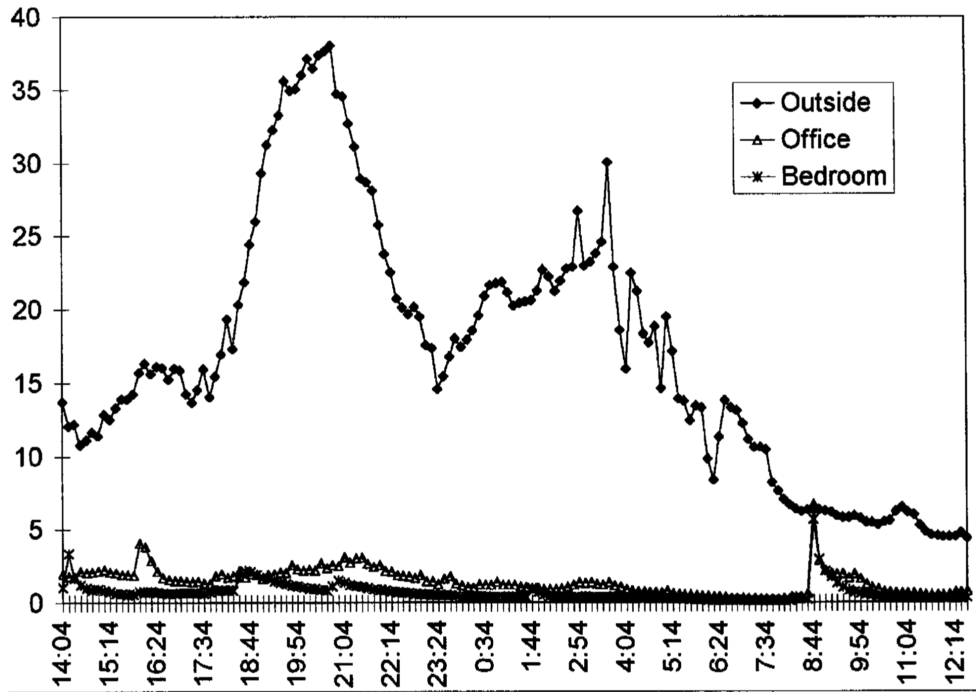


Figure 4
Sample Data, Balanced with HEPA Intake Filter
PM1, µg/m³ vs time

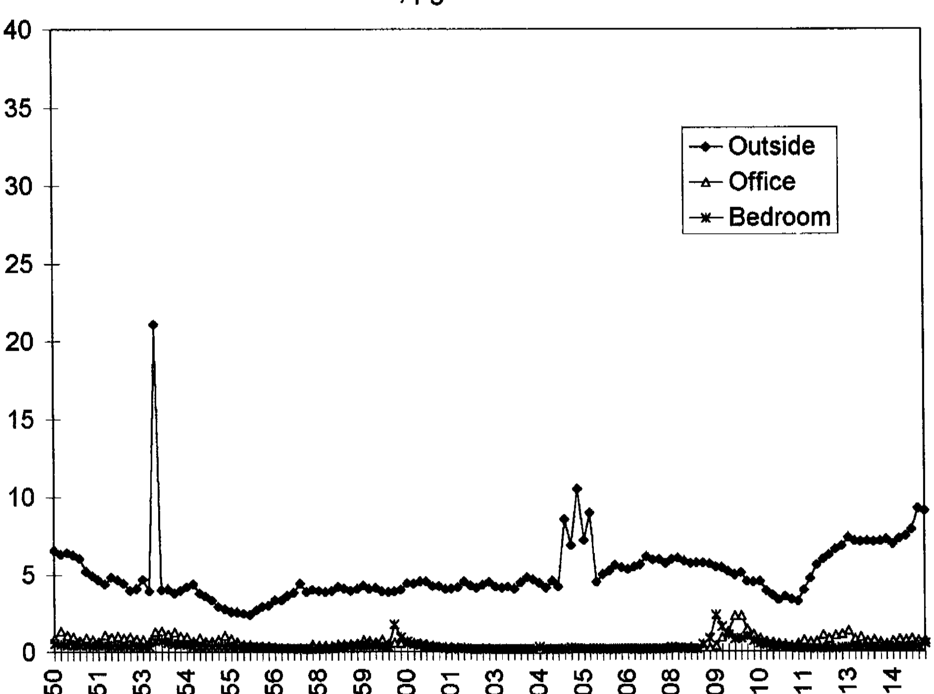


Figure 5
Sample Data, Exhaust Only with No Filtration
PM1, µg/m³ vs time

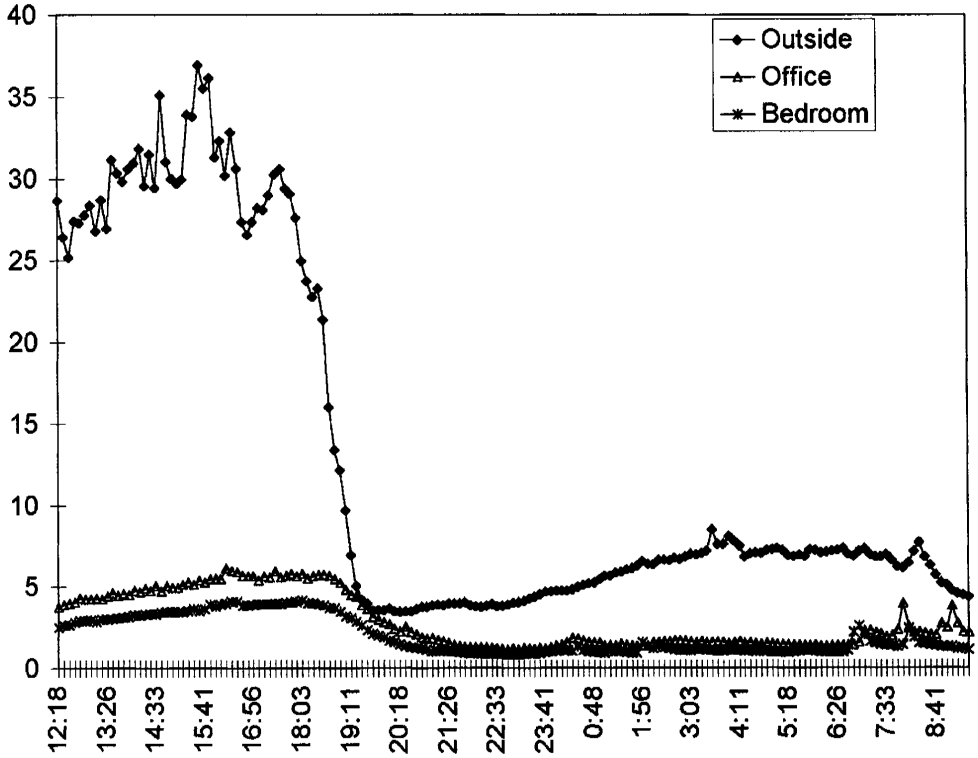
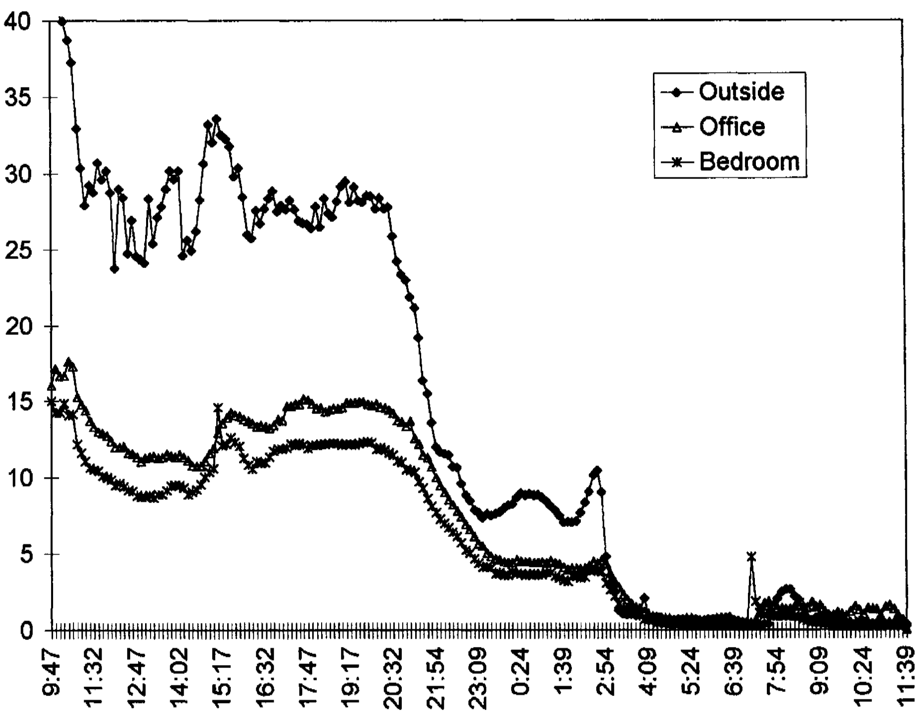


Figure 6
Sample Data, Supply Only with No Filtration
PM1, µg/m³ vs time



3.2 Filtration of Incoming Outdoor Air by The Building Envelope

The following mass-balance model was applied to the aggregated data as if each of the conditions were at a steady-state (Eq 3 from reference 3).

$$C_i = \{K_v(1-f)C_o + S/V\}/(K_v+K_T)$$ *equation 1*

Where:

- Ci = Concentration, indoors (mass/volume)
- K_v = Air Exchange, Air Changes per Hour (ACPH)
- C_o = Concentration, outdoors (mass/volume)
- S = Source Strength, indoors[4] (mass/time)
- V = Volume of house/space
- f = Filtration factor, 0 = no filtration of incoming air, 1 = 100% filtration.
- K_T = Decay rate, Air changes per hour, as follows:

$$K_T=V_d(A/V)$$ *equation 2*

Where:

- V_d = Deposition velocity[5] (distance/time)
- A = Surface area available for deposition. In this case, taken as the total interior surface area of the house (809 m^2)

This model was used to calculate the incoming outdoor air filtration rates required to reproduce the observed results of the experiments.

The model was applied to the PM1 and PM10 data-sets separately and the results are shown in Tables 4 and 5 respectively. Predicted and actual indoor concentrations were compared and using the following limiting conditions:

1) The filtration factor for the Supply HEPA condition is 0.99

2) The filtration factor for the Supply No Filter will approach 0.00

Table 4

Set-Up	Filtration Factor PM1	Correlation (r)	Standard Error
Supply No Filter	0.06	0.99	44%
Exhaust No Filter	0.43	0.98	15%
Balanced No Filter	0.07	0.95	28%
Balanced HEPA	0.88	0.76	26%
Supply HEPA	0.99	0.59	8%

4 Source strength for the model was established by solving for a source strength under the Supply HEPA experiment condition with the filtration factor set at 0.99 and using the deposition velocities established by iterative solution for the entire data set. This resulted in source-strengths of 385 µg/hr and 1781 µg/hr being established for the PM1 and PM10 data-sets respectively. The Source Strength value (S) thus established was used for all of the experimental condition as a fixed value. In fact source strength is highly variable, according to the activity level of the occupants.

5 Deposition Velocity was varied for each of the PM1 And PM10 data-sets until the best correlations were achieved for all of the conditions while meeting the limiting conditions set out above. Using this approach, effective deposition velocities of 0.022 and 0.03 cm/s were established for the PM1 and PM10 data sets respectively, resulting in decay rates of rates of 1.49 ACPH (PM1) and 2.04 ACPH (PM10). These decay rates are within the range of rates reported by references 8 and 7

Table 5

Set-Up	Filtration Factor PM10	Correlation (r)	Standard Error
Supply No Filter	0.06	0.99	53%
Exhaust No Filter	0.37	0.97	13%
Balanced No Filter	0.04	0.73	138%
Balanced HEPA	0.81	0.45	106%
Supply HEPA	0.99	0.20	40%

The results for both data sets show decreasing correlation as the filtration efficiency increases. This occurs due to the high variability of the actual source strength of interior particles when compared to the fixed value used for the predictive model. For data sets where the indoor particle level is principally a function of indoor re-suspension (source strength) correlation is expected to be lower. Higher correlations are found as expected for the experimental conditions where indoor particle levels are dominated by outdoor particle levels.

The Balanced No Filter condition shows filtration rates which are similar to those for the Supply No Filter condition. The Exhaust No Filter condition results show that the filtration effects of the building envelope are approximately 0.43 and 0.37 for PM1 and PM10 respectively. This result is slightly lower than the range of values (0.47 to 0.88) reported by reference 7 for this range of particle sizes.

4 CONCLUSIONS

4.1 Direct Entry of Unfiltered Air

Direct entry of air which is not filtered for fine particulates will contribute to raising the indoor levels of respirable and inhalable particles to levels above those which would normally be expected in a home which did not have direct entry of outdoor air, or in which the entry routes for outdoor air are filtered. This is true even in comparison to exhaust-only ventilation systems of similar air change rates, as the building envelope of the house is capable of removing a substantial portion of the incoming fine-particle load, even at small diameters.

For houses which are currently equipped with an HRV-based system which is not connected to a central forced-air recirculation system, a fine-particle filtering system should be considered for application to the incoming air.

For homes equipped with an outdoor air intake directly connected the return of a forced air system, or where an HRV is connected to the forced air system, the use of a fine-particle air filter for the central system should be considered. Such a fine-particle filter will treat both incoming outdoor air as well as recirculated house air.

4.2 Exhaust Only Ventilation Systems

These types of ventilation systems can be considered to be moderately protective of the indoor environment with respect to the penetration of outdoor fine particles due to the filtering effect of the building envelope. While the actual filtering effect may vary from house to house depending on the manner of construction, it is reasonable to conclude that such systems are superior to those which allow unfiltered air to enter directly into the house. In the absence of combustion equipment which could be depressurized by the action of such a system, these types of systems may be operated at all times of the year in Canada, and can be considered as beneficial during winter operation as entry of dry outside air can serve to prevent wetting of building envelope components by exfiltrating air. In southern climates where building interiors are cooler than the outdoor dewpoint, this type of ventilation system may result in the wetting and subsequent deterioration of building envelope components.

4.3 Supply Ventilation with Filtration

Although this system was demonstrated to be have higher performance with respect to outdoor particulate exclusion from the house, this type of system cannot be recommended for winter-time use in the Canadian climate. In the winter, exfiltrating air forced into the building envelope by the operation of such a system could cause wetting of the building envelope components and lead to damage of those components in the longer term. Such a system could be used in Canadian summer-time conditions and in southern climates where building interiors are kept cooler and dryer than outdoors. Pressurization of the building envelope during the summer or in a southern climate with cool dry inside air would have a beneficial effect on the condition of the building envelope components.

4.4 Balanced Ventilation with Filtration

Balanced ventilation with filtration was found to have performance which approached that of the Supply-Only-with-Filtration system. The performance of such a system would be increased with increasing building envelope airtightness. Such a system is often chosen for Canadian homes where combustion appliances may be affected by the negative pressure induced by an exhaust-only type of ventilation system.

REFERENCES

1. **Bowser D**, Fugler D, Kwan W, EVALUATION OF RESIDENTIAL FURNACE FILTERS, Canada Mortgage and Housing, 1999, Cat. No. NH15-318/1999E, ISBN 0-660-17813-3

2 **CAN/CGSB-149.10-M86**; DETERMINATION OF THE AIRTIGHTNESS OF BUILDING ENVELOPES BY THE FAN DEPRESSURIZATION METHOD; Canadian General Standards Board; December 1986

3 **Freijer JI**, Bloemen HJ. Th, MODELING RELATIONSHIPS BETWEEN INDOOR AND OUTDOOR AIR QUALITY, J. Air & Waste Management Association, vol 50: pp292-300, 2000

4 **HRAI-SkillTech**; RESIDENTIAL AIR SYSTEM DESIGN STUDENT REFERENCE GUIDE; Heating Refrigerating and Air Conditioning Institute of Canada; 1998 Edition; August 1998

5. **Walker IS**; Wilson DJ; THE ALBERTA AIR INFILTRATION MODEL; University of Alberta Dept of Mechanical Engineering Technical report # 71, January 1990

6. **Wilson DJ**; Walker IS; COMBINING AIR INFILTRATION AND EXHAUST VENTILATION; Preceding of INDOOR AIR '90, Toronto 1990, pp 467-472

7 **Abt E.**, Suh HH, Catalano P., Koutrakis P., THE RELATIVE CONTRIBUTION OF OUTDOOR AND INDOOR PARTICLE SOURCES TO INDOOR CONCENTRATIONS, Environmental Science & Technology (accepted)

8 **Thatcher Tracey L**; Layton Davis W; DEPOSITION, RESUSPENSION & PENETRATION OF PARTICLES WITHIN A RESIDENCE; Atmospheric Environment, Vol. 29, No13, pp1487-1497; 1995

9 **Ozkaynak H**; Xue J; Spengler JD; et al; PERSONAL EXPOSURE TO AIRBORNE PARTICLES & METALS: RESULTS FROM THE PARTICLE TEAM STUDY IN RIVERSIDE CALIFORNIA; J Expo Anal Environmental Epidemiology, 6:1, pp57-78, Jan-Mar 1996