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Evaluation of Five Simple Ventilation Strategies Suitable for Houses Without Forced-Air Heating

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ABSTRACT

Houses without forced-air heating systems may not experience adequate distribution of their outdoor air supply. This project examined five simple ventilation systems suitable for such houses. Four were exhaust-only, using either only local exhaust fans in the kitchen and bathrooms or the local exhaust fans supplemented with a partially distributed exhaust system with pickups in each bedroom. Each approach was tested with deliberate passive inlet vents (both distributed and centralized) both open and closed. The fifth system was a supply and exhaust system with small-sized ducts supplying outdoor air to each room and the local exhaust fans providing the exhaust.

The five ventilation systems were installed in a two-story house that also has an electric forced-air heating system. Using tracer gas techniques, the air distribution patterns provided by each system for a wide range of weather conditions were measured and compared with similar reference measurements in the house with no mechanical air exchange with the outdoors and with only the forced-air furnace fan operating to circulate the air within the house.

The local exhaust fan system with no passive inlet vents was found to provide inadequate distribution of the outdoor air supply, only marginally better than simple air leakage alone. With the distributed passive inlet vents open, the local exhaust fan system was found to distribute more outdoor air to the ground-floor rooms than the upper-story bedrooms. The partially distributed exhaust system was effective at improving the ventilation air distribution to the bedrooms. The minimal ducted supply system provided the best outdoor air distribution to all the habitable rooms.

INTRODUCTION

Adequate ventilation is essential in houses to ensure acceptable indoor air quality (IAQ) and to control condensation. In Canada, the measure of adequate ventilation in a house is compliance with the Canadian Standard CAN/CSA-F326-M91 (CSA 1991), which specifies the minimum outdoor air change rate for the entire house as well as ventilation rates for individual rooms to ensure adequate air distribution within the house, not unlike ASHRAE Standard 62-1989 (ASHRAE 1989).

Houses with forced-air heating systems that circulate air to most rooms in the house through ducts are generally regarded as well ventilated when the furnace includes a fresh air supply duct and the furnace fan is operating. Many houses without fresh air supply ducts may experience sufficient air supply through air leakage, and a forced-air heating system helps to evenly distribute that fresh air throughout the house. Houses with alternative heating systems that do not include ducts may not experience adequate distribution of their fresh air supply. The research described in this paper examined simplified ventilation system designs suitable for houses that do not have the ducted air delivery system of forced-air heating (Reardon 1995).

The simplified ventilation strategies considered in this project were exhaust-only and balanced approaches. The exhaust-only strategies either used only local exhaust fans in the kitchen and bathrooms or included a centralized exhaust system with pick-up grilles in each bedroom in addition to the kitchen and bathroom fans. Make-up air was provided either through one or more deliberate passive inlet vents or by air leakage. The balanced strategy used the kitchen and bathroom fans for its exhaust side and a ducted supply system for its supply side. The ducted supply system was sized to provide only ventilation air requirements, not the larger flow rates required in a forced-air heating system.

These various ventilation systems were tested by installing them in a modern, wood-frame, two-story research house in Ottawa, Ontario, Canada. The air distribution performance of each system was evaluated, using tracer gas techniques, for a wide range of typical Canadian weather conditions during a late autumn to late spring heating/shoulder season in Ottawa. The existing electric forced-air heating system originally installed in

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the research house provided two reference cases for useful comparison with the various test ventilation systems: with and without the furnace fan operating continuously to circulate the air within the house interior with all windows, doors, and vents closed.

The results of these tracer gas tests are presented and discussed. This research addressed only the air distribution performance of the various ventilation strategies. Conclusions, based on the tests' results, about which ventilation strategies merit further examination and development toward market-ready prototypes are offered at the end of this paper. In a subsequent research project, the impacts on thermal comfort, noise, and energy consumption of the various ventilation systems will be studied and their realistic installation costs evaluated.

EXPERIMENTAL FACILITY—THE RESEARCH HOUSE

The experiments were conducted in a two-story house research facility in Ottawa (Reardon 1995). The house was built in 1989/90 using standard residential wood-frame platform construction techniques, with a full-depth, poured concrete basement on a level grade. The dimensions of the house are 8.33 m by 9.55 m (27.3 ft by 31.3 ft) with the second story's ceiling 5.96 m (19.5 ft) above grade. Ceiling heights are 2.44 m (8 ft) on each story. The house is oriented with its front facade facing exactly true north. The heating is provided by a forced-air electric furnace. Electric baseboard units are also installed to allow non-forced-air heating situations to be studied. The furnace and all the forced-air ducts are contained within the heated building envelope.

The layouts of the rooms on each story in the research house are illustrated in Figure 1. The room labels are identified in Table 1. All the partition walls are of sealed drywall construction. Hollow-core wooden doors on prehung frames are installed in each room with 19-mm (3/4-in.) undercuts between the bottoms of each door and the painted plywood floor.

VENTILATION REQUIREMENTS FOR THE RESEARCH HOUSE

The minimum ventilation requirements for the various rooms in the research house, as specified in the CSA F326 standard, are listed in Table 1. These are typical for a three-bedroom house. The total outdoor air supply flow rate requirement for the

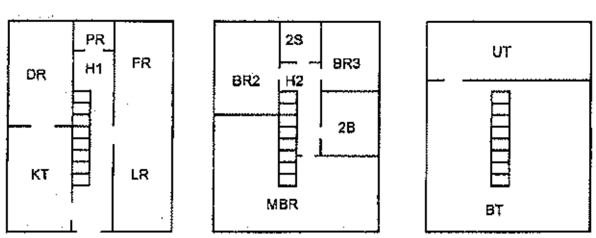

Figure 1 Floor plan layouts in the research house facility.

house based on the sum of the room-by-room requirements is 65 L/s (138 cfm), which is equivalent to just under 0.5 air changes per hour (ACH) and well above the standard's minimum requirement of 0.3 ACH. On a floor-by-floor basis, these requirements represent outdoor air supply flow rates of 25 L/s (53 cfm) for the second floor, 25 L/s (53 cfm) for the first (ground) floor, and 15 L/s (32 cfm) for the basement level. Where appropriate, the tested ventilation systems were designed to provide for these zonal floor-by-floor ventilation requirements. The standard does not specify minimum ventilation requirements for spaces such as hallways, vestibules, and storage rooms and closets, which are not regarded as "habitable rooms." The standard also requires capabilities for either continuous exhaust of 30 L/s (64 cfm) for the kitchen and 10 L/s (21 cfm) for each bathroom or intermittent exhaust of 50 L/s (106 cfm) for the kitchen and 25 L/s (53 cfm) for each bathroom.

DESCRIPTION OF VENTILATION SYSTEMS

Most modern Canadian houses already have exhaust fans installed in their kitchens and bathrooms. The continuous operation of these fans represents the simplest mechanical ventilation system for a house. Continuing with exhaust-only mechanical ventilation, a straightforward approach to improve air distribution to closed rooms, such as bedrooms, would be to directly exhaust air from all the closed rooms using a centralized exhaust fan with pickups in each closed room. A logical approach to improve the fresh air performance of exhaust-only systems would be to provide deliberate inlet vents for their make-up air requirements. A direct approach to provide ventilation air to each room would be a mechanical supply system with ducted delivery outlets in each room, balanced by either centralized or distributed exhaust to avoid pressurizing the house interior. The CSA F-326 standard also limits the allowed amount of building pressurization to avoid encouraging the migration of interior moisture into wall cavities in the building envelope. The tested ventilation systems are described below and are illustrated in Figures 2, 3, and 4.

Local Exhaust System

Configuration A (Figure 2, vents closed) consisted of local exhaust fans in the kitchen and in each of the two bathrooms (main floor powder room [PR] and second-floor bathroom [2B]) operating at 30 L/s (64 cfm), 10 L/s (21 cfm), and 25 L/s (53 cfm), respectively. The kitchen and powder room fans were intended to provide together the mechanical ventilation for the basement and the first floor. The bathroom fan was intended to meet the ventilation needs of the second floor. Make-up air entered the house through general air leakage. Total mechanical exhaust from the house was 65 L/s (138 cfm).

Local Exhaust System with Vents

Configuration B (Figure 2, vents open) was a combined passive and mechanical ventilation system consisting of the same setup and fan flow rates as in configuration A plus deliberate air intake openings in the dining room and the living room

TABLE 1 Minimum Ventilation Air Requirements

Space Classification (Room Type)	Minimum Ventilation Rate [L/s]	Number of Rooms of Type	Total Requirement for Type [L/s]
Master Bedroom [MBR]	10 (21 cfm)	1	10
Basement [BT]	10	1	10
Single Bedrooms [BR2, BR3]	5 (10.6 cfm)	2	10
Living Room [LR]	5	1	5
Dining Room [DR]	5	1	5
Family Room [FR]	5	1	5
Other Habitable Room	5	0	0
Kitchen [KT]	5	1	5
Bathrooms [PR,2B]	5	2	10
Utility Room [UT]	5	1	5
Total Minimum Ventilation Required for House			65 (138 cfm)

for the ground floor and in each bedroom for the second floor. All the vents were circular holes cut into sheet metal inserts in the casement window panels. The diameters of these vents were 102 mm (4 in.) in the master bedroom, 76 mm (3 in.) in each of the other two bedrooms, and 134 mm (5.25 in.) in each of the two ground-floor locations: living room and dining room. These sizes were determined using the sharp-edged orifice relationship, a discharge coefficient of 0.6, and the seasonal average pressure difference across the building envelope of 3.6 Pa. This pressure difference had been determined from a previous research project in the same house in which envelope pressures were continuously monitored at 22 locations around the house exterior for one complete year (Reardon 1993; Reardon and Shaw 1993). The bedroom vents were sized to admit the flow requirements for each bedroom, and the vents on the ground floor were sized to each admit half of the balance of the house ventilation requirement. Total mechanical exhaust from the house was 65 L/s (138 cfm).

Partially Distributed Exhaust System

Configuration C (Figure 3, vent closed) consisted of the same exhaust fans and flow rates in the kitchen and powder room to provide the mechanical ventilation for the ground floor and the basement combined, an exhaust system for the upstairs with a return air grille in each bedroom (the exhaust fan and ducts would typically be located in the attic), and a reduced flow of 10 L/s (21 cfm) through the exhaust fan in the second-floor bathroom. The exhaust flow rates from the bedrooms were 10 L/s from the master bedroom and 5 L/s (10.6 cfm) from each of the other two bedrooms. Background air leakage was relied upon for make-up air. Total mechanical exhaust from the house was 70 L/s (148 cfm).

Partially Distributed Exhaust System with Vent

Configuration D (Figure 3, vent open) consisted of the partially distributed exhaust (PDE) system as described above in configuration C, plus one centralized passive outdoor air intake ducted from the outside to open into the stairwell between the first and second floors and sized at 102 mm by 457 mm (4 in. by 18 in.) to provide the total house outdoor air supply requirement. This vent/supply duct could typically be installed in one or more floor joist spaces. Total mechanical exhaust from the house was 70 L/s (148 cfm).

Minimal Ducted Supply System

Configuration E (Figure 4) consisted of a minimal ducted supply (MDS) and return system. The return system was an exhaust arrangement identical to configuration A. The supply system was composed of two subsystems: one supplied tempered outdoor air to the second-floor rooms and one supplied tempered outdoor air to rooms on the first floor and in the basement at the flow rates specified in Table 1. The supply system was divided into two subsystems to be a suitable design approach for retrofit situations. The fan, preheater, and ducts of the second-floor supply system could typically be installed in unused attic space. The equipment and ducts for the basement and first-floor supply system could be installed in and from the basement. Retrofitting ducts for the second floor from the basement would often be impractical in real situations. This test system was assembled from polyvinyl chloride (PVC) domestic drain pipe and fittings, with 50 mm (2 in.) diameter delivery branches whose exits were dampered and balanced. Total exhaust and supply airflow rates were each 65 L/s (138 cfm).

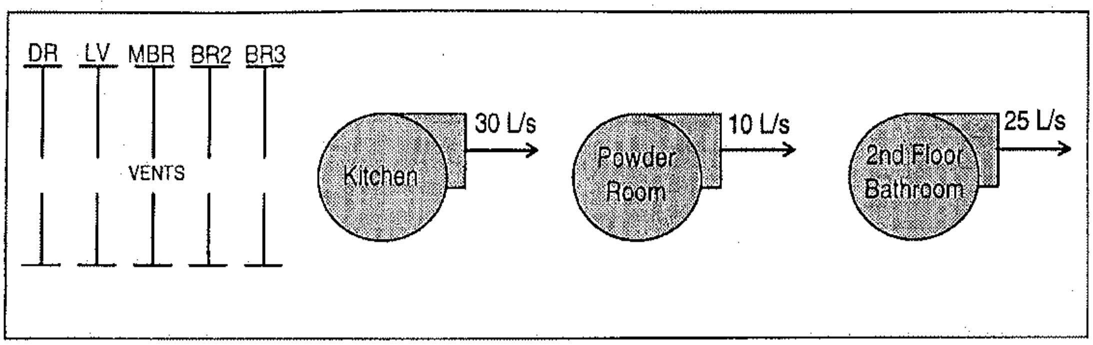

Figure 2 *Schematic illustration of local exhaust fan strategy—configuration A has vents closed, configuration B has vents open.*

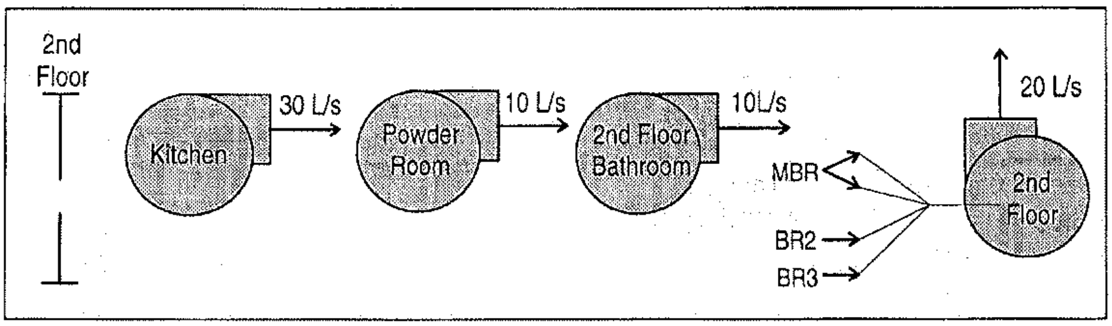

Figure 3 *Schematic illustration of partially distributed exhaust strategy—configuration C, vent closed; configuration D, vent open.*

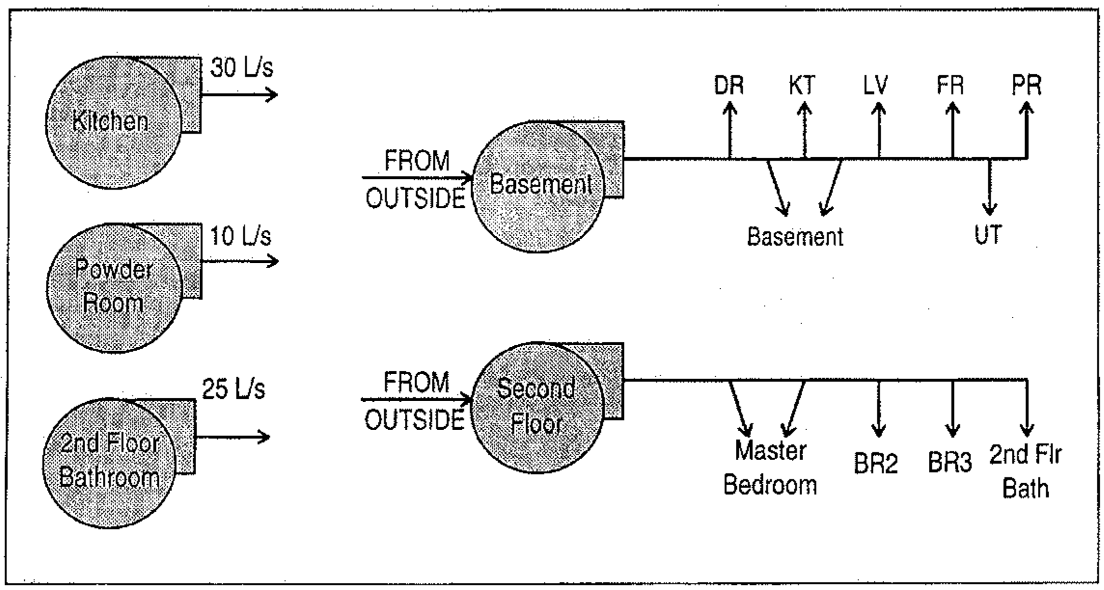

Figure 4 *Schematic illustration of minimal ducted supply system—configuration E.*

Reference Case Without Circulation

In this reference case, all doors and windows were closed tightly, all ventilation fans were turned off and their outlet openings were sealed, the forced-air heating system's supply and return grilles were sealed, and the furnace fan was turned off. The only mechanism for air exchange with the outdoors was air leakage.

Reference Case with Circulation

This reference case was the same as configuration F except the forced-air heating system's supply and return grilles were open and the furnace fan was running continuously to circulate the air inside the house. The only mechanism for air exchange with the outdoors was air leakage. The furnace fan operation should have had no effect on the air exchange with outdoors because, as is typical for most Canadian houses, all the ducts are located within the building envelope.

THE BUILDING ENVELOPE AIRTIGHTNESS FOR EACH VENTILATION CONFIGURATION

The fan depressurization technique (CGSB 1986; ASTM 1987) was used to measure the airtightness characteristics of the exterior envelope of the whole house for each of the ventilation system configurations. For each measurement, the openings of all the ventilation fans to the outdoors were carefully sealed to prevent their flow area from being included in the building airtightness measurement. The measured results include the accidental leakage area of the building envelope and the equivalent leakage area of the deliberate vents of each configuration. The measured flow coefficient, flow exponent, equivalent leakage area (ELA), and normalized leakage area values for each test configuration are listed in Table 2. Also listed in Table 2 are the net exhaust flow rates of each ventilation system configuration and the predicted house depressurization created by those net exhaust flow rates, based on the measured airtightness characteristics.

As expected, the ELA values of configurations A, C, and E are virtually identical because the envelope conditions were identical; all the fan outlets and inlets were sealed for these measurements. The increased ELA for configurations F and G was due to the removal of the special seal of the inlet for the basement minimal ducted supply system (configuration E); it was in place for the measurements of configurations A through E. The ELA of configuration B, due to its passive inlet vents, was more than double the value for configurations A, C, E, and F/G; and the ELA for configuration D, due to its single passive inlet vent, was almost double that of configuration B. The additional leakage area provided by the single passive inlet vent of configuration D should easily accommodate its extra 5 L/s make-up air requirement.

EXPERIMENTAL METHODS

Tracer gas techniques were used to examine the air distribution patterns in the two-story research house for the seven ventilation system configurations. These techniques involved a system to repeatedly sample the air in the various rooms and to measure the concentration of the tracer gas or gases in those air samples. The gas sampling and analysis system was operated automatically by a computerized data-acquisition and control system that allowed hands-off operation of each test once the test conditions were set up and the test was started.

The two tracer gases used in these tests were nitrous oxide (N_2O) and sulfur hexafluoride (SF_6). An absorptive infrared analyzer was used to measure the concentrations of N_2O in the 0 to 200-ppm range. A gas chromatograph with an electron capture detector and fitted for backflushing for rapid sample analysis was used to measure the concentrations of SF_6 in the 0 to 200-ppb range. Air samples were pumped from central loca-

TABLE 2 Measured Building Envelope Airtightness Characteristics and Interior Depressurizations for Each Ventilation System Configuration

Config. ID	Flow Coeff.* C [L/s Pa^n]	Flow Exp.* n	ELACGSB ** @10 Pa [cm^2]	NLA*** [cm^2/m^2]	Net Exhaust Flow [L/s]	House Negative Pressure* [Pa]
A	21.59	0.656	393	1.34	65	5.4
B	60.15	0.582	922	3.15	65	1.1
C	22.53	0.650	404	1.38	70	5.7
D	105.66	0.611	1731	5.92	70	0.5
E	21.83	0.654	396	1.35	0	0
F,G	24.33	0.636	423	1.45	0	0

*Air leakage curve, $Q[L/s] = C[L/s\ Pa^n] \bullet (\Delta P[Pa])^n$, ref. (CGSB 1986).
**ELA calculated according to standard CAN/CGSB-149.10-M86, ref. (CGSG 1986).
***Total exterior above-grade envelope area, $A = 292.54\ m^2$, NLA = ELA/A.

tions near the centroid in each room through a 16-position sampling valve to the gas analyzers by flexible plastic tubing. Earlier work (Evans and Shaw 1988) has demonstrated that normal rectangular rooms typically achieve well-mixed conditions within 10 to 30 minutes of tracer gas injection and remain well mixed thereafter throughout a normal concentration decay for room air change rates in the range of 0 to 1 ACH. This formed the basis for the assumption that these air samples drawn from the centroid of each room well represented the air throughout their room. The concentration measurement sampling rate was approximately 45 seconds per sample, so a complete cycle of the 16 valve positions occurred every 12 minutes.

The exhaust duct of each of the three exhaust fans was instrumented to precisely measure the flow rate through each fan. Each of the four pickup branches of the PDE system (configurations C and D) was similarly instrumented to measure the individual exhaust flow rates in each branch. Each of the 13 supply branches of the MDS system (configuration E) was also instrumented to measure the individual supply flow rates in each branch. Each flowmeter was composed of an averaging tube spanning the duct's diameter and a static pressure tap at the duct wall and was calibrated against a laminar flow element with an accuracy of 0.5% of reading. The velocity pressures were measured using differential pressure transducers. The precision of the calibrated flowmeters is better than 4%. These flow rates were automatically monitored and recorded continuously throughout each test by the data-acquisition system.

Simultaneous Room-by-Room Air Distribution Tests

For these tracer gas tests, the forced-air furnace fan and ducts were used to distribute and mix the dose of a single tracer gas to a uniform concentration throughout the entire house. A mixing time of 30 minutes was sufficient with all the interior doors opened wide and without any additional ventilation or vents open. At the end of the mixing period, the forced-air ducts were sealed; all bedroom, bathroom, and basement doors were closed; and operation of the test ventilation system was started. Automatic monitoring of the tracer gas concentration in each room and in the hallways on the ground- and second-floor levels was started at the same time as the injection of the tracer gas dose and continued for 2.5 hours. The logarithm of the concentrations of the tracer gas in each room and hallway was plotted against time. Either of the two tracer gases could be used for these tests. The principal objective of these tests was to identify differences in air distribution patterns provided by the various ventilation strategies.

Master Bedroom Total Air Change Rate Tests

These tests were set up in an attempt to determine the actual total air change rate in the master bedroom (MBR), including the inflows of outdoor air and interior air from other rooms. This total flow rate (air distribution) into the MBR would allow comparison of the overall air distribution behavior of each ventilation system, not just its outdoor air supply flow rate to the MBR. The master bedroom was selected for these tests for two reasons. First, its ventilation requirement is twice that of most other rooms in the house. Second, as an upper-story room, much of its inflow can be expected to be interior air from other rooms, especially lower-story rooms, due to the influence of stack effect, which may confound the simultaneous room-by-room air distribution tests.

The master bedroom door was sealed to isolate the MBR from the rest of the house interior. The SF_6 tracer gas was injected into the MBR through remote pumping, where it was mixed using box fans. After a 30-minute mixing period, the MBR door was unsealed but remained closed, and its mixing fans and injection pump were switched off. The furnace fan was off and its ducts were all sealed; all the bedroom, bathroom, and basement doors were closed; and operation of the test ventilation system was started. Automatic monitoring of the tracer gas concentrations in each room and hallway was started at the time of the tracer gas injection and was continued for at least 6.5 hours.

The following equation was used with nonlinear regression techniques to fit the first two hours of the decay of the SF_6 tracer gas concentration in the MBR, following the initial mixing period, to determine the total air exchange taking place in the MBR:

$$C(t) = C_0 \cdot \exp(-I_{Local} \cdot t) \tag{1}$$

where

$C(t)$ = gas concentration (ppm or ppb, as appropriate),

C_0 = initial gas concentration (ppm or ppb),

I_{Local} = local decay rate and estimate of the local air change rate (ACH), and

t = time of decay from initial time zero (h).

This procedure should not be confused with the standard single tracer gas technique used to measure the outdoor air change rate in a single-zone building as defined in ASTM Standard E-741 (ASTM 1993).

RESULTS

Ten simultaneous room-by-room tests and four master bedroom tests of each ventilation strategy were conducted between the late fall and late spring of the 1993/94 heating season to cover a broad range of weather conditions in Ottawa. The ranges of outdoor air temperatures (OATs) at which each ventilation system configuration was tested are listed in Table 3. On-site measurements of wind speed and direction were not available during the test period. Each configuration was tested for a comparably wide range of OATs, from very cold conditions to quite mild conditions. The coldest temperatures are representative of typical severe cold winter conditions (ASHRAE [1993] indicates a winter design temperature of −27°C [−16.6°F] for Ottawa), and the mildest temperatures in each range are typical of mid- to late spring conditions in Ottawa. These temperature ranges represent typical heating and shoulder season conditions in Ottawa.

TABLE 3 Temperature Ranges for the Tracer Gas Tests

Config. ID	Outdoor Temperatures for Simultaneous Room-by-Room Air Distribution Tests [°C]	Outdoor Temperatures for Master Bedroom Total Air Change Rate Tests [°C]
A	−23, −16, −9, −8, −7, −5, 2, 3, 5, 10, 11, 17	−26, −13, −8, 0
B	−24, −13, −13, −3, 1, 2, 3, 4, 10, 11	−26, −15, 3, 16
C	−19, −10, −9, −9, −1, 4, 5, 8, 11, 12, 19, 19	−24, −19, −4, 2, 5
D	−23, −20, −15, −11, −7, 1, 4, 5, 6, 8, 12, 15	−19, 1, 6, 17
E	−14, −9, −7, 0, 2, 5, 8, 10, 11, 12	−9, −9, 7, 9
F	−16, −14, −13, −8, −1, 2, 6, 8, 12, 13, 15	−16, −15, 3, 11
G	−19, −15, −11, −1, 2, 5, 8, 10, 11, 14	−18, 0, 0, 8, 8

Since at the start of each test, the tracer gas concentrations in each room were the same, differences in the rates of decay for the various rooms, therefore, provide good indications of the relative amounts of outdoor air entering individual rooms, either directly or indirectly.

As mentioned earlier, the flow rates through each exhaust fan, each pickup branch of the PDE system, and each supply branch of the MDS system, as appropriate, were monitored continuously throughout each tracer gas test. These direct flow rate measurements were analyzed for each test and the results indicated that all the design flow rates were maintained consistently, within the measurement accuracy of 4%, throughout each test. Therefore, for tests of the local exhaust system, exhaust flow rates of 30 L/s from the kitchen, 10 L/s from the powder room, and 25 L/s from the second-floor bathroom were held constant. For tests of the PDE system, exhaust flow rates of 30 L/s from the kitchen, 10 L/s from the powder room, 10 L/s from the second-floor bathroom, 10 L/s from the master bedroom, and 5 L/s from each of the other two bedrooms were held constant. For tests of the MDS system, exhaust flow rates of 30 L/s from the kitchen, 10 L/s from the powder room, and 25 L/s from the second-floor bathroom and supply flow rates of 10 L/s to the master bedroom and the basement room and 5 L/s to each of the other rooms in the house were held constant.

Configuration F—Reference Case Without Circulation

Figure 5 reports the simultaneous room-by-room tracer gas decay curves measured for a configuration F test at an OAT of −13°C (8.6°F). This figure illustrates that under these conditions of natural air exchange, the individual stories behaved as distinct well-mixed zones. This suggests that (a) basement leakage openings play a major role in the air exchange by natural infiltration and (b) stack effect dominates this infiltration air exchange.

Configuration G—Reference Case with Circulation

Figure 6 shows the simultaneous room-by-room tracer gas decay curves measured for a configuration G test at an OAT of −19°C (−2.2°F). This figure illustrates that the mechanical recirculation caused by continuous furnace fan operation creates a well-mixed condition throughout the house. These tests indicate the effectiveness of the forced-air heating system at evenly distributing the ventilation air throughout the house, despite the closed interior doors. Therefore, the door undercuts sized according to the CSA F326 standard do not seem to hinder the good air circulation of the forced-air system to rooms with closed doors.

Configuration A—Local Exhaust System

The simultaneous room-by-room tracer gas decay curves measured for two configuration A tests at OATs of −23°C (−9.4°F) and 11°C (51.8°F) are shown in Figures 7a and 7b. In Figure 7a, at a very cold OAT, the three bedrooms behave almost as one well-mixed zone, with a shallow decay curve compared to the much

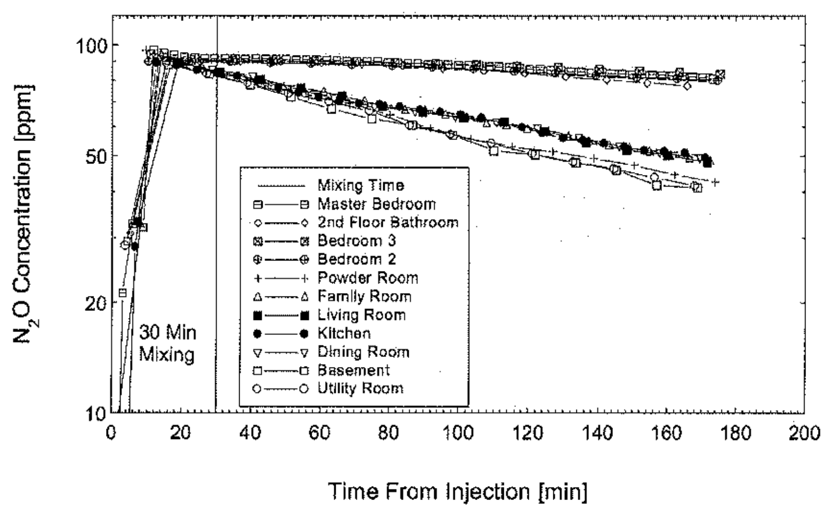

Figure 5 *Simultaneous room-by-room decay measurements for configuration F at -13°C. Reference case - windows and vents sealed, fans off, furnace fan off.*

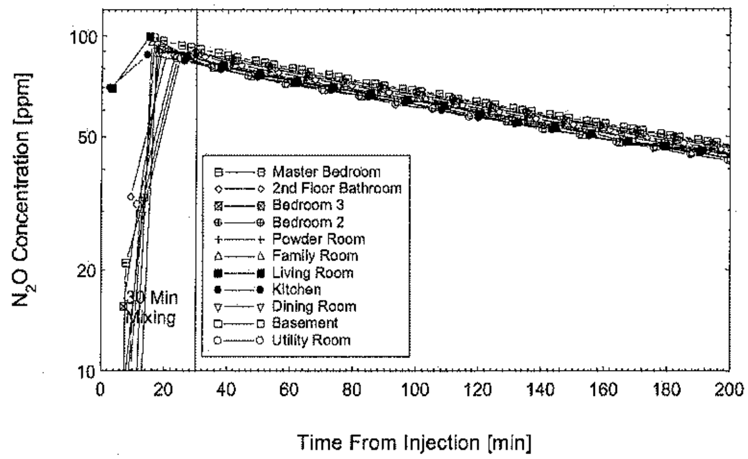

Figure 6 *Simultaneous room-by-room decay measurements for configuration G at –19°C. Reference case—windows and vents sealed, fans off, furnace fan on.*

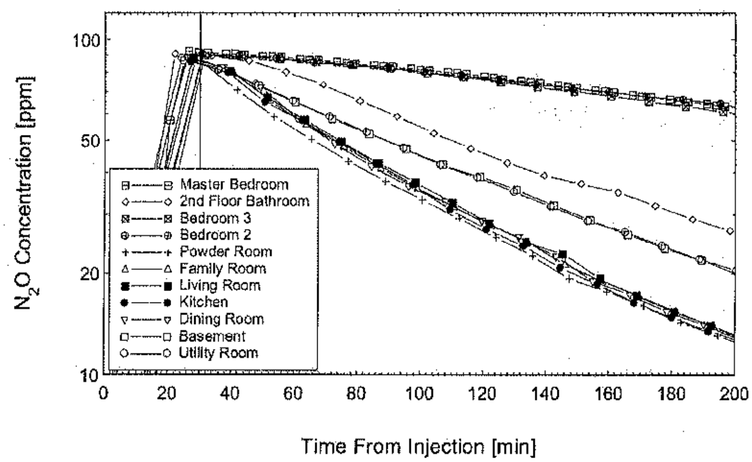

Figure 7a *Simultaneous room-by-room decay measurements for configuration A at –23°C. Local exhaust system—vents sealed.*

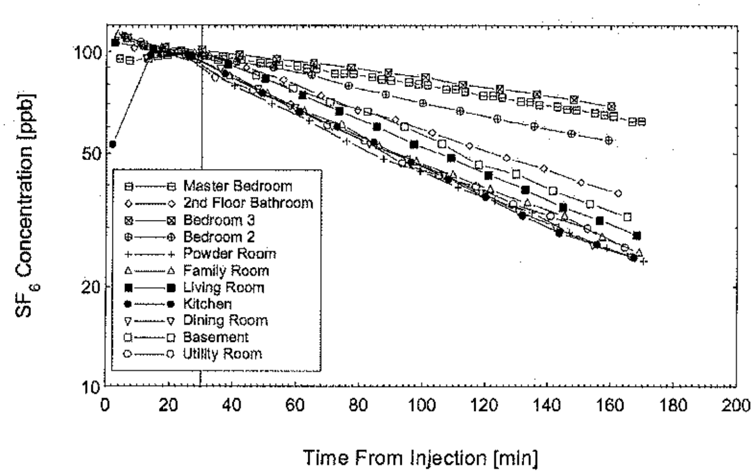

Figure 7b *Simultaneous room-by-room decay measurements for configuration A at +11°C. Local exhaust system—vents sealed.*

steeper decay curves for the rest of the zones and rooms in the house, including the second-floor bathroom. This is consistent with a strong stack effect where air leaks out of the upper story, so virtually all the air flowing into the bedrooms would be indoor air from rooms on the lower stories while most of the air flowing into rooms on the lower stories would be direct leakage from outdoors. The larger decay rate in the second-floor bathroom is a consequence of the direct exhaust from that room to the outside, which would cause an increased flow into that room from the rest of the house interior. However, in Figure 7b, at much milder conditions, the decay curves of the bedrooms have spread out and steepened slightly while the decay curves for the rooms on the lower floors have become shallower and grouped closer to each other and to the decay curves for the bedrooms. This is consistent with mild stack effect, where the adverse envelope pressure differences, acting to drive leakage air from indoors to the outdoors for upper-story rooms, would be very small and able to be overcome and reversed by the overall house depressurization impact of the exhaust fans' operation—5.4 Pa (0.022 in.w.g.), as indicated in Table 2.

Configuration B—Local Exhaust System with Vents

The simultaneous room-by-room tracer gas decay curves measured for two configuration B tests at OATs of −24°C (−11.2°F) and 11°C (51.8°F) are graphed in Figures 8a and 8b. A comparison with the configuration A results for similar temperatures indicates that the deliberate vents in configuration B have aggravated the uneven distribution of outdoor air between the upper-story bedrooms and the rest of the house.

Table 2 indicates that the deliberate (make-up air) vents increased the overall equivalent envelope leakage area by 529 cm^2, or 134%, and reduced the house interior depressurization caused by the 65 L/s total exhaust flow to 1.2 Pa (0.005 in. w.g.) compared to configuration A. This decrease in the pressures driving airflow through the basement leaks would result in a

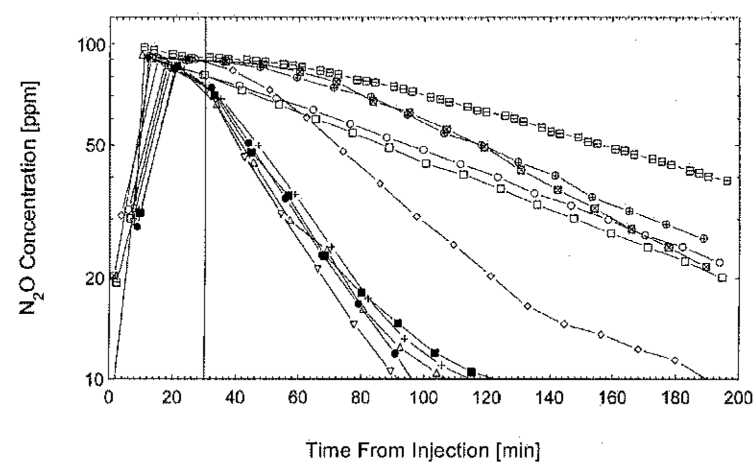

Figure 8a *Simultaneous room-by-room decay measurements for configuration B at −24°C. Local exhaust system —vents open.*

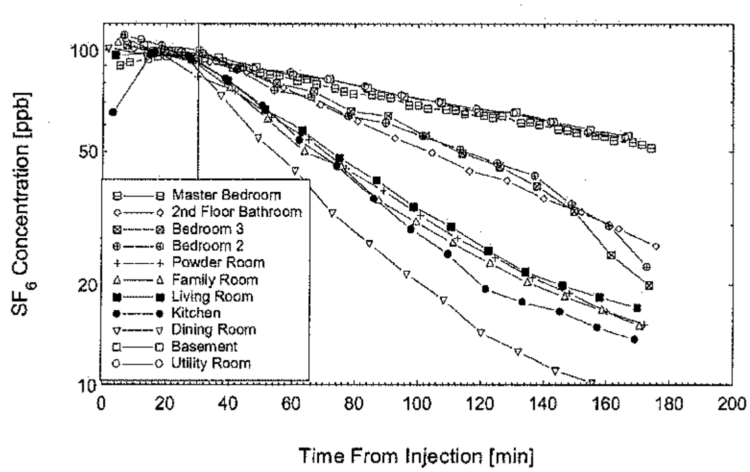

Figure 8b *Simultaneous room-by-room decay measurements for configuration B at +11°C. Local exhaust system—vents open.*

smaller infiltration airflow into the basement and a lower neutral pressure level (NPL) for configuration B than for configuration A. These observations are illustrated in Figures 8a and 8b. The decay rates and, hence, the amounts of outdoor air entering the basement rooms decrease most dramatically for the increase in OAT, becoming the lowest of all the zones in Figure 8b, even smaller than in all the bedrooms.

Configuration C—Partially Distributed Exhaust System

The simultaneous room-by-room tracer gas decay curves measured for two configuration C tests at OATs of −19°C (−2.2°F) and 11°C (51.8°F) are graphed in Figures 9a and 9b. A comparison of configurations A and C indicates that the partially distributed exhaust (PDE) system's distributed pickup seems to have been somewhat successful in better distributing the supply of outdoor ventilation air to the second-floor rooms, as indicated by their steeper decay curves and, hence, greater decay rates.

Figure 9a at −19°C (−2.2°F), when compared to Figure 7a, illustrates the impact of the PDE system's distributed pickup to reduce the concentrations in all of the bedrooms while stack effect dominance still clearly distinguishes the three stories as separate zones. Figure 9b at 11°C (51.8°F) illustrates a diminished influence of stack effect for the milder OAT, thereby reducing the amount of outdoor air entering the lower floors and bringing them closer to the values on the second floor. At this mild temperature, the distributed direct mechanical exhaust from each bedroom maintains an improved distribution of outdoor air to the bedrooms compared to the local exhaust system of configuration A (Figure 7b).

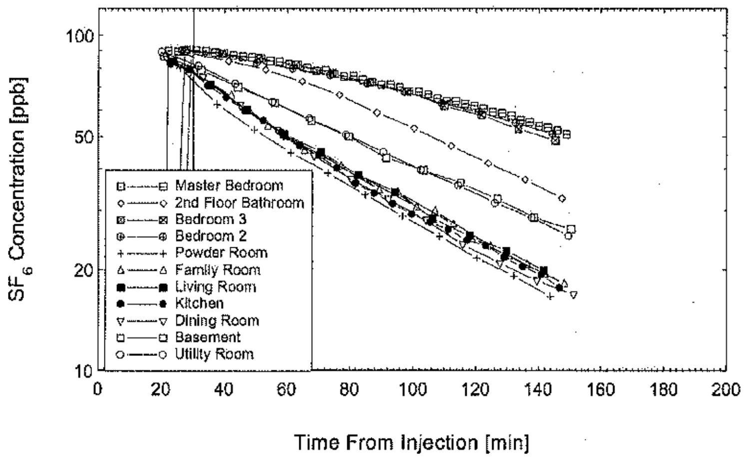

Figure 9a Simultaneous room-by-room decay measurements for configuration C at −19°C. Partially distributed exhaust system —vent sealed.

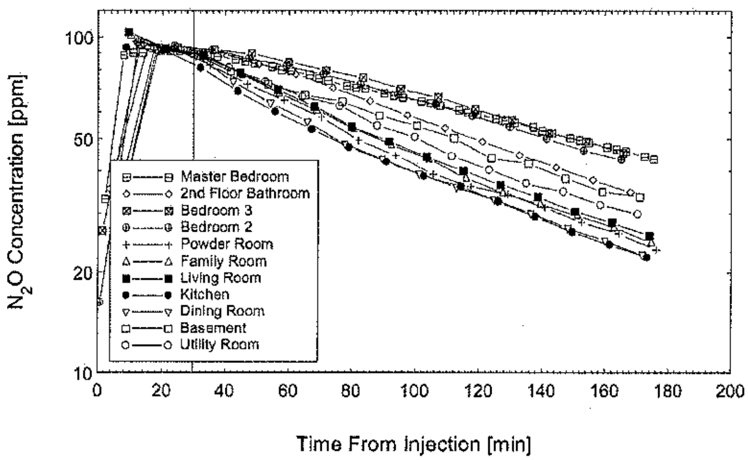

Figure 9b Simultaneous room-by-room decay measurements for configuration C at +11°C. Partially distributed exhaust system —vent sealed.

Configuration D—Partially Distributed Exhaust System with Vent

The simultaneous room-by-room tracer gas decay curves measured for two configuration D tests, at OATs of –23°C (–9.4°F) and 12°C (53.6°F), are graphed in Figures 10a and 10b. The test results in Figure 10a for very cold conditions show that the three stories definitely behave as three distinct zones, with the ground floor and the second-story bedrooms each well mixed, not dissimilar to Figure 9a for configuration C at cold OATs. The results in Figure 10b indicate that for a mild OAT the rooms on the first floor behave separately (much less like a cohesive single zone) and the basement apparently receives the least outdoor air (shallowest decay curve). Similar to the observations stated for configuration B above, these results probably reflect the large increase in envelope leakage area provided by the single centralized vent and the small depressurization of the house interior resulting from the operation of its exhaust fans (Table 2 indicates a depressurization effect of only 0.5 Pa [0.002 in.w.g.] with the ELA of 1,731 cm^2 [1.8 ft^2]). The pressures driving infiltration airflow into the basement would be the smallest, and the NPL could also be expected to be the lowest of all the exhaust-only configurations. When compared with configuration C results at a similar mild OAT, second-floor rooms display similar decay rates and seem to receive similar amounts of outdoor air, while the first-floor rooms seem to receive more outdoor air in configuration D, as indicated by their steeper decay curves and, hence, greater decay rates.

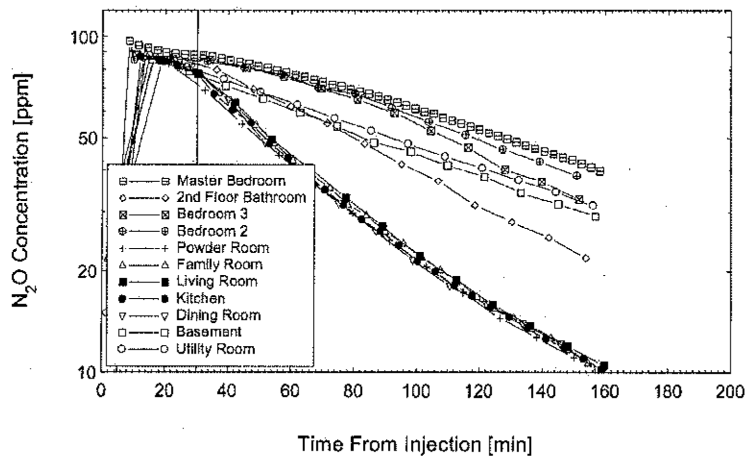

Figure 10a Simultaneous room-by-room decay measurements for configuration D at –23°C. Partially distributed exhaust system —vent open.

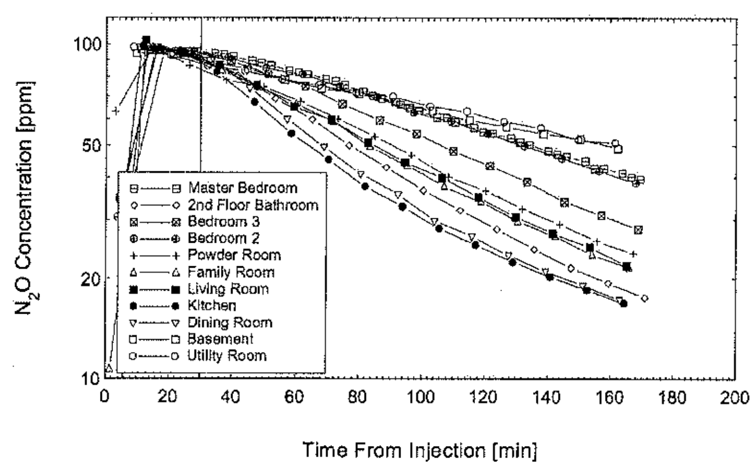

Figure 10b Simultaneous room-by-room decay measurements for configuration D at +12°C. Partially distributed exhaust system—vent open.

Configuration E—Minimal Ducted Supply System

The simultaneous room-by-room tracer gas decay curves measured for two configuration E tests at OATs of −14°C (6.7°F) and 12°C (53.6°F) are graphed in Figures 11a and 11b. The results indicate that configuration E provides the best outdoor air distribution to all the habitable rooms, as indicated by the relatively uniform decay rates. Comparison of these results with those for all the other configurations tested indicates that configuration E provided the best air distribution to the closed bedrooms, as shown by their steepest decay curves.

These two figures indicate that the whole house, with the exception of the powder room, is generally well mixed with configuration E and show that the results are not significantly influenced by the outside air temperature. This may be due in part to the balanced nature of configuration E, where mechanical supply and exhaust flow rates were equal, and in part to the lack of any deliberate vents. Since configuration E was a balanced ventilation system, it should have had no impact on the pressure distribution acting to drive infiltration and exfiltration airflows through leaks in the building envelope.

Master Bedroom Total Air Change Rate Test Results

The master bedroom total air change rate tests dosed and mixed the tracer gas only in the master bedroom. Therefore, the decay of SF_6 in the MBR and the air change rate determined from its exponential decay curve fit should represent the total inflow of air to the master bedroom, likely a combination of interior air with little or no SF_6 content and outdoor air via direct air leakage, deliberate inlet venting, or mechanical supply. This

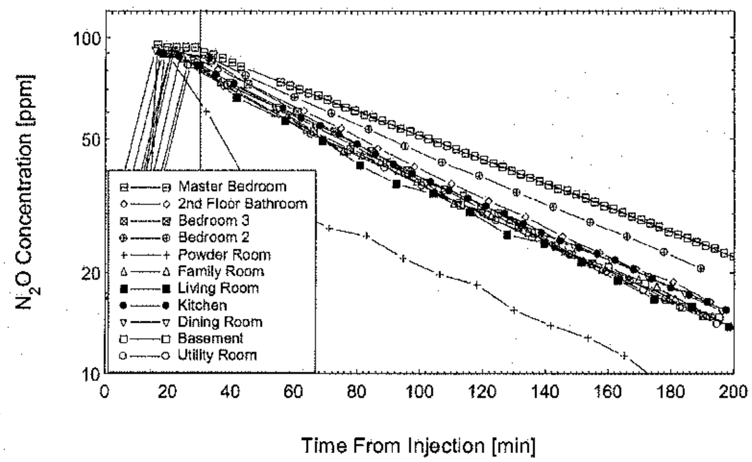

Figure 11a *Simultaneous room-by-room decay measurements for configuration E at −14°C. Minimal ducted supply system with local exhaust system—no vents.*

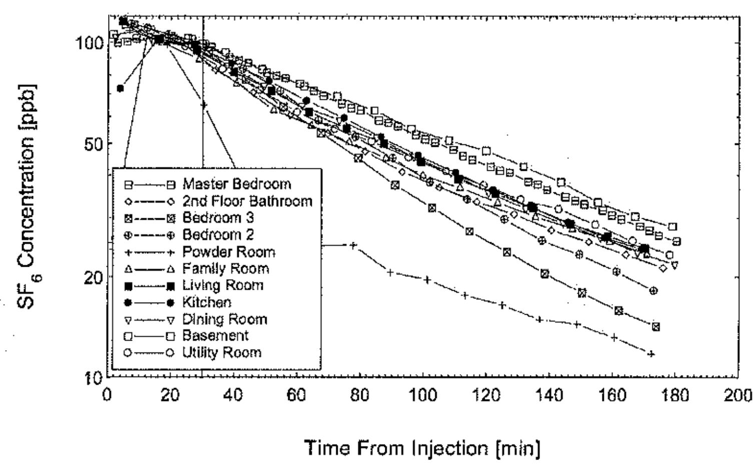

Figure 11b *Simultaneous room-by-room decay measurements for configuration E at +12°C. Minimal ducted supply system with local exhaust system—no vents.*

total airflow into the master bedroom is of interest because not all indoor air is necessarily unfit for ventilation purposes. In fact, indoor air traditionally has been used as part of house ventilation.

The total air change rates in the MBR were calculated using Equation 1 to fit the measured decay of SF_6 concentrations during these tests. The total air supply flow rates to the MBR were calculated by multiplying the total air change rates by its internal volume. The averages of these MBR total air supply flow rates are listed in Table 4 for each configuration. The ranges of these flow rates are also indicated in Table 4. The range indications are simply the minimum and maximum total air supply flow rates normalized by the standard's 10 L/s requirement for the MBR and expressed as percentages.

TABLE 4 Average Total Air Supply Flow Rates Measured in the Master Bedroom Total Air Change Rate Tests

Config. ID	Total Air Supply Flow Rates for the Master Bedroom, Average [L/s]Range	
	Average [L/s]	Range [% of CSA Req't.]
A	4.5	41-48
B	8.0	54-121
C	12.1	118-125
D	12.6	118-136
E	11.9	113-133
F	4.0	27-51
G	34.1	200-402

Of the five systems, the local exhaust systems (configurations A and B) provided an average total air supply flow rate to the MBR that was less than the 10 L/s recommended by the CSA F326 standard. In fact, configuration A without any vents provided little more than the simple air infiltration reported for configuration F, although a little more consistently (with less scatter) than simple air infiltration. Configuration B results exhibited the greatest relative scatter (broadest range) in the measured total supply flow rates for the MBR, probably reflecting the greatest susceptibility to stack effect and wind due to its well-distributed additional deliberate envelope leakage (its vents). Both the PDE systems and the MDS system (configurations C, D, and E) seemed to provide average total air supply flow rates in the master bedroom of approximately 12 L/s (25 cfm). Therefore, the deliberate exhaust of air from the MBR or the deliberate supply of air to the MBR provided the same total airflow into that room. The results also indicate that the large recirculation flow rates of configuration G, with the furnace fan operating continuously, provided the largest total supply flow rates to the MBR, averaging 34 L/s (72 cfm).

CONCLUSIONS

The results of the experiments on the local exhaust-only strategy led to the following conclusions.

- The kitchen and bathroom fans alone do not provide adequate air distribution to the various individual rooms.
- With make-up air provided only by air leakage, the rooms on the lower stories receive almost all the outdoor air. When supplemented by deliberate passive vents distributed in the second-story bedrooms and in the main-floor rooms, no significant improvements in the air distribution flow patterns were observed.
- This mechanical ventilation strategy generally provided better air distribution than simple air infiltration and exfiltration.

The experiments on the partially distributed exhaust system produced more encouraging results.

- Both with and without deliberate make-up air venting, this strategy provided better air distribution to the critical closed bedrooms on the second floor than the local exhaust strategy.
- The measured total air change rates in the master bedroom are greater than the 10 L/s recommended by the CSA F326 standard, even though some portion of the ventilation air may come from other parts of the house.

The experiments on the minimal ducted supply system balanced with the local exhaust fans confirmed that this mechanical supply strategy successfully provided the best air distribution to all the rooms in the house. Since it was a balanced approach, the background leakage of air contributed to, but did not dominate, the interior airflow patterns in these tests.

Based on these results, future work will focus on the partially distributed exhaust and minimal ducted supply systems (configurations C, D, and E). This future work will address other parameters of system performance such as noise, thermal comfort, energy consumption, and installation costs.

ACKNOWLEDGMENTS

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