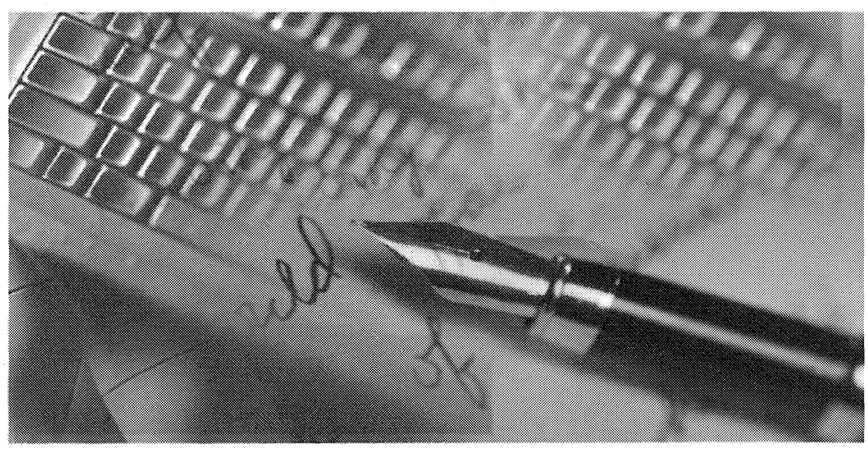
RESEARCH REPORT

EVALUATION OF RESIDENTIAL FURNACE FILTERS

APPENDICES



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Evaluation of Residential Furnace Filters APPENDICES

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INDEX to APPENDICES

A HOUSE DESCRIPTIONS

A.1 House Selection Criteria

1) All house have the following common features:
   - single family detached residence
   - continuously occupied during tests (i.e. not vacant)
   - forced air system
   - no smokers

2) All testing was carried out during the "heating season" that is to say between the first of day of November and the last day of April.

A.2 House Characteristics

Table 10
Characteristics of 6 Test Houses

HOUSE	1	2	3	4	5	6	Max.	Min.	Avg.	Units
Volume	524	722	1115	1088	1045	509	1115	509	834	m^3
Floor Area (including basement)	215	263	406	334	349	197	406	197	294	m^2
% Carpeted	49%	58%	34%	54%	33%	46%	58%	33%	46%	%
Draft Type	DV	DV	no	Nat	Nat	Nat				
Fuel	Gas	Gas	ATAHP	Gas	Gas	Oil				
Adults	2	1	2	2	2	2	2	1	2	Number
Children	0	2	2	0	3	1	3	0	1	Number
Pets	0	1	0	2	0	1	2	0	1	Number
Location	Sub.	Sub.	Rural	Sub	Urb	Rural				
ela_{10}	733	557	1154	1393	1871	546	1871	546	1042	cm^2
ACH50	2.1	2.1	2.3	3.3	4.3	2.7	4	2	3	
Age	22	6	10	10	52	9	52	6	18	Years

A.3 House & Furnace Fan Operation

1) All house were operated in "normal winter-time" mode, that is with doors and windows mostly shut and the heating systems on.

2) The furnaces were operated as much as possible in an as-is mode, that is to say if the homeholder usually operated the furnace fan continuously, then testing was carried out with continuous fan operation. An exception to this

was made for house #4 were the intermittent heating cycle which was normal for the house resulted in furnace fan runs time of less than 20%. For this house, testing was carried out with the furnace fan on "continuous" operation for one day and "auto" operation for the next so that both continuous and intermittent operation data were available for each of the filters tested as well as the "no filter" condition.

3) In some cases, notably houses #4 & 5, the bypass filter installation did not allow the same operating cycles as for the full flow filters. The operating regimes of the individual homes is shown in Table 4, 11.

Table 11
Furnace Fan Operation

HOUSE	Operation with Full-Flow Filters	Operation with Bypass Filter	Bypass Filter Type
1	continuous Single Speed	continuous Single Speed	HEPA
2	continuous Single Speed	Continuous Single Speed	TFP
3	auto/intermittent (average 85% on)	auto/intermittent (average 81% on)	HEPA
4	auto/intermittent & Continuous (see text)	continuous only	HEPA
5	High/Low (3% high speed)	continuous high speed only	HEPA
6	High/Low (10% high speed)	High/Low (1% high speed)	HEPA

B PRELIMINARY TESTING OF 10 FILTERS

B.1 General Arrangement

House Number 1 (the principal investigator's house) was equipped with a ducting arrangement which allowed more precise measurement of in-duct particles and airflow than was typical for Houses 2 through 5. Although the "test duct section" for this house is specially configured for filter testing, it is connected to a more or less conventional heating and air conditioning duct system with an air turn-over rate of 2.2 air turnovers per hour.

The general ducting arrangement is shown in Figure 33 and provides for:

1) precision air flow measurement of the airflow prior to entry into the filter;

2) measurement of the velocity pattern of the air leaving the face of the filter;

3) precision static-pressure measurement upstream and downstream of the filter;

4) even distribution of air across the face of the filter using turning vanes.

5) variation of airflow over a range of 100 to 800 L/s by means of blower speed and duct resistance.

6) measurement of blower power-consumption.

7) mounting of the filters of varying thickness and configuration[27]

B.2 Airflow testing

1) The test duct section was set up for each of the full-flow filters and with no filter.

2) The full-flow filters tested[28] were 16 x 25 nominal size and are listed in Table 1.

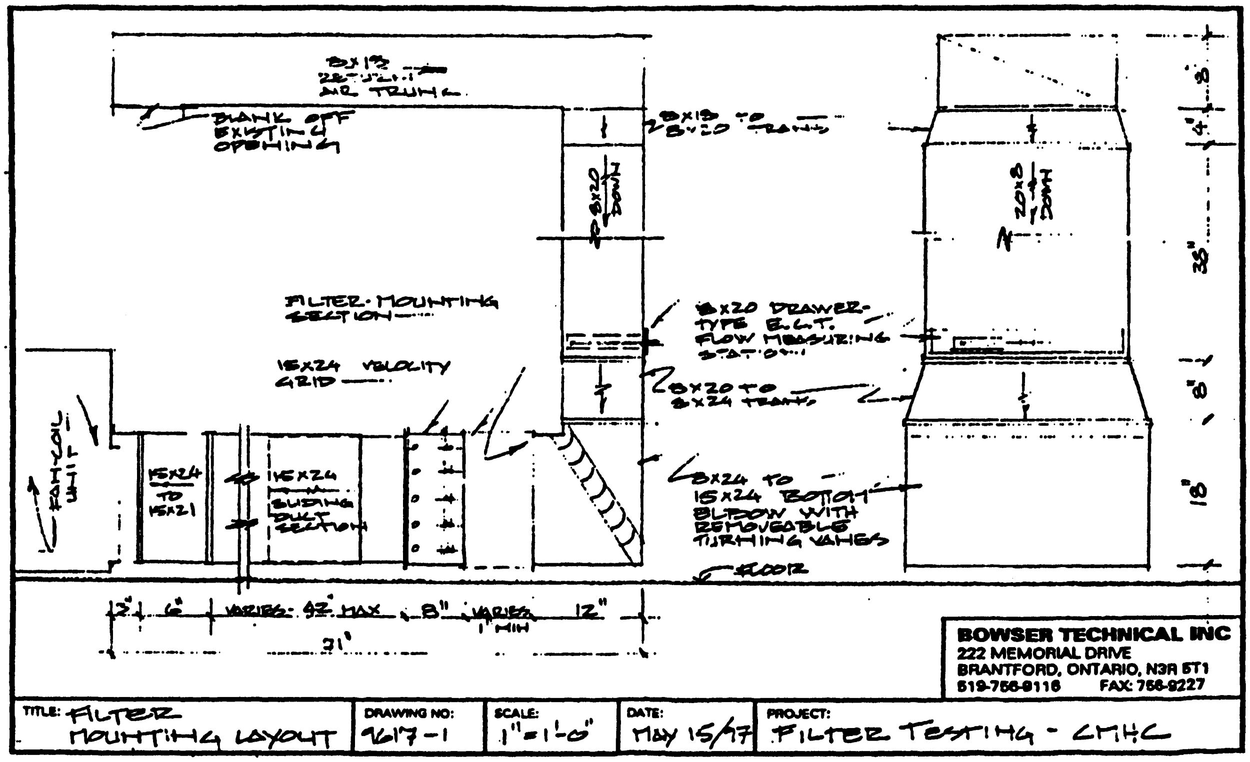
3) All measurements were taken with the air-handler set on "high", "medium" and "low". No attempt was made to maintain a uniform airflow for all filters.

4) All of the tests were taken with the turning vanes in place at the bottom

[27] Filters were mounted using "normal" clearances, that is to say without special sealing such as tape or gaskets. Nevertheless, the filters were evenly supported on at least three sides with no gaps at any point around the perimeter. This is to say that the mounting was the best practice that could be expected in normal installation.

[28] Of the two bypass filters, only the TFP was tested over the full range of airflow. In general, the effect of both bypass filters was to increase the total airflow in whichever central system they were attached to.

Figure 33, Filter Test Arrangement; House #1



elbow (see test duct diagram) and with clean filters.

5) Testing without the turning vanes and with dirty filters were not undertaken.

6) All pressure measurements were taken with an Energy Conservatory DG-2 Pressure gauge. The gauge is accurate to +/- 0.1 Pa (0.004 in. wg.)

7) Airflow was measured using an Environmental Control Technologies Airflow Measuring Station mounted upstream of the filter station. The station had been previously calibrated using a precision pitot-tube traverse at the same location.

8) Face velocity was measured using custom-fabricated transverse velocity-pressure averaging bars mounted at the face of the filter mounting position. These bars had been previously calibrated using a precision pitot-tube traverse.

9) Measurements were taken as follows:

   a) Airflow (at airflow station)
   b) Face velocity (at each of 5 transverse bars)
   c) Static pressures:
      - immediately upstream of the filter position
      - immediately downstream of the filter position
      - at the supply air discharge from the air-handler

10) Pressure readings were converted to velocity (and airflow) taking account of air temperature and barometric pressure.

11) For each filter (and the "no filter" set-up) an airflow vs resistance curve was generated by fitting the two points obtained to a curve with the general definition:

$$CP^n = Q$$

where:
- C = flow coefficient, (flow @ pressure unit of 1)
- P = pressure difference
- n = flow exponent, dimension-less
- Q = flow

12) Airflow at pressures other than the measured points were calculated using the "C" and "N" values derived for each filter.

Table 12
Characteristics of 10 Filters Tested in House #1

Code	Generic Description	Costs: List	Costs: Contractor	Costs: Installed	Costs: Annual	Costs: note	Consumer Quoted Performance	Manufacturer Claimed Performance	Independent Test (AFTL): DOP	Independent Test (AFTL): Average Arrest.	Independent Test (AFTL): Average Dust Spot	Independent Test (AFTL): Particle Size	TEST Results: E% PM1	TEST Results: E% PM10	TEST Results: CADR 10 L/s
ORD	Ordinary Furnace Filter - Full Flow	$2	$2	$2	$8	2	Change Monthly	made from recycled material	n/a	not provided		no	-3%	-2%	-11
1"PLT	1"Pleated Media Filter - Full Flow	$7	$7	$7	$48	2	eliminates 92% of airborne allergens, 2-3 times more efficient than standard filters						6%	4%	17
1"MED	1"Pleated Media High Quality - Full Flow	$22	$22	$22	$100	2	99% of particles in your air consist of micro-particles, 20 times better than ordinary filters, 7 times better than ordinary pleated filters		not provided				32%	25%	97
PAS.E	1" Passive Electrostatic - Full Flow	$100	$65	$100	$0	4	can remove up to 95% of the symptom causing dust, pollen, mould and animal dander	93% Average Arrestance	n/a	0.93	<20	no	10%	6%	30
E.PAD	Electronic Charged pad - Full Flow	$150	$100	$150	$34	2	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%		Declined, will test to 52.2 when available			0.5 um < 20% Hanley	15%	11%	44
4"MED	4"Pleated Media - Full Flow	$400	$200	$500	$60	5,6	effective range 1 micron and above, more than 90% effective at removing whole pollen and plant spores	32% average dust spot, 92% arrestance	n/a	0.32	0.92	Yes	19%	19%	60
95MED	95% dust-spot pleated media - Full Flow	$200	$140	$400	$200	1,6	90-95% efficient	95% Average Dust Spot	99% Average Arrestance			n/a	58%	56%	155
F50	Electronic Plate & Wire Type - Full Flow	$500	$350	$700	$0	4	removes 95% of airborne particles, effective range 0.01 micron and above, 10 to 20 times more efficient than standard throw-away filter	75% average dust spot, 98% arrestance	n/a	0.98	0.75	yes	95%	94%	298
TFP	Turbulent Flow Precipitator - Bypass	$750	$500	$1,000	$39	7	removes 99.9% of all allergy and hay fever causing pollens and spores, removes 97.5% of all airborne house dust in less than 24 hours in a modern airtight home	0.5 micron, 84%, 0.7-0.9 87%, 1 92% 2 -3 95%, 5 + 99% according to ASHRAE 52.1		0.96	0.78	yes	22%	21%	65
HEPA	HEPA - Bypass	$1,700	$1,250	$2,200	$93	3	removes 99.97% of particles larger than 0.3 micron	99.97% D.O.P.					51%	51%	175

Notes

1 installed cost includes for cost of custom cabinet/rack
2 annual cost assumes 4 replacements per year
3 annual cost based on $370 element with 4 year life
4 assumes cleaning by homeowner @ no charge
5 assumes new installation, cost to replace E.S.P. is $125 list
6 annual element replacement
7 replace 2 of 6 elements annually

C WHOLE-HOUSE TESTING

C.1 Test Cycles

The following test cycles were used with occasional variations:

a) No filter .... 48 hrs
b) 25 mm Media .... 48 hrs
c) Electrostatic Pad .... 48 hrs
d) 100 mm Media .... 48 hrs
e) Bypass Filter HEPA or TFP
f) Electrostatic precipitator .... 48 hrs

Testing was for a minimum of 48 hrs for each filter with at least two over-night periods of data.

C.2 Sampling Locations

1) Particle samples were obtained from 5 locations as follows:

a) **Outside**
b) **Return air** duct (before filter)
c) **Supply air** duct (after filter[29])
d) **Living area**/family room (where "at home" activity most often occurs).
e) **Bedroom.** (The bedroom selected was for the "index person", for whom personal sampling was also be carried out. If possible, the index person was not an adult.)

2) Sampling height in rooms 5 to 7 ft.

C.3 Filter Mounting

1) All full-flow filters were mounted in the conventional return air location adjacent to the furnace, immediately downstream of the base elbow for a high-boy side-inlet furnace configuration as shown in Figure 34.

2) Turning vanes were installed for House #1 and #2 only.

3) Bypass type filters were mounted in accordance with their respective manufacturer's instructions, with the configurations being generally similar to that shown in Figure 35.

4) All of the filters were mounted were mounted using "normal" clearances, that is to say without special sealing such as tape or gaskets. Nevertheless, the filters were evenly supported on at least three sides with no gaps at any point around the perimeter. This is to say that the mounting was the best practice that could be expected in normal installation.

[29] Where physical limitation prevented sampling directly following the filter, the downstream sampling point was located in the supply duct from the furnace. This may have introduced measurement effects which arose from induction of air from the mechanical room into the furnace cabinet, downstream of the filter.

Figure 34
Typical Full-Flow Filter Installation

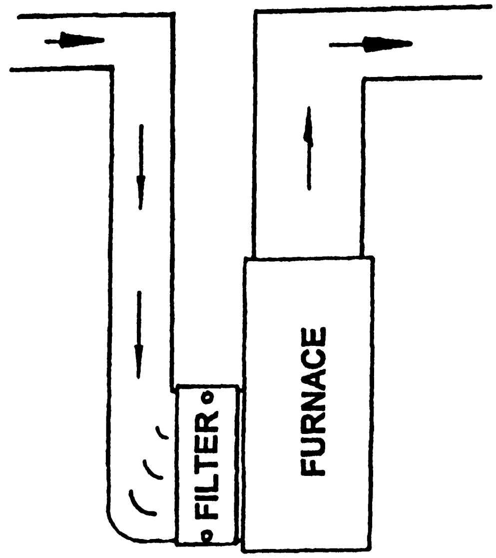
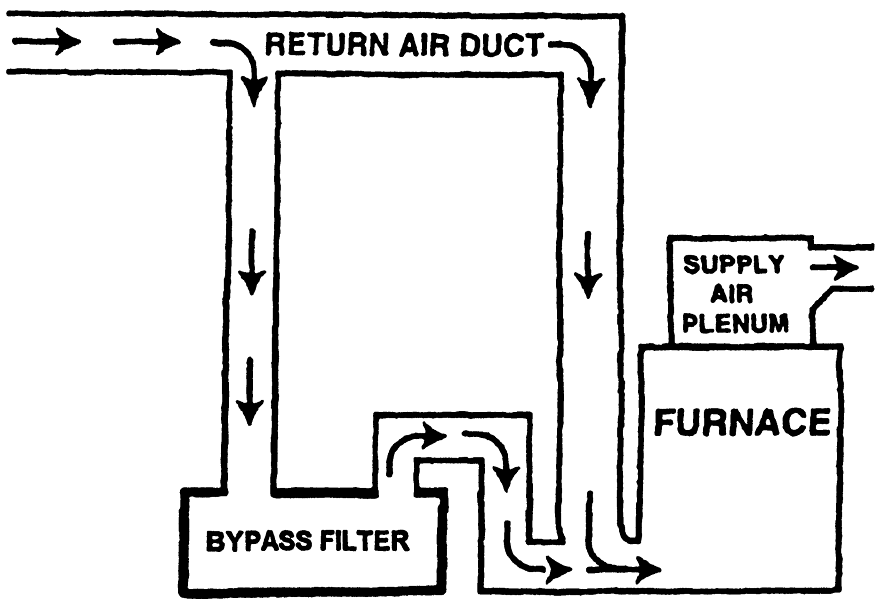


Figure 35
Typical Bypass Installation



D PERSONAL SAMPLING

D.1 Equipment

Personal sampling was carried out using an APC 1000 particle counter with a pick-up tube located in the wearer's breathing zone. Refer to G.2 for a detailed description of the particle counter. This apparatus was contained in a body-pack which allowed the wearer to move freely. Initial monitoring was limited by battery life of the unit, however the addition of an auxiliary battery to the body-pack alleviated this problem. Some wearers reported discomfort due to the weight of the pack (2 kg).

D.2 Sampling Accuracy

Comparison testing between the personal sampler and the fixed-location sampling rig showed that the results were comparable with a possible error of +/- 10% for PM10, 13% for PM5 and 10% for PM1 (See appendix H.9).

D.3 Data Treatment

Data periods for which personal samples are available are over 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.

E ESP FIELD SURVEY

Twenty households equipped with electrostatic precipitation air cleaners[30] (ESP) were located. Homeholders were offered a "complete electronic air cleaner tune-up" as an incentive. Although twenty homes were visited, valid and complete data was only obtained for 11 homes due to the failure of the first ozone-measurement instrument. Valid data was obtained for a further 4 homes, but only for the "second visit" phase. The second instrument (DASIBI 1000 AH) was used for all of ozone measurements in the 15 sets of valid ozone data.

For each home, the survey was carried out approximately as follows:

E.1 First visit:

- obtain ozone & particulate levels, outside, inside, before and after filter
- record condition of air cleaner & installation details,
- measure system airflow (temperature rise method) and pressure drop, power consumption (volts x amps)
- check cell continuity and power-pack electrical charging
- record operating cycle of air-handler as to continuous/high/low/auto
- survey homeholder as to cleaning cycles, etc
- remove cells for cleaning and turn off power supply to filter
- repair any defects in the air cleaner power supply or cell-charging system prior to the second visit.
- verify airtightness of the home (first or second visit) according to CGSB 149.10.[ref 13]

E.2 Between Visits

- weigh cells and pre-filters.
- clean cells using 2 repeat applications of "Alki-Foam" alkali air-conditioning coil cleaner, rinsing and drying with forced warm air.
- weigh (clean) cells and pre-filter

E.3 Second Visit:

- replace clean cells, turn on power supply to filter.
- check cell continuity and power-pack electrical charging
- obtain ozone & particulate levels, outside, inside, before and after filter
- measure system airflow and pressure drop, power consumption (volts x amps)

[30] Also known as plate and wire type electronic air cleaners.

F PORTABLE CLEANER

F.1 Bedroom Area

A single, portable in-room filtration unit[31] was tested in a bedroom[32] environment of House #1. Testing was for nine consecutive days of 24 hours during which the bedroom was occupied in a regular pattern of:

Daytime . . . . unoccupied
Nighttime . . . . two persons sleeping
Morning & evening . . . . brief activity

Data was recorded for nine consecutive days under the operating schedule shown in Table 13. The central air handler in the house was operated continuously without a filter and particle samples taken in the main return air duct of the forced air system on 8.75 minute intervals. In-room particle samples were taken at a point approximately 2 m over the bed on 8.75 minute intervals. All samples were taken using the particle counting rig described in appendix G.1.

Table 13
Operating Schedule, Bedroom Portable Filter Test

DAY	1	2	3	4	5	6	7	8	9
Filter	off	off	off	on	on	on	off	off	off
Supply Air to Room	open	sealed	sealed	open	sealed	sealed	open	open	open
Door to Hallway	open	close	open	open	close	open	open	open	open

F.2 Office Area

A single, portable in-room filtration unit[33] was tested in a "Home Office"[34] environment located in the basement of House #1. Testing was for eight consecutive days of 24 hours during which the office was occupied in a regular pattern of:

Daytime . . . . occupied (approx 12 hrs)
Nighttime . . . . unoccupied (approx 12 hours)

The office is equipped with a computer, and laser printer both of which are on during the hours of occupation. The central air handler in the house was operated continuously without a filter and particle samples taken at the main return air duct of the forced air system. In-room particle samples were taken at a point approximately 2 m over the main work-station on 8.75 minute intervals. All samples were taken using the particle counting rig described in appendix G.1.

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31 Commercially available unit, operated at low speed airflow rate with CADR of 59 L/s. Unit is capable of higher airflow rates/CADR values of 118 and 142 L/s at medium and high blower speeds.

32 Floor area = 14 m^2, volume = 39 m^3

33 Commercially available unit, operated at low speed airflow rate with CADR of 59 L/s.

34 Floor area = 18 m^2, volume = 40 m^3

G INSTRUMENTATION

G.1 Sampling Rig

G.1.1 Components

1) vacuum pump:
   - Gast # 1532 carbon-vane rotary oil-less type
   - exit air from pump (& system) is passed through a HEPA filter before return to the house.

2) sample lines:
   - 9 mm flexible soft copper (7.9 mm i.d.) with maximum length of 50 ft. (velocity of 1.73 metres/second at 5 Lpm flow)
   - short lengths of 6.5 mm i.d. teflon-lined flexible connector tubing
   - isokinetic inlets of 19 mm diameter are used giving an intake velocity of 0.30 metres/second

3) flow-regulation:
   - Dwyer MMA rotameter with integral flow-regulating valve.
   - each rotameter was calibrated to an accuracy level of +/- 5% of the indicated flow against a primary airflow calibration device.
   - flows are measured;
     -total system flow (25 Lpm)
     -each bypass line (5 Lpm when not sampling)
     -particle counter exit flow (2.8 Lpm)
     -sampling line bypass flow (2.2 Lpm)

4) Valves & timers:
   - brass-body diaphragm type solenoid actuated valves, 25 mm nominal, 8 mm port size.
   - digital self-timers for MET-1 particle counter, using a 60 to 75 second sampling period with a 30 to 45 second hold (purge) period between samples
   - trigger interlock for the Bio-Test particle Counter, using a 90 second sample period with a 15 second purge period

5) Impact separator;
   - Air-metrics, 10 μm greased plate separator @ 5 Lpm flowrate

6) Particle counter: (see notes on particle counter following)

G.1.2 Sampling Airflow

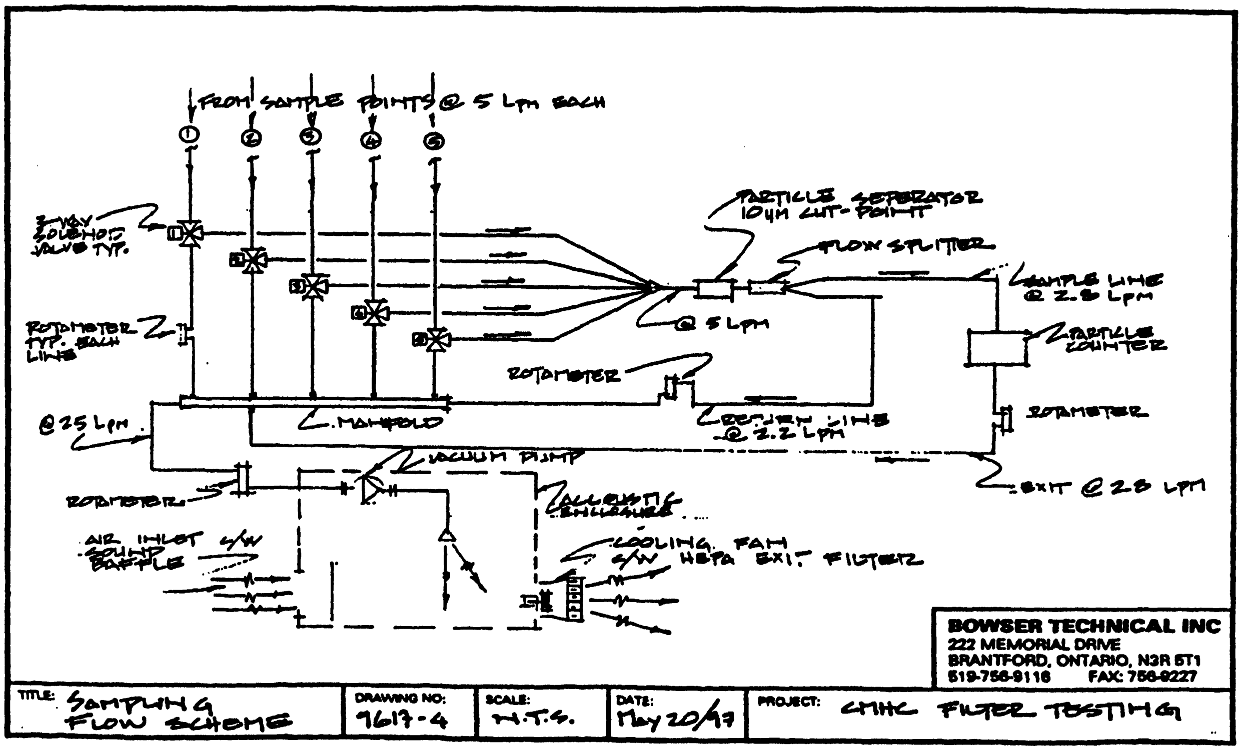
1) The rig generates a continuous flow of 5 Lpm (Litres per minute) from each location and switches the active sampling line on an interval of 90 or 105 seconds.

2) The active sampling flow is first passed through the impact separator which removes particles above 10 µm before passing into the particle counting instrument.

3) The particle-counter flow-rate is 2.8 Lpm. This lower flow is separated from the 5 Lpm flow is separated using a low-angle (15°) equal-velocity flow-separator.

4) Flow is maintained at a constant 5 Lpm in all sampling lines, whether or not a sample is being taken.

Figure 36, Schematic, Sampling Rig



G.1.3 Particle Sampling Accuracy

Particle sampling accuracy for the sampling rig was assessed during a series of extensive co-location test in House #1.

1) Tube-loss testing showed that 16 m 6.35 mm i.d. (19 mm isokinetic inlet for still air, 9 mm inlet for moving air in duct) copper tube resulted in a particle loss of less than 5%.

2) External leakage and carry-over between sampling paths within the sampling rig was determined to be less than 1% by using HEPA purge filters on alternate sampling lines. This test sequence was repeated for each of the 6 test houses on sampling start-up to verify the integrity of the sampling rig.

3) Particle loss with the sampling rig was determined to be between 0 and 10% for particles less than 5 µm and between 60 and 80% for particles between 5 and 10 µm.

4) Based on tests of sampling loss and carry-over within the sampling rig in adding to tubing losses, a series of correction factors was developed for each of the rig sampling paths, according to particle size. Combined losses (sampling rig and tubing) averaged 6%, 8% and 68% for particles less than 1 μm, particles between 1 and 5 μm, and between 5 and 10 μm respectively. With application of these correction factors, overall confidence levels increased to +/- 5% for PM10, PM5 and PM1 values. Collocation test were repeated at the end of the field work and it was determined that the original correction factors had not changed substantially.

5) Testing without a filter in place showed the upstream and downstream sampling stations in house #1 to be reliable with respect to each other with a confidence level of 2%.

6) Sampling rig station agreement was verified by a collocation test at start up for each of the 6 houses. In all of the cases except house #6, agreement between sampling stations was +/- 5% before the start of testing. In the case of house # 6, the sampling line to the family room did not agreed and so an interim correction factor was developed to correct for the apparent lack of agreement. The cause of the error (a partially blocked sampling line to the family room) was found and corrected part-way through the testing sequence for this house. At this point, the station -to-station agreement was re-verified and the original correction factors re-instated.

G.2 <u>Particle Counters</u>

1) MET-ONE Model 237B Laser particle counter. Continuous data collection in four channels:

0.5 to 0.7 μm
0.7 to 1.0 μm
1.0 to 5.0 μm
5.0 μm & above

or

2) BIO-TEST APC 1000 Laser particle counter. Continuous data collection in four channels:

0.3 to 0.5 μm
0.5 to 1.0 μm
1.0 to 5.0 μm
5.0 μm & above

3) Both particle counters were calibrated using Latex-Polystyrene spheres by their respective approved calibration lab. The MET-ONE particle counter was calibrated before and after data-collection. The BIO-TEST counter experienced a pump failure and was not able to be calibrated at the end of data collection.

G.3 <u>Weather Station</u>

1) Weather data was obtained with a portable, on-site weather station (Davis Instruments Monitor II) which records:
    a) indoor %RH and temperature
    b) barometric pressure
    c) outdoor temperature
    d) windspeed and direction

2) Windspeeds are recorded at the eave height of the house, at a point approximately two house-heights away from the house, in an area which avoids obstructions as much as possible.

3) The air-tightness of the house was measured using a blower-door test apparatus according to the CGSB 149.1 test method. [ref 13]

4) Ventilation flows are measured directly with an in-line flow measuring station. (Environmental Control Technologies type)

G.4 Duct-System Air-Flow Monitoring

1) The furnace system air flow was measured for each of the following conditions:
    - no filter
    - each of the 5 filters (10 filters in house 1)
    - at high & low speeds for each filter if the furnace operates at high and low speeds
    - via the bypass filter when a bypass filter was in place.

2) Airflow was measured at a central point in the return air duct (and the bypass duct) using an appropriately sized Environmental-Control Technologies (ECT) air-flow grid[35]. The grid was calibrated using a pitot-tube traverse at the measuring location in question. Furnace temperature rise was used to cross-check the measured flows.

3) Airflow to each room was measured at the supply register using a capture-hood together with an ECT-style airflow grid. Pressurization or depressurization of the room with the door closed was also measured.

4) The furnace blower operation was monitored using differential pressure switches set to detect fanoff/lowspeed/highspeed blower operating states. Differential pressure switch operation was recorded using "state-change" data loggers manufactured by Onset Corp. which recorded the time of change from one state to another.

5) During testing, the furnace blower fanoff/lowspeed/highspeed "status" was monitored using a data logger. By combining the measurements of airflow

[35] Manufactured by various manufacturers under license from Environmental Control Technologies Inc. This type of airflow grid is commonly used as a permanent air-flow measuring station in ventilation and V.A.V. systems.

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.

G.5 Electrical/Fan Power Measurement

1) The electrical power consumption of the furnace and filters was measured in each operating condition as appropriate (off/lowspeed/highspeed) with no filter and for each of the 5 filters.

2) Electrical & power consumption measurements consisted of amperage (clamp-on ammeter with 10-turn multiplication coil) and watts (true RMS-watts power-meter).

3) These measurements were combined with the monitored information gathered by the furnace fan status data-logger (see G.4) to produce an estimate of the actual fan and filter power-consumption during the data-period.

G.6 Ozone Measurement

1) Ozone monitoring was conducted using a DASIBI 1000AH Ambient Ozone Monitor (UV sampling chamber photometer).

2) The unit had been factory calibrated immediately prior to use in this project and the recommended self-calibrating routine was carried out before the start of testing and at the end of testing. No significant variations from the initial calibration were noted.

G.7 Verification of Gravimetric Estimates

1) In order to verify the accuracy of the approximations used to transfer counts to gravimetric information, collocation testing was carried out using gravimetric test methods.

2) Gravimetric apparatus consisted of an Airmetrics filter holder and impact separator assembly using either a 10 µm or 2.5 µm (2-stage) greased-plate type impact separators. Collection filters used were Pallflex 47 mm type T60A20. Airflow was 5 Lpm (Litre per minute).

3) Filter were desiccated and pre-weighted. Measuring resolution was to 0.01 mg (milligram). An average of .5 blanks (unexposed) were used per sample filter. Weight gain by the blank filters was not more than 0.02 mg.

4) For PM_{10}, one filter was exposed for 164 hours. The PM_{10} value obtained gravimetrically was 7% less than that obtained used the approximation method set out in H.1. The uncertainty value of the gravimetric method was +/- 9%.

5) For PM 2.5, three filters were exposed for periods ranging from 128 hours to 186 hours. Variance between the gravimetric values and the values approximated by the methods set out in H.1 and H.2 ranged between -17% and +45% with the arithmetic mean variance being +13%.

H CALCULATIONS

H.1 Gravimetric Values from Particle Counts:

1) Results are expressed in gravimetric terms whenever possible, as follows:
   - PM_1 the particle mass concentration below 1µm, expressed in µg/m³.
   - PM_5 the particle mass concentration below 5µm, expressed in µg/m³.
   - PM_{10} the particle mass concentration below 10µm, expressed in µg/m³.

2) $PM_{2.5}$ values are expressed only when required to compare with other data and standard values. The method of calculation for PM2.5 is described in H.2.

3) The particle count data is converted to a gravimetric value expressed in µg/m³ (micro-grams per cubic metre) as follows:

$$4/3*Pi*[(S_A)/2/1{,}000{,}000]^3*(C_P)*(D_P)*1{,}000{,}000=PM_{xx}$$

Where:

- S_A = average size of particle (diameter)
- C_P = Concentration of particles (count per m³)
- D_P = Density of Particles, (assumed to be spherical)
- PMxx = Particulate matter where "xx" represents the cut-size, for example PM_{10} is Particulate matter < 10 µm, in micrograms/m³ (µg/m³)

4) Based on the results of the experiments carried out as described in G.7, the assumptions of density and diameter listed in Table 14 were used:

Table 14
Particle Density and Diameter Assumptions
Used for Conversion of Counts to Gravimetric

Particle Size Range	Density	Diameter	Settling Velocity[1]
below 1 µm	7,000 kg/m³	0.75 µm	0.012 cm/s
between 1 and 5 µm	2,500 kg/m³	2.0 µm	0.03 cm/s
between 5 and 10 µm	1,000 kg/m³	6.0 µm	0.108 cm/s
1) Settling velocity according to Stokes Law			

H.2 Predicting PM 2.5

1) Estimated values of the particle mass concentration below 2.5 µm ($PM_{2.5}$) were calculated by assuming that the particle mass concentration varies in a straight line between the PM_1 and PM_5 values generated according to the procedure described in H.1

2) Verification of the calculated value was carried out in a series of collocation experiments described in G.7.

3) $PM_{2.5}$ values are reported only where useful in relating to outside data due to the higher levels of uncertainty for these values as compared to those for PM_{10} [see G.7]

H.3 Upstream/Downstream Efficiency

1) Based on the data from the upstream and downstream sampling points, a *collection efficiency* "CE" was derived for PM_{10}, PM_5 and PM_1 values, based on the mean particle concentrations at the sampling points over the duration of the data period. For example:

$$CE_{10} = (\mathring{A}PM_{10UP} - \mathring{A}PM_{10DN}) / \mathring{A}PM_{10UP}$$

where:

CE_{10}	=	collection efficiency @ 10 micrometres and below
$\mathring{A}PM_{10UP}$	=	arithmetic mean concentration PM_{10} upstream
$\mathring{A}PM_{10DN}$	=	arithmetic mean concentration PM_{10} downstream

2) For non-continuous blower operation, counts during the "blower off" periods were not included in the computation of the upstream or downstream values.

3) When a bypass filter was tested, the air stream leaving the bypass filter was not sampled, rather the mixed airflow after blending was sampled. The measured efficiency is for the total airstream and varies according to fraction of airflow which passes directly through the filter. The efficiency of a bypass filter with respect to the air passing directly through it can only be calculated indirectly.

4) With the exception of House #1, the downstream sampling point was not calibrated to the upstream sampling point at the "no filter" condition, therefore, some baseline errors may exist due to sampling point location.

H.4 Leakage into Blower Cabinet

Only houses # 1 and # 3 had downstream sampling points which were immediately downstream of the filter. All other houses had downstream sampling point located in the furnace supply air duct. For these houses detailed examination of the data during non-occupied periods showed that when the upstream concentrations fell below approximately 2 $\mu g/m^3$ the instantaneously recorded efficiency became highly variable. This effect was more pronounced with higher-efficiency filters. This was apparently due to the effect of air being entrained into the blower cabinet downstream of the filter. The source of this air was usually the mechanical room of the home which was well connected aerodynamically to outside sir. During unoccupied periods, outside air usually contained much higher particulate concentrations so that the effect of even small quantities of this air being entrained into the blower cabinet downstream of the filter but upstream of sampling point would appear as a serious decrement in the instantaneous efficiency of the filter. The effect of this error was minimized by using the "mean concentration" of the of upstream and downstream particle samples over the data period but otherwise the data was not adjusted for this effect. Where it was suspected that these errors were having a significant effect on the collected data[36], the suspect data was not included in the data summarizations.

H.5 Clean Air Delivery - Air Handler (CAD_{AH})

H.5.1 Flow Efficiency

A *flow efficiency* "QE" was calculated based on the CE value calculated according to H.3 and multiplied by the arithmetic mean system total airflow during the data-period.

H.5.2 System Airflow

The system airflow for a given data period was calculated using the average of the calculated airflow during each 8m 45s cycle. The calculated airflow obtained by assigning each 1m 45s data sub-cycle a status of "high" "Low" or "Off" according to the time-mark of the data-logger. The airflow measured at "high" or "low" for the furnace filter combination under test was assigned to each sub-cycle according it's status. Refer to G.4 for a description of the airflow measurement methods.

H.6 Clean Air Delivery - Decay ($CADR_D$)

H.6.1 Generating Decay Curves

During testing in House #1, decay curves were intentionally generated by vacuuming with a vacuum cleaner without bag. It was found however, that good quality decay curves occurred in any event in the houses during the transition period between activity and non-activity. Consequently, the decay curves used for the analysis are those which occurred naturally in the subject houses and were not "artificially" generated by using a vacuum cleaner or other type of particle generating procedure.

Data points used for regression were selected after the beginning of the decay curve to allow for equalization of uneven mixing effects in the house.

H.6.2 Data Inputs

The data inputs used were:

- outside particle concentration (real time) PM_1, PM_5 and PM_{10}; C_{out}
- bedroom and family room particle concentrations, (real time), PM_1, PM_5 and PM_{10}
- predicted air-change rate in L/s real-time (see H.7 for calculation method); Q_i
- house volume; V

36 Data from House 5 was not included in summaries for this reason.

- settling area (assumed to be the floor area of the house); A_d

H.6.3 General Calculation

The bedroom and family room particle concentrations were combined to give a "house average' value and to allow for room-to-room diffusion effects. Outside air was assumed to carry particles into the house at a penetration rate of 0.5; that is to say that the envelope of the house was presumed to remove approximately 50% of the particles contained in the outside air as the outside air passed though the envelope. This value is discussed in more detail in H.6.6. Incoming outside air and the consequent particle load were assumed to be perfectly mixed with the house air.

$$A = CADR_D + V_d \times A_d \qquad \text{Eq. 1}$$

$$C = \frac{Q_i \times C_i}{A + Q_i} \times \left[1 - EXP\left(-\frac{(A+Q_i)\times t}{V}\right)\right] + C_o \times EXP\left(-\frac{(A+Q_i)\times t}{V}\right) \qquad \text{Eq. 2}$$

$$C_i = C_{out} \times P_f \qquad \text{Eq. 3}$$

Where:

A	=	Constant calculated by non-linear regression of the house average particle concentration
$CADR_D$	=	Effective Clean Air Delivery Rate - Decay
V_d	=	Deposition velocity
A_d	.	Deposition Area - Floor Area of House
Q_i	=	Air Change Rate (infiltration)
C_i	=	Concentration of Infiltrating Air
C_{out}	=	Concentration of Outdoor Air
P_f	=	Penetration factor
V	=	Volume of House

H.6.4 Sum of Squares

The sum of squares was minimized by using the solve routine in MS EXCEL to change A so that $$\sum \frac{d(C-C^*)^2}{dA} = 0$$

where: C = predicted concentration
C^* = observed concentration

In many of the regressions data was added and removed with insignificant change in the regression constant.

H.6.5 Residuals

The residuals (actual concentration - residual concentration) were checked to ensure that they were randomly distributed. When the residuals were not randomly distributed, points were removed or added to give randomly distributed residuals. If the constant A did not change appreciably (10%) from the randomly distributed residual case the regression was left as is.

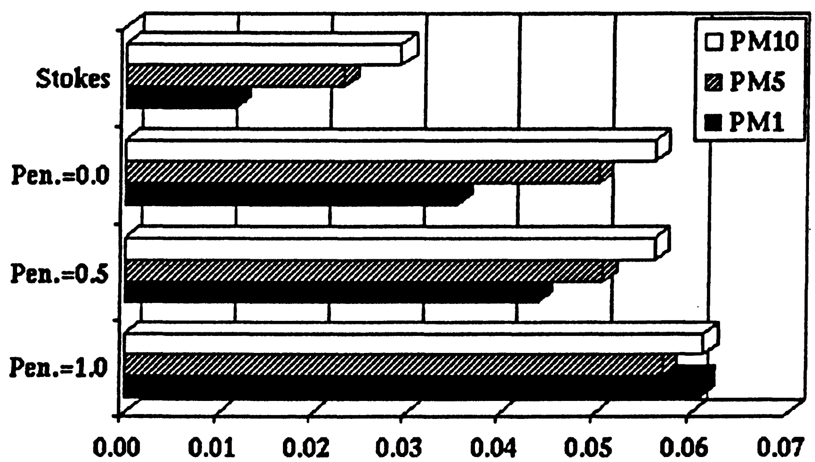
H.6.6 Particle Penetration Rate

Particle penetration was modified by multiplying the infiltration flow rate with the penetration. Each regression was evaluated with a penetration of 1.0, 0.5 and 0.0. Infiltration and exfiltration efficiencies are the equal in the regression. Based on the results of this analysis, it was concluded that penetration is likely below 0.5 for PM_{10} and PM_5. The best curve fits were obtained by lowering penetration to 0.5 or 0 (least sum of squares). For PM_1 penetration rates are probably about 0.5, however there is less certainty for this conclusion than for PM_5 or PM_{10}.

H.6.7 Particle Density and Size

The particle size and density used are those listed in Table 14 on page A-21. Some regression curves with particle density of 1,000 kg/m^3 were also prepared and compared to the curves prepared using the particle sizes and densities set out in Table 14. The regression constant was not changed greatly when this was done.

Figure 37
Settling Rate (cm/s) predicted by Stokes Law vs No Filter $CADR_D$, All Houses, Varying Penetration Rates 040



H.6.8 Stoke's Law Settling Velocity

The settling velocity was predicted using Stoke's law for PM1, PM5 and PM10 using mass-weighted averages based on the particle sizes and densities set out in Table 14 on page A-21. Stoke's law predicts the settling velocity well for low Reynolds numbers, little brownian motion and a still settling media. Reynolds numbers are low for the particle size range being examined. Assuming that the area for collection in the house is the floor area, the deposition velocities calculated from regression with no filter are much higher than those predicted by Stoke's law. Figure 37 shows these results for each of the penetration cases. This difference may be due other collection methods that were not taken into account i.e. Brownian diffusion or electrostatic forces. The true deposition area including furniture and other surfaces, including 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 which is predicted by Stoke's law.

H.7 Air-Change Calculations

1) The air-change rate was estimated using monitored weather data and the airtightness characteristics of the house using the AIM-2 [ref 17] analysis method.

2) Combined natural and mechanical ventilation effects were modelled using the Keil-Wilson [ref 18] relationship.

3) Data was collected and air change calculations are carried out at 15 minute intervals.

H.8 Ozone Source Strength

Ozone source strength is reported as micro-litre/sec (μl/s), calculated by:

$$(O_d - O_u) * Q_{ah} = O_{ss}$$

Where:

O_d = O^3 downstream concentration, ppb
O_u = O^3 upstream concentration, ppb
Q_{ah} = Air Handler flowrate, L/s
O_{ss} = O^3 source strength, μl/s

H.9 Personal vs In-Room Samples

Using the data collected from the personal sampler, values of PM10, PM5, and PM1 were approximated using assumptions and approximations described in H.1. The values obtained from the personal sampler using this method were compared to the values obtained using the fixed-point sampling rig in a series of collocation tests. The comparability of the two methods is shown in table 15.

Table 15
Comparability of Personal Sampler with Fixed-Point Sampler, Based on Collocation Testing

Particle Range	Average Error	Standard Deviation
PM10	-7%	10%
PM5	-8%	13%
PM1	-14%	10%

H.10 Electrical Energy Prices

During the winter months it is recognized that the electrical consumption of the blower motor serves to heat the space. If the principal space-heating fuel is not electric and is less expensive than electricity, the actual cost of additional electrical consumption will not be a function of the value of the offset principal fuel relative to the cost of the electrical energy. In order to reflect this consideration, a relatively low electrical energy purchase price of $0.05 per kwh is used to estimate electrical purchases during the heating season to reflect this.

During the shoulder months when neither heating or cooling is required, the consumption of a furnace blower motor can be considered to be completely superfluous. If air-conditioning is used in a home, the additional electrical load from a furnace fan motor beyond that actually required to cool the home can be considered as an additional load to the air conditioning unit, requiring additional run time (and subsequent energy expenditure) to remove. For this reason, the relatively high value of $0.10 per kwh has been selected to reflect the value of additional electrical purchases during the shoulder and cooling seasons.

For the purposes of the this study the heating season is considered to extend from October 1st to March 31st, a period of 6 months.

I OUTDOOR PARTICULATE DATA

I.1 PM10 Data

Outdoor PM10 data (24-hour) was obtained from the Ontario Ministry of Environment and Energy (MOEE) for 21 Ontario locations for the Calendar year 1997. The average annual mean value from the 1997 Ontario data is 22.9 $\mu g/m^3$. The highest mean from any one site is 36.8 $\mu g/m^3$ and the lowest mean is 13.8 $\mu g/m^3$.

Other studies have reported the outdoor Inhalable Suspended Particulate (PM10) data shown in Table 16.

Table 16
Outdoor Inhalable Suspended Particulate Data (PM_{10})
from Other Studies

Reference	Location	Details	PM10 Daytime/ Unspecified	PM10 Night-time
Bahadori et al. 1995	Nashville TN	10 Air Conditioned Homes 12, 12 hr periods each home	33 $\mu g/m^3$	32 $\mu g/m^3$
Wallace et Al. Indoor Air '93, (PTEAM)	Riverside, CA	175 Homes, 48 day period	95 $\mu g/m^3$	86 $\mu g/m^3$
Lioy et Al. 1990	Phillipsburg NJ	Grey Iron Pipe Mfg is Local Source	60 $\mu g/m^3$	
Colombe et Al. 1990	Orange CA	10 Homes	61 $\mu g/m^3$	
Mumford et Al. 1991	Not known	8 Mobile Homes, 6.5 hours/day, 3 days per week, 2 weeks	18 $\mu g/m^3$	
Janssen et Al. 1995	Amsterdam (urban) and Wageningen (rural)	Wintertime	32-34 $\mu g/m^3$	

Detailed data was also obtained for the PM10 sampling station at Buchanan Park Public School in Hamilton Mountain. (MOEE site # 29324). This site was considered the most representative of the outdoor data obtained in this study for the following reasons:

1) It is geographically the closest (30 km vs 40 km or more)
2) It is in a residential area (most other MOEE sites are near industries or commercial areas).

Table 17 shows the general relationship between the PM10 values recorded at the Hamilton Mountain Site and the values recorded in this study. In general, the outdoor PM10 levels recorded in this study are comparable or somewhat lower than that obtained at the closest ambient atmospheric monitoring site. The ambient site would normally be expected to record higher PM10 levels as it is a suburban site close to a large city with regularly vehicular traffic, whereas the sites monitored in this study

Table 17
Comparison of Outdoor ISP (PM_{10}) Data with Hamilton Mountain Site

	Mean	Maximum	Minimum	Number of Samples
Hamilton 1997 Year	17	52	9[1]	49
Hamilton Nov '97 to April '98[2]	20	32	8	17
Study	10[3]	68[3]	9[4]	60

Notes:
1. 10th percentile of the data (minimum not available)
2. 28 non-consecutive individual days for the period of November 1997 through April 29th 1998. This period encompasses the period of the testing conducted for this study.
3. Maximum from individual data files, usually 10 to 24 hour averages
4. Minimum of House Summary values. House summary value is average of 10 days.

are suburban, semi-rural or rural, with samples taken in rear or side-yards. Several of the sites do not have regular vehicular traffic in the immediate area.

I.2 PM2.5 Data

Table 18
Outdoor Respirable Suspended Particulate Data ($PM_{2.5}$) from Other Studies

Reference	Location	Details	$PM_{2.5}$ Daytime/ Unspecified	$PM_{2.5}$ Night-time
Bahadori et al. 1995	Nashville TN	10 Air Conditioned Homes 12, 12 hr periods each home	23 μg/m³	22 μg/m³
Wallace et Al. Indoor Air '93, (PTEAM)	Riverside, CA	175 Homes, 48 day period	49 μg/m³	51 μg/m³
Sheldon et al. 1989	Onondaga, NY	224 homes	17 μg/m³	
Sheldon et al. 1989	Suffolk, NY	209 homes	22 μg/m³	

Outdoor $PM_{2.5}$ data is not available from a public air quality monitoring agency for the region where the testing took place.

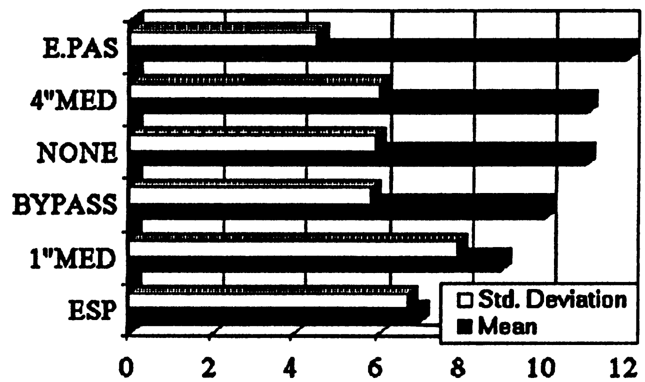
Other North American studies have reported the outdoor fine Respirable Suspended Particulate ($PM_{2.5}$) data shown in Table 18.

Mean outdoor $PM_{2.5}$ concentration measured over the course of this study was 7.9 μg/m³. Single day values ranging from 20 μg/m³ to 2 μg/m³ were recorded.

There is insufficient information to speculate as to why the outdoor $PM_{2.5}$ is significantly lower than that recorded in the other North American studies.

I.3 Variability of Outdoor Data

Figure 38
Outdoor PM_{10}, All Data
Arithmetic Mean and Standard Deviation .028



Outdoor particle levels were found to be extremely variable over the time period that each filter was tested, and between houses. Each filter and the "No Filter" case were tested for a period of 24 to 48 hours in each of the 6 homes. Outdoor particle levels were found to vary up to a factor of 7.5 from one test period to another. Figure 38 shows The arithmetic mean and standard deviations of outdoor particle level for all data-periods for each filter, sorted from lowest to highest outdoor level. In particular for the ESP and 1"MED filters, the standard deviation approaches the arithmetic mean value indicting a high level of uncertainty and the need for testing periods of longer duration in order to obtain meaningful results.

J PREVIOUS RESEARCH

Note:
The following is a discussion of some predecessor and relevant research. The discussion focusses on differences rather than similarities and should not be viewed as negating the validity or relevance of these studies. Refer to Section 1.10 for synopsis of these studies.

Raab - CMHC [ref 16]

This study did not involve actual testing and relied on information gathered for manufacturers and independent test reports when available. The study did not report on the "bypass' filtration configuration which was not being used at the time, nor did it report on passive electrostatic or charged pad filters types.

McCuaig - CMHC [ref 11]

This study reported on the tested characteristics of ordinary, medium pleated and electrostatic filters used in residential forced air systems. The study did not report on the "bypass' filtration configuration which was not being sued at the time. A particle counter was used to evaluate upstream vs downstream particle counts in one house with artificially injected tobacco smoke and some other artificial dust samples. There was no in-space or outside particle level monitoring nor was there control of the activity levels in the home or the air change rate during he test. A total of four homes were also evaluated for airflow characteristics with several filters.

Offermann et al [ref 8]

Offermann reported on the effect of residential type filters on particle removal in an unoccupied test chamber which approximated an apartment-sized living quarters. High particle levels were generated using a cigarette smoking machine and the decay of particle concentrations was measured at several locations with no filtration and with filtration. The air handling rate was approximately 700% higher (11.7 air turnovers per hour) than would be experienced in a typical Canadian home[37].

Offermann reported results expressed "Effective Cleaning Rate" being 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.

No account was made for air change between the space and outside as according to the authors, the chamber was tightly sealed against air leakage.

Airflow rates in the Offermann study ranged from 269 to 412 L/s which is comparable to the range of air-flows in this study, however the probable static pressure drops (at the filter) from 6 Pa to over 250 Pa in the Offermann Study. Most residential air-handling systems are not tolerant of individual components which generate pressure drops of more than 100 Pa and it is probable that the device velocities in the Offermann study were substantially higher than for this project.

Burroughs et al [ref 15]

Air turnover rate for the air-handling system was 5.4, which is approximately 360% more than would be expected in a typical Canadian home. Particle measurements

37 1.5 Air Turnovers is recommended by The HRAI Residential Air System Design Manual [ref 14].

were made upstream, downstream and in the basement area. There were no particle measurements upstairs, and outdoor particle levels were measured but not at the same time that the indoor sampling occurred. Household activity was not controlled during the experiment, and a major indoor source of particles was present in the form of a wood-working shop. The air handling system had substantial sections of ductwork located in the attic which was not well sealed from the outside environment. Most Canadian homes do not have ductwork located outside of the house envelope and thus there is very little interaction between the duct-work air and the outdoor air, except when a direct outdoor air intake is used.

The co-author of the Burroughs study, Kevin E. Kinzer is the Technical manager of the Construction and Home Improvement Market Division of 3M. 3M manufactures and distributes one of the filters tested.