National Research Council Canada
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NRC-CNRC

Client Report

A-3527.1 Revised

Ventilation System for New and Existing Houses with Baseboard Heating

for

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

8 December 1995

construction

Institute for Research in Construction

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NOTE: LE RÉSUMÉ EN FRANÇAIS SUIT IMMÉDIATEMENT LE RÉSUMÉ EN ANGLAIS.

Ventilation Systems for New and Existing Houses With Baseboard Heating

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Report No: A-3527.1 Revised
Report Date: 8 December 1995
Contract No: A-3527
Reference: Agreement for Collaborative Work dated 15 February 1993
Laboratory: Building Performance

124 pages
Copy No. 1 of 4 copies

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ABSTRACT

Adequate ventilation is essential in houses to ensure acceptable indoor air quality and to control condensation. In Canada, the measure of adequate ventilation in a house will be compliance with the Canadian standard CAN/CSA-F326-M91 "Residential Mechanical Ventilation Systems", which specifies the minimum outdoor air change rate for the entire house as well as ventilation rates to individual rooms to ensure adequate air distribution within the house.

Houses with forced-air heating systems which circulate air to most rooms in the house through ducts are generally regarded as well ventilated when the furnace fan is operating. Houses with alternative heating systems which do not include ducts may not experience enough ventilation air supply or adequate air distribution. This project examined five simple ventilation systems suitable for houses without forced-air heating systems. Four of the simple ventilation systems 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 of these exhaust-only approaches were tested with deliberate passive inlet vents (both distributed or centralized) both open and closed. The fifth system was a supply and exhaust system with minimally-sized ducts supplying ventilation air to each habitable room, and the local exhaust fans providing the exhaust.

The five ventilation systems were installed in the NRC two-storey research house which also has an electric forced-air heating system. The ventilation performance of each system was measured for a variety of weather conditions using single and multiple tracer gas techniques. Their air change rates and room-by-room ventilation rates were measured and compared with similar reference measurements in the house with no ventilation and with only the forced-air furnace fan operating.

The exhaust-only system using only local exhaust fans with no passive inlet vents open was found to provide inadequate ventilation performance, only marginally better than simple air leakage alone. With the distributed passive inlet vents open the local exhaust system was found to over ventilate the ground floor rooms and still underventilate the upper storey bedrooms. The partially distributed exhaust system was effective at improving the ventilation air distribution to the bedrooms, especially with a centralized passive inlet vent open. The minimal ducted supply system provided the required air distribution to all the habitable rooms.

Keywords: ventilation, air distribution, tracer gas techniques, residential, experiments

ACKNOWLEDGMENTS

The project was supported financially by the Canadian Electrical Association, Canada Mortgage and Housing Corporation, the Electrical and Electronic Manufacturers Association of Canada (now named Electro-Federation Canada), Gas Technology Canada, and the National Research Council of Canada. That support is gratefully acknowledged.

The contributions of the following individuals are also gratefully acknowledged. Robert Evans renovated the research house, installed the ventilation systems and instrumentation, and conducted most of the tracer gas tests. Juergen Weichert set up the data acquisitions systems for flow rate, temperature and pressure monitoring, and helped analyze the measured data. Robert Magee set up the data acquisition system for measuring the tracer gas concentrations. Robert MacDonald conducted the final few tracer gas tests and measured the airtightness of the building envelope and components for each of the ventilation system test configurations. Peter Adams and Cecil Lau assisted in the data analysis as co-op workterm students. Chia-yu Shaw and Sherif Barakat provided expert advice during the project and helpful comments in their reviews of the final report. The CEA Project Monitors William Jones and Michel Falardeau and the Project Engineer Peter Gelineau provided helpful advice during the project and reviewed the final report. John Haysom, Canadian Codes Centre NRC, and Duncan Hill, CMHC, provided helpful comments in their reviews of the final report.

SUMMARY

Adequate ventilation is essential in houses to ensure acceptable indoor air quality and to control condensation. Adequate ventilation means that not only does the ventilation rate for the whole house meet the recommended value but also all individual rooms in the house receive their recommended ventilation rates, as specified in the Canadian standard CAN/CSA-F326-M91 "Residential Mechanical Ventilation Systems". Those requirements have already been adopted into the 1993 Ontario Building Code and the 1995 National Building Code of Canada.

The new ventilation performance standards present tremendous challenges for house builders to meet the ventilation air distribution requirements without installing a complete, fully-ducted, forced-air heating and ventilation system. They may also make it difficult for alternative heating systems, such as electric baseboards and hydronic systems, to comply with the new building codes. Work has been carried out by others, such as the Canada Mortgage and Housing Corporation and the Ontario New Home Warranty Program, to develop designs that will satisfy the CSA F326 requirements for houses with forced-air heating systems. The project described in this report examined simplified ventilation system designs suitable for houses that do not have the ducted air delivery system of forced-air heating.

The simplified ventilation systems considered in this project were exhaust-only and balanced systems. The exhaust-only systems used either only typical 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. For each of these exhaust-only approaches, make-up air was provided either through one or more deliberate passive inlet vents or by air leakage through accidental openings in the exterior building envelope. The balanced system used the kitchen and bathroom fans

for its exhaust side and a minimal ducted supply system for its supply side. The minimal 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 system designs were tested experimentally by installing them in the NRC/IRC two-storey research house. This house was built using conventional modern Canadian wood-frame construction methods in 1989. The air distribution performance of each system was measured, using both single and multiple tracer gas techniques, for the full 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 the research house provided two reference cases for useful comparison with the various test ventilation systems: the house with all windows, doors and vents closed and both with and without the furnace fan operating continuously to circulate the leakage air within the house interior.

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

- The kitchen and bathroom fans alone do not meet the overall house air change criterion, despite their total measured exhaust being equal to the whole house ventilation requirement, nor do they provide adequate air distribution to the various individual rooms.
- With make-up air provided by air leakage, the lower storey's rooms are adequately ventilated, but the critical bedroom areas are underventilated.
- When supplemented by deliberate passive inlet vents distributed in the second storey bedrooms and in the main floor rooms, the house overall was overventilated, with the ground floor rooms substantially overventilated.
- Despite the overall excess ventilation with deliberate passive inlet vents open, closed bedrooms still received too little ventilation air.

For the critical bedrooms on the second floor, these two test cases could be characterized as a centralized single-point exhaust system with distributed passive supply either via accidental leaks or via deliberate purpose-provided inlet vents. The distributed passive vents did not serve successfully as air inlets in the second storey bedrooms, but instead served as exfiltration sites and, matched by the deliberate openings in the lower envelope, helped to increase the overall air change rate for the house, primarily driven by stack effect.

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.
- With only accidental air leakage as the make-up air supply, not enough outdoor air was provided to the bedrooms to fully comply with the new standards, despite sufficient measured exhaust from each bedroom.
- For the same conditions, the ground floor rooms were adequately supplied with outdoor air, and the basement rooms were somewhat overventilated.
- With a single centralized passive inlet opening however, the bedrooms were better ventilated, the basement rooms were adequately ventilated, and the ground floor rooms experienced modest overventilation.

For the second storey, this system could be characterized as a distributed mechanical exhaust with a single centralized passive supply. This strategy was judged as suitable for further development. By providing only one passive inlet, relatively centralized with regard to building height and probably near the neutral pressure level, this arrangement was not so susceptible to stack effect dominance as was the distributed passive venting arrangement of the local exhaust fan strategy above.

The experiments on the minimal ducted supply system balanced with the local exhaust fans confirmed that this mechanical supply strategy successfully provided adequate outdoor air supply and good 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 air flow patterns in these tests. This was demonstrated by modest excess ventilation in the basement rooms.

The single tracer gas technique used in this research proved to be an effective method for determining the amount of fresh air supplied to each room in the house. However, it tends to underestimate the ventilation rate somewhat in rooms where the majority of inflow is from other rooms in the house. The multiple tracer gas technique, while neither intended nor able to quantitatively identify all the interzonal flow rates among all the rooms, was useful to compliment the single tracer gas measurements of fresh air supply rates with measurements of the total air supply rates to the master bedroom as an illustrative example. The verification of these methods was made possible by the measurement of flow rates through each ventilation system component for all the tests.

RÉSUMÉ

Une bonne ventilation est essentielle dans les habitations pour que la qualité de l'air intérieur y soit acceptable et que la condensation soit maîtrisée. Au Canada, pour que la ventilation d'une habitation soit appropriée, elle doit être conforme à la norme canadienne CAN/CSA-F326-M91 intitulée «Ventilation mécanique des habitations», laquelle précise le taux minimum de renouvellement d'air pour une habitation entière ainsi que les débits de ventilation de chaque pièce devant assurer une bonne distribution d'air dans la maison.

Les maisons pourvues d'installations de chauffage à air pulsé qui font circuler l'air dans la plupart des pièces d'une habitation au moyen de conduits sont généralement considérées comme bien ventilées lorsque le ventilateur du générateur de chaleur est en marche. Dans les habitations chauffées d'une autre façon et non dotées de conduits de ventilation, la diffusion d'air de ventilation peut ne pas être suffisante ou la répartition de l'air inappropriée. Cette étude a examiné cinq installations de ventilation simples convenant aux habitations dépourvues d'installation de chauffage à air pulsé. Quatre de ces installations simples procédaient par extraction seulement. Il s'agissait donc soit de simples ventilateurs d'extraction installés dans la cuisine et les salles de bains, soit de ventilateurs d'extraction ordinaires auxquels on avait ajouté un système d'évacuation à distribution partielle comportant des bouches d'extraction dans chaque chambre. Chacune de ces méthodes axées sur l'extraction a été mise à l'essai dans une habitation dotée d'orifices d'admission d'air passifs (installation distribuée ou centrale) à commande manuelle. Les essais ont été menés à orifices ouverts et à orifices fermés. La cinquième installation, à alimentation et à évacuation, se composait de petits conduits distribuant l'air de ventilation à chaque pièce habitable, les ventilateurs d'extraction assurant l'évacuation.

Les cinq installations de ventilation ont été mises en place dans la maison de recherche de deux étages du Centre national de recherches, laquelle est également pourvue d'une installation de chauffage à air pulsé fonctionnant à l'électricité. La performance de chaque système à l'égard de la ventilation a été évaluée dans diverses conditions climatiques au moyen d'un gaz traceur simple et de plusieurs gaz traceurs. Les taux de renouvellement d'air et les débits de ventilation d'une pièce à l'autre ont été mesurés et comparés avec des mesures de référence similaires prises dans la maison en l'absence de ventilation et à un moment où seul le ventilateur de l'installation de chauffage à air pulsé était en marche.

Le système à extraction seulement n'ayant recours qu'aux ventilateurs d'extraction locaux fonctionnant à orifices d'admission passive fermés n'a pas offert une bonne performance de ventilation, ne faisant guère mieux que les seules fuites d'air. Lorsque les orifices d'admission passive étaient ouverts, les ventilateurs d'extraction ont ventilé excessivement les pièces situées au rez-de-chaussée tandis que les chambres situées à l'étage demeuraient insuffisamment ventilées. Le système d'extraction à distribution partielle s'est avéré efficace pour améliorer la distribution de l'air de ventilation aux chambres, surtout lorsqu'un orifice central d'admission passive était ouvert. L'installation d'admission à petits conduits a favorisé une bonne distribution d'air pour toutes les pièces habitables.

Mots clés : ventilation, distribution d'air, gaz traceur, résidentiel, essais

RÉSUMÉ

Il est essentiel d'assurer une ventilation suffisante dans les maisons pour garantir la qualité acceptable de l'air intérieur et éliminer la condensation. Pour y parvenir, non seulement le taux de ventilation pour l'ensemble de la maison doit-il respecter la valeur recommandée, mais toutes les pièces individuelles de la maison doivent aussi recevoir leur taux de ventilation recommandé, conformément à la norme canadienne CAN/CSA-F326-M91, «Ventilation mécanique des habitations». Ses exigences ont déjà été adoptées dans l'édition 1993 de l'Ontario Building Code et dans l'édition 1995 du Code national du bâtiment du Canada.

Les nouvelles normes de performance en matière de ventilation obligent les constructeurs de maisons à relever un défi de taille pour satisfaire les besoins de distribution d'air de ventilation sans devoir installer un système de chauffage et de ventilation à air pulsé relié à un réseau complet de conduits de distribution. Il peut également se révéler difficile pour les autres systèmes de chauffage, tels que plinthes électriques et systèmes à eau chaude, de se conformer aux nouveaux codes du bâtiment. D'autres organismes, comme la Société canadienne d'hypothèques et de logement, et le Régime de garantie des logements neufs de l'Ontario, ont consacré des travaux à la mise au point de systèmes permettant aux maisons équipées de systèmes de chauffage à air pulsé d'être conformes aux exigences de la norme CSA F326. La recherche dont le présent rapport fait état a porté sur des systèmes de ventilation simplifiés convenant aux maisons dépourvues d'une installation de chauffage à air pulsé avec réseau de conduits de distribution.

Les systèmes de ventilation simplifiés retenus dans le cadre de cette recherche ne concernent que les systèmes à extraction seulement et les systèmes à débits équilibrés. Les systèmes à extraction seulement ne faisaient appel qu'à des ventilateurs d'extraction ponctuels types placés dans la cuisine et les salles de bains, ou encore à un système d'extraction centralisé avec grilles de reprise dans chaque chambre en plus des ventilateurs de cuisine et de salle de bains. Dans le cas des ventilateurs à extraction seulement, l'air de compensation était acheminé soit par une ou plusieurs prises d'admission passives ou par les fuites d'air résultant du manque d'étanchéité de l'enveloppe extérieure du bâtiment. Le système équilibré utilisait les ventilateurs de la cuisine et de salle de bains pour les fins d'extraction et un réseau minimal de conduits pour l'approvisionnement. Le réseau minimal de conduits d'approvisionnement était dimensionné uniquement pour répondre aux besoins d'air de ventilation, et non pour satisfaire les importants débits requis pour un système de chauffage à air pulsé.

Ces différents systèmes de ventilation ont fait l'objet d'essais expérimentaux après avoir été installés dans la maison de recherche de deux étages située à l'IRC du CNRC. Cette maison a été réalisée selon les méthodes canadiennes traditionnelles de construction à ossature de bois ayant cours en 1989. La performance en matière de distribution d'air de chacun des systèmes a été mesurée en exploitant des techniques faisant aussi bien appel à un seul qu'à de multiples gaz de traçage pour la gamme complète des conditions météorologiques types au Canada au cours de la saison s'échelonnant de la fin de l'automne jusqu'à la fin du printemps à Ottawa. Le système de chauffage électrique à air pulsé qui a été installé à l'origine dans la maison de recherche a permis d'établir deux cas de référence se prêtant à une comparaison utile avec différentes systèmes de ventilation d'essai; la maison avec toutes ses fenêtres, ses portes et ses évents fermés, avec et sans

le ventilateur de l'installation de chauffage fonctionnant continuellement pour faire circuler les fuites d'air à l'intérieur de la maison.
Les résultats des expériences tentées sur le système d'extraction ponctuel ont permis de tirer les conclusions suivantes :

- o Les ventilateurs de la cuisine et de la salle de bains ne parvenaient pas à eux seuls à assurer le renouvellement d'air requis pour l'ensemble de la maison, malgré que le débit total de l'air évacué mesuré fut égal au besoin de ventilation de toute la maison, pas plus qu'ils n'acheminaient suffisamment d'air aux différentes pièces individuelles.

- o L'air de compensation étant assuré par les fuites d'air, les pièces du niveau inférieur étaient suffisamment bien ventilées, à l'exception des chambres.

- o L'ajout d'orifices d'admission d'air passifs aux chambres du deuxième étage et aux pièces du rez-de-chaussée assurait une surventilation générale de la maison, les pièces du rez-de-chaussée étant considérablement surventilées.

- o Malgré la surventilation générale qu'entraînent les prises d'air passives laissées en position ouverte, les chambres fermées recevaient toujours trop peu d'air de ventilation.

En ce qui concerne les chambres du deuxième étage, pour ces deux cas d'essais, l'équipement correspondait essentiellement à un système d'extraction centralisé ponctuel avec distribution d'air passive assurée par les fuites d'air fortuites ou les orifices d'admission d'air prévus à cet effet. Les orifices de distribution passifs n'ont pas réussi à servir efficacement de prises d'air dans le cas des chambres du deuxième étage, mais ont plutôt tenu lieu de bouches d'exfiltration et, assortis aux ouvertures délibérées dans le bas de l'enveloppe, ont permis d'accroître le taux de renouvellement d'air global de la maison, en raison surtout de l'effet de tirage.

Les expériences tentées sur le système d'extraction à distribution partielle ont donné des résultats plus encourageants :

- o Avec ou sans orifices délibérés d'air de compensation, cette stratégie a donné lieu à une meilleure alimentation en air des chambres fermées du deuxième étage.

- o Lorsque l'air de compensation n'est assuré que par les fuites d'air fortuites, la quantité insuffisante d'air extérieur parvenant aux chambres ne permettait pas de respecter pleinement les nouvelles normes, en dépit de l'extraction suffisante mesurée dans chaque chambre.

- o Dans les mêmes conditions, les pièces du rez-de-chaussée étaient suffisamment alimentées en air extérieur, et les pièces du sous-sol quelque peu surventilées.

- o Avec un seul orifice d'admission passif centralisé, les chambres étaient mieux ventilées, les pièces du sous-sol suffisamment ventilées et les pièces du rez-de-chaussée légèrement surventilées.

Pour ce qui est du deuxième étage, on peut établir qu'il s'agit essentiellement d'un système d'extraction mécanique avec distribution, pourvu d'un seul conduit d'approvisionnement passif centralisé passif. Cette stratégie, a-t-on jugé, mérite d'être étudiée davantage. En ne ménageant qu'un seul orifice d'admission passif, assez bien centralisé par rapport à la hauteur du bâtiment et probablement situé près du plan neutre, ce système n'était pas aussi sujet à subir la prédominance de l'effet de tirage que le système avec orifice passif de distribution du ventilateur d'extraction ponctuel précédent.

Les expériences tentées sur le système à réseau minimal de conduits d'approvisionnement, équilibré par les ventilateurs d'extraction ponctuels, ont confirmé que cette stratégie d'approvisionnement mécanique assuraient une alimentation suffisante en air extérieur et une bonne distribution de l'air dans toutes les pièces de la maison. Puisqu'il s'agit d'un système à débits équilibrés, les fuites d'air en arrière-plan ont contribué, lors de ces essais, aux profils des débits d'air intérieur sans toutefois les dominer. Cette situation a été corroborée par la légère surventilation des pièces du sous-sol.

La technique faisant appel à un seul gaz de traçage, qui a été exploitée dans le cadre de cette recherche, s'est révélée efficace pour déterminer la quantité d'air frais acheminée vers chaque pièce de la maison. Par contre, elle tend à sous-estimer quelque peu le taux de ventilation dans les pièces où la majorité de l'air admis provient des autres pièces de la maison. La technique faisant appel à de multiples gaz de traçage, quoique non destinée à indiquer quantitativement tous les taux de débit interzones parmi toutes les pièces, ni en mesure de le faire, a été utile pour ajouter, à titre d'exemple, les mesures obtenues à l'aide du gaz de traçage unique des taux d'approvisionnement en air frais aux mesures des taux d'approvisionnement total en air acheminé vers la chambre principale. La vérification de ces méthodes a été rendue possible en mesurant les taux de débit de chaque composant du système de ventilation lors de tous les essais.

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1. OBJECTIVES

The objective of this project was to identify designs of simple ventilation systems that are suitable for new and existing houses that lack fully ducted forced-air heating systems, such as those with electric or hydronic baseboard heating. The proposed ventilation systems were compared with a conventional forced-air heating system in the IRC two-storey research house, in terms of air change rates and air distribution patterns in the house. The intended result was to contribute to the development of design strategies which can meet the ventilation performance requirements contained in the Canadian Standards Association standard CAN/CSA-F326-M91 "Residential Mechanical Ventilation Systems"[1].

2. INTRODUCTION

This research project set out to identify some simplified ventilation systems which would be suitable for use in both new and existing houses that did not have a forced-air heating system to provide ventilation air distribution. The yardstick for determining adequate ventilation performance was the relatively new CSA F326 standard, which has been or soon will be referenced in several building codes in Canada. The general approach taken was to use tracer gas techniques to measure the actual air distribution performance of the tested ventilation systems as implemented in a real two-storey house built using typical, modern Canadian wood-frame construction. The project has been sponsored by several agencies in Canada, including the Canadian Electrical Association, the Electrical and Electronic Manufacturers Association of Canada (now the Electro-Federation Canada), Gas Technology Canada, and the Canada Mortgage and Housing Corporation, in addition to the Institute for Research in Construction of the National Research Council of Canada.

The research project and its results are described in this report. The current situation regarding ventilation in houses, some of the theory and general concepts involved in natural and mechanical air movement specific to houses, and the expected beneficiaries of this work are discussed in the background section. Descriptions of the experimental facility: the NRC/IRC two-storey research house, its ventilation requirements, and the ventilation systems tested are contained in subsequent sections. The instrumentation systems and details of the experimental procedures are described in the next sections. The test conditions are described generally in the following section, after which the results of the single and multiple tracer gas tests are presented and discussed in separate sections. Finally, the major conclusions from the research and recommendations, including future investigations, are presented in the final sections of the report. Several appendices present detailed descriptions and information to supplement the contents of the main text of the report.

3. BACKGROUND

Traditionally, houses in Canada have relied upon natural driving forces coupled with relatively leaky building envelope construction to provide their ventilation by air leakage. The general principles of natural ventilation and air infiltration and exfiltration in buildings are well described elsewhere [2]. Several studies, most recently the 1989 cross-Canada airtightness survey [3,4], have indicated that modern house construction is now typically too airtight for air leakage to dependably provide all the ventilation needs in houses. The common view now is that mechanical ventilation is required in most houses.

The CSA standard F326 "Residential Mechanical Ventilation Systems" was created to address the need for standardized requirements for mechanical ventilation in houses. It takes a performance requirement approach in specifying the minimum ventilation rates for individual rooms in the house and the limits for the amount of supply/exhaust imbalance and pressure differences created across the building envelope by mechanical ventilation. Both the 1993 Ontario Building Code [5] and the 1995 National Building Code of Canada [6] have adopted the CSA F326 standard as a performance standard requirement, and have provided several prescriptive design alternatives that are intended to provide ventilation performance approaching that called for in the standard.

Houses with forced-air heating systems have usually been regarded as having adequate indoor air distribution when the furnace fan is operating. Investigative work has been carried out by agencies such as the Canada Mortgage and Housing Corporation and the Ontario New Home Warranty Program to develop ventilation design strategies that can meet the CSA F326 requirements in such houses. The results of those studies have contributed to the prescriptive measures which have been incorporated into the new building codes. The investigation of several simple ventilation system design strategies suitable for houses without forced-air heating systems was the subject of the project described in this report.

Despite the generally agreed upon need for mechanical ventilation in houses, air infiltration and exfiltration through leaks and deliberate openings in the building envelope will contribute to the total outdoor air exchange in a house. Natural driving forces and air flow patterns may also help or hinder the intended action of a mechanical ventilation system. For example, during cold weather when stack effect (the pressure distribution caused by the difference between indoor and outdoor air temperatures) is strong, the natural pressure distribution acting on the exterior envelope can impede the effectiveness of a basement or first floor exhaust fan by imposing an incremental back pressure of up to 10 Pa on the fan, in addition to its duct losses. Similarly, stack effect can help the effectiveness of a second storey exhaust fan. Wind, although it is neither as steady nor as predictable as stack effect, can similarly help or hinder mechanical ventilation.

Through the pressure distribution they create on the exterior of the building, both wind and stack effect can have a substantial impact on the effectiveness of passive inlet and exhaust vent openings. For example, stack effect during cold weather tends to drive air flow into the house through both deliberate and accidental openings in the lower parts of the building envelope, inside the house from lower floors to upper floors and out of the house through openings in the upper parts of the building envelope. Similarly, wind tends to drive air flow into the house through openings in the windward facade(s), inside the house from windward to leeward rooms, and out of the house through openings in the leeward facades and the roof. Therefore, during cold weather, the natural air flow patterns inside the house are generally from lower windward zones, which will experience the greatest inflow of fresh air from outdoors, to upper leeward zones, from which the major portion of exfiltration air will leave the house.

Consequently, while the upper leeward zones will likely receive the least supply of air directly from outside, they may eventually receive a substantial portion of the total leakage air flowing through the house. In the absence of strong pollutant sources in the house, these zones may accordingly receive a good airflow of relatively fresh air. On the other hand, upper windward zones and lower leeward zones, where stack effect and wind compete with each other, may experience very little or no airflow due to natural ventilation.

Ventilation air supply to bedrooms in the house has received special concern by regulatory and standards writing agencies because occupants typically spend up to eight hours or more in these rooms, usually with the bedroom doors closed, while they are unconscious and unable to react to stuffy or unacceptable air quality. A closed door presents an impediment to ventilation air flow into these rooms, and the typical duration of stay increases the risk of harmful exposure to any air contaminants present in the bedroom air. In addition, the normal air flow patterns in the house due to stack effect, which dominates natural ventilation for much of the year in the typical Canadian climate, tend to provide the least direct supply of fresh air to the upper storey where bedrooms are usually located in a multi-storey house.

Most modern houses in Canada already have one or more exhaust fans, installed typically in the kitchen and bathroom(s). These fans therefore constitute the simplest mechanical ventilation system–an exhaust-only system. These local exhaust fans serve two purposes. First, they are intended to exhaust airborn pollutants directly from their source location, operated usually intermittently during pollutant generation—cooking in the kitchen and bathing in the bathrooms. Second, by their exhaust action, these fans tend to depressurize the house interior which helps to draw their make-up air in through openings in the building envelope. The next simplest system would be to supplement these local exhaust fans with passive inlet vents to help and direct the inflow of make-up air from outdoors. A seemingly logical choice of location for some of these vents would be in the bedrooms where the supply of fresh air is a major concern. This approach should work in the absence of stack effect and wind. However, the natural air flow patterns caused by stack effect would suggest in general that passive vents in the upper portion of the building envelope (i.e., in bedrooms) might not succeed as air inlets unless the exhaust flow through the fans is sufficiently strong to raise the neutral pressure level in the house above the elevation of all the vents so that the envelope pressure distribution is acting inward at all the vent openings.

The experimental investigation described herein was carried out in the NRC two-storey research house. An earlier series of experiments in that house [7,8], in which envelope pressures due to natural driving forces and mechanical exhaust had been measured for a complete year, had indicated that mechanical exhaust could raise the neutral pressure level sufficiently high for second storey vents to succeed as air inlets. Those experimental results had also revealed useful information regarding typical design pressures for sizing passive inlet vents at various elevations in the house.

Several other relatively simple design approaches would seem to offer some improvement of the distribution of ventilation air in the house. One is to deliberately exhaust air from each room where the ventilation requirement is a concern with the intention being to thereby draw make-up air into those directly exhausted rooms. The inlet of the make-up air could be via accidental or deliberate openings in the envelope, with concerns similar to those stated above regarding vent locations and the exterior pressure distribution. Another more complex design approach would be to deliver ventilation air directly to each room as required, through a duct system not unlike that of a forced-air heating system but sized for the ventilation air flow requirements only. This project examined the ventilation air distribution performance of all of these ventilation system design strategies.

The principal beneficiaries of this work are expected to be codes and standards writing organizations such as the Canadian Standards Association and the national and provincial building codes, gas and electric utilities (e.g., Consumers Gas and Hydro-Québec), industry umbrella organizations such as the Canadian Electrical Association, manufacturers of baseboard heating equipment, builders and contractors. The building code community and builders urgently need prescriptively-described alternatives to current and developing performance standards. Electric utilities need improvements in energy efficient technologies to curb the expanding growth in electricity demand. Manufacturers need inexpensive ventilation system options for baseboard heated houses to maintain a market for such heating equipment. Builders and contractors require prescriptively-described designs for inexpensive ventilation systems that can be installed both in new houses to satisfy the new building codes and indoor environment standards and in existing houses to improve ventilation in retrofitted buildings.

4. DESCRIPTION OF THE RESEARCH HOUSE

The experiments were conducted in the two-storey house research facility at the Montreal Road Campus of the National Research Council in Ottawa. It 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 with the second storey's ceiling 5.956 m above grade. Ceiling heights are 2.44 m on each storey. The electrical wiring is standard for residential construction. The house has no water supply or plumbing system. The house is oriented with its front facade facing exactly true north.

The exterior wall construction is comprised of the following: 12.7 mm painted gypsum wallboard, 0.15 mm polyethylene vapour barrier, 38 mm x 140 mm wood studs, R20/RSI 3.5 glass fibre batt insulation (ceiling R40/RSI 7 glass fibre batt insulation), 12.7 mm oriented strand board, No.15 organic felt sheathing paper, and vinyl siding exterior cladding. The windows are all tight-sealing casement style with double-pane insulated glazing units. The sliding patio door is a standard double-pane insulated glazing unit.

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 house has three flues and two basement vents which are all fitted with motorized dampers which open into the basement. These allow a variety of envelope leakage distributions to be simulated manually or automatically. All the forced-air ducts are exposed within the heated envelope and instrumented to measure individual flowrates. A separate air handling unit is installed to optionally provide mechanical ventilation to the first storey; the electric furnace can be configured as an air handling unit for the second storey.

The layouts of the rooms on each storey in the research house are illustrated in Figure 1. Except for the powder room, which was a renovation for this project, the room layouts on the ground floor and the basement are part of the permanent original house construction. All partition walls are completely finished drywall construction. Prior to the renovations in preparation for this project, the second storey had no partitions. Partitions were added to create the floor layout illustrated in Figure 1. The second floor partitions were built using drywall panels on wood stud framing. For speed of assembly, joints were sealed using duct tape rather than standard drywall paper tape and joint compound "mudding" was not applied to joints or screw heads. No additional electrical wiring was added in these partition walls. Hollow core wooden doors on prehung frames were installed in each room with 19 mm (3/4 inch) undercuts between the bottoms of each door and the painted plywood floor.

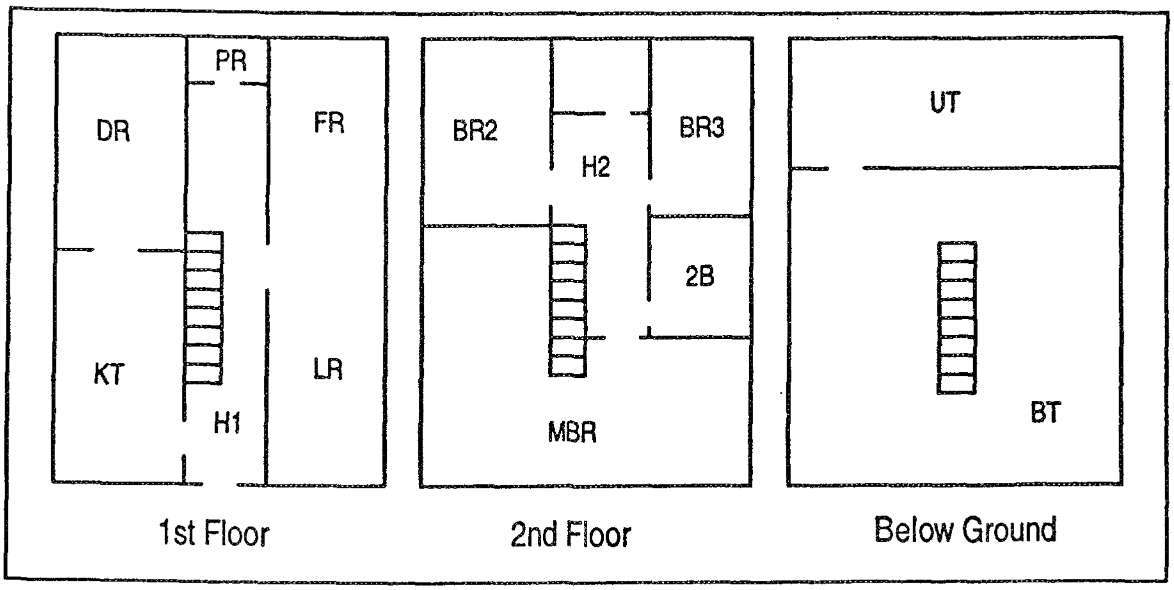

Figure 1 - Floor Plans of the Three Storeys in the Research House

5. 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 requirement for the house based on the sum of the room-by-room requirements is 65 L/s. When taken on a floor-by-floor basis, these individual room requirements represent ventilation rates of 25 L/s for the second floor, 25 L/s for the first (ground) floor and 15 L/s 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 for the kitchen and 10 L/s for each bathroom, or intermittent exhaust of 50 L/s for the kitchen and 25 L/s for each bathroom.

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	10	1	10
Basement	10	1	10
Single Bedrooms	5	2	10
Living Room	5	1	5
Dining Room	5	1	5
Family Room	5	1	5
Other Habitable Room	5	0	0
Kitchen	5	1	5
Bathrooms	5	2	10
Utility Room	5	1	5
Total Minimum Ventilation Required for House			65

6. DESCRIPTION OF THE VENTILATION SYSTEMS TESTED

Most houses built in recent years in Canada already have exhaust fans installed in their kitchens and bathrooms. The continuous operation of these already existing fans represents the simplest mechanical ventilation system for a house. Continuing with the exhaust-only mechanical ventilation approach, 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 pick-ups in each closed room. The logical approach to improve the fresh air performance of exhaust-only systems would be to provide deliberate 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. These design ideas are not the only possible alternatives for house ventilation, but they form the basis for the investigation being reported here.

Five simple ventilation systems were investigated in this research project. Four were based on an exhaust-only strategy, and the fifth incorporated the deliberate supply of ventilation air to each "habitable room" as defined in the CSA F326 standard. Detailed descriptions of each test configuration, including the two reference cases, follow the discussion of the design approaches below.

The general design approaches for the tested systems were the following. The first approach (Configurations A and B) was to use typically existing local exhaust fans running continuously (which is not typical in most homes), with and without deliberate provisions for the supply of make-up air through passive inlet vents. The second approach (Configurations C and D) was to try to improve the distribution of air to closed bedrooms on the second storey by directly exhausting air from each bedroom, according to its ventilation requirement, with and without deliberate provisions for the supply of make-up air through a centralized passive inlet vent. The third approach (Configuration E) was to deliberately supply ventilation air to each "habitable" room, according to its requirement, with a duct system sized specifically for the ventilation supply flow rates, and to exhaust an equal volume of air from the house with the local exhaust fans. These supply ducts were therefore substantially smaller in size than those typical of a forced-air heating system whose ducts must carry larger flow rates to meet heating and cooling loads. The closed bedrooms were expected to pose the greatest challenge to comply with the ventilation air distribution requirements. Air distribution to the rooms on the ground floor with all doors open was of less concern.

The typical fans used in the first design approach were kitchen and bathroom fans. In the test house this provided one exhaust fan in the second storey (the bathroom) and two in the first storey (the kitchen and the powder room). The bathroom fan on the second storey represented a single exhaust site for that zone. The selection of locations for the second storey passive inlet vents in this approach (one in each bedroom) were based on trying to deliberately distribute the passive supply of make-up air to each closed bedroom. The two fans in the first storey represented a partial distribution of exhaust for the rest of the house (first storey and basement) and passive inlet vents were placed in two rooms in the first storey which did not have exhaust fans (living room and dining room) to partially distribute the passive supply of make-up air to the rest of the house. The first storey, with most doors between its rooms open, was not expected to pose the same challenge to air distribution as the second storey with all the bedroom and bathroom doors closed. For the critical second storey zone, this system could be characterized as single central exhaust with distributed passive supply (whether by accidental air leakage or via deliberate vents).

The second design approach supplemented the typical local exhaust fans of the first approach with a mechanical exhaust system which picked up exhaust air in each bedroom at the required flow rates. The combination of this so-called partially distributed exhaust system for the bedrooms and the second floor bathroom exhaust fan provided well distributed mechanical exhaust for the second storey. The deliberate passive make-up air venting for this approach was provided by a single inlet to the hallway space as a centralized location for both the second storey and for the whole house. The mechanical exhaust for the basement and the first storey was the same as in the first approach, provided by the kitchen and powder room exhaust fans. Therefore, this second approach, especially for the critical second storey zone, could be characterized as distributed exhaust with centralized passive supply.

The third design approach was a balanced system with both supply and exhaust. It made use of the typical local exhaust fans of the first approach for the exhaust component. The supply component of the system provided ventilation air directly to each habitable room through ducts according to the flow rate requirements in the CSA F326 standard. The total supply flow rate matched the total exhaust flow rate to provide a balanced ventilation with no impact on the natural pressure distribution around the building's exterior envelope.

The main features of the tested systems are described below. Also included below are descriptions and designations of the two reference cases–the house with no deliberate ventilation, and with the forced-air furnace fan in continuous operation. Details of the actual installed systems and their construction are described in Appendix A.

A **Local Exhaust System** Configuration A consisted of basic exhaust fans in the kitchen and in each of the two bathrooms (main floor powder room and second floor bathroom) operating at 30 L/s, 10 L/s and 25 L/s 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. No deliberate provisions were included for the supply of make-up air. Make-up air entered the house through general air leakage. Total mechanical exhaust from the house was 65 L/s. This system configuration is illustrated schematically in Figure 2.

B **Local Exhaust System with Vents** Configuration B was a combined passive and mechanical ventilation system consisting of the same set-up and fan flow rates as in Configuration A plus deliberate air intake openings in the dining room and the living room for the ground floor, and in each bedroom for the second floor. 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 one half of the balance of the house ventilation requirement, based on the seasonal average pressure difference of 3.6 Pa (see Appendix A and ref.7). Total mechanical exhaust from the house was 65 L/s. Configuration B is illustrated schematically in Figure 3.

C **Partially Distributed Exhaust System** Configuration C 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 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 from each of the other two bedrooms. No deliberate provisions were included for the supply of make-up air. Background air leakage was relied upon for make-up air. Total mechanical exhaust from the house was 70 L/s. This system configuration is illustrated schematically in Figure 4.

D **Partially Distributed Exhaust System with Vent** Configuration D consisted of the partially distributed exhaust 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 to admit the house total ventilation air supply requirement. Total mechanical exhaust from the house was 70 L/s. Configuration D is illustrated schematically in Figure 5.

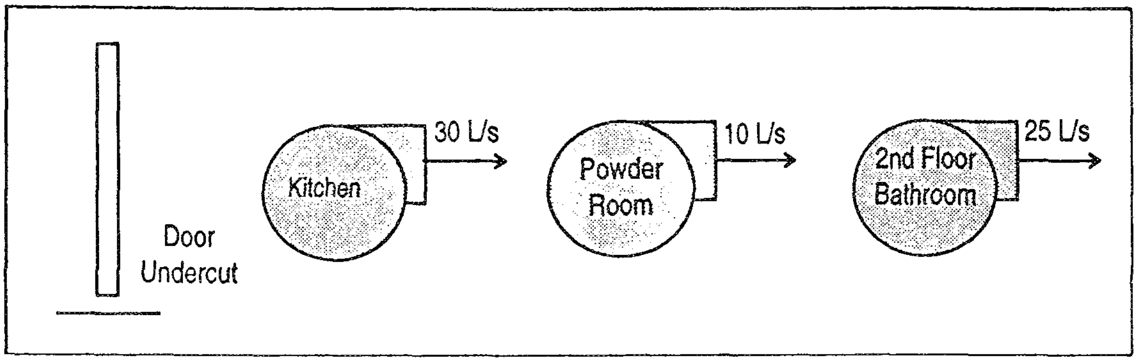

Figure 2 - Schematic Illustration of Ventilation System Configuration A
Local Exhaust System

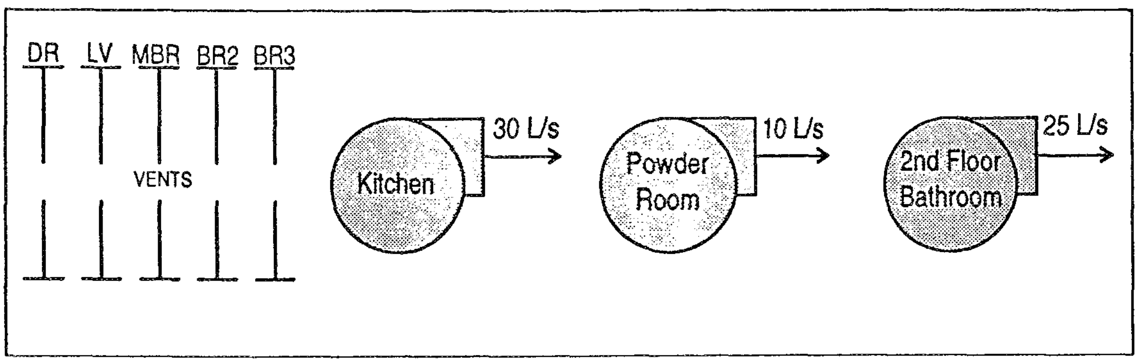

Figure 3 - Schematic Illustration of Ventilation System Configuration B
Local Exhaust System with Vents

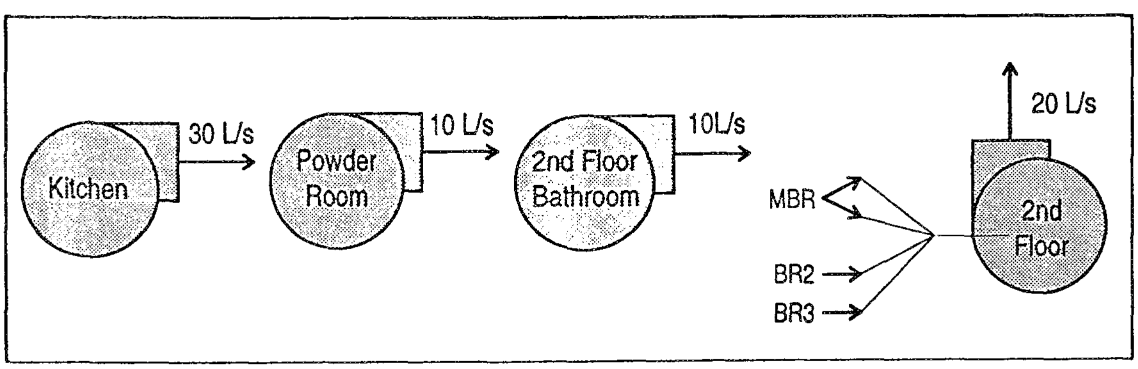

Figure 4 - Schematic Illustration of Ventilation System Configuration C
Partially Distributed Exhaust System

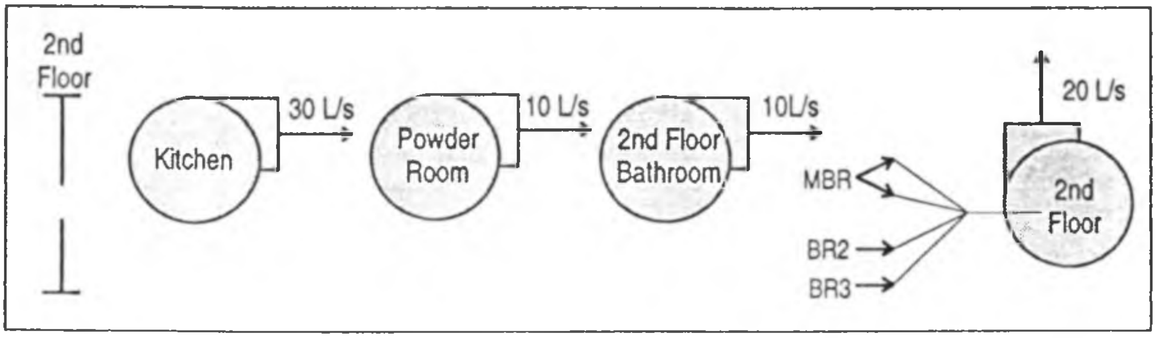

Figure 5 - Schematic Illustration of Ventilation System Configuration D
Partially Distributed Exhaust System with Vent

E **Minimal Ducted Supply System** Configuration E consisted of a minimal ducted supply and return system. The return system was an exhaust arrangement identical to Configuration A. The supply system comprised 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 rates specified in the CSA F326 standard. 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, including high sidewall delivery grilles. Retrofitting ducts for the second floor from the basement would often be impractical in real situations. Total exhaust and supply air flow rates were 65 L/s. This system configuration is illustrated schematically in Figure 6.

F **Reference Case without Circulation** In this reference case all doors and windows were closed tightly, all 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 was by accidental air leakage.

G **Reference Case with Circulation** This reference case was the same as Configuration F except the forced air heating systems' 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 by accidental air leakage.

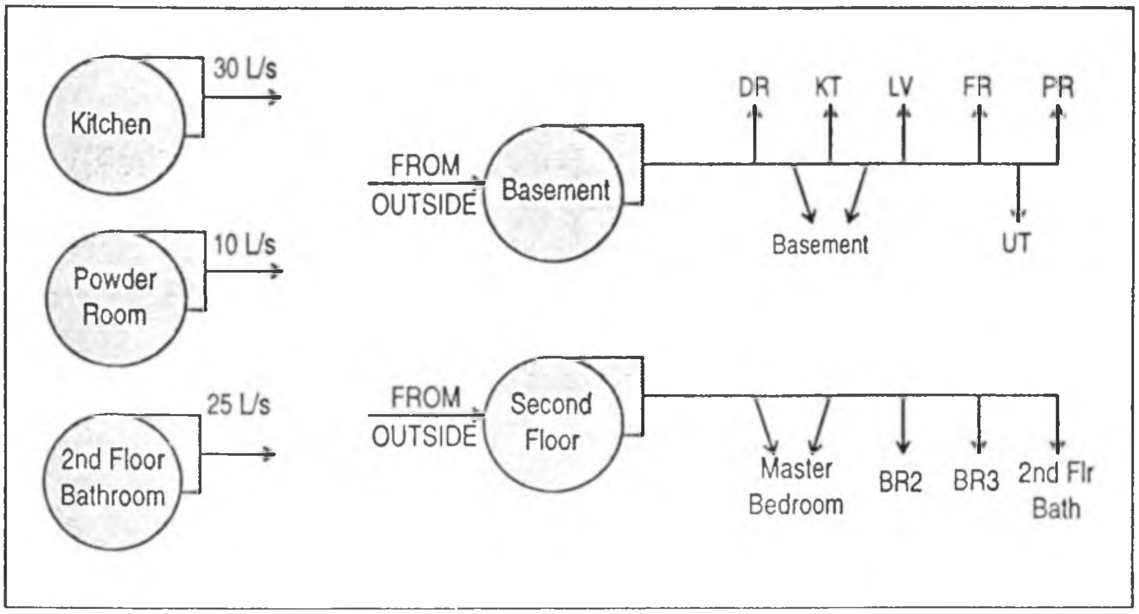

Figure 6 - Schematic Illustration of Ventilation System Configuration E
Minimal Ducted Supply System

The 65 L/s total minimum ventilation requirement for the house was determined by applying specifications in Table 1 of the CAN/CSA-F326-M91 standard according to its clause 5.1.1. However, Table 4 and clause 5.2.2.2(c) of that standard indicate that for an exhaust-only mechanical ventilation system the room-by-room rates should be doubled for all Category A rooms, namely all the rooms except the kitchen, bathrooms and utility room in this house. The total ventilation rate for the whole house would thereby be 110 L/s. Clause 5.11 of the standard, however, requires that the ventilation system be equipped with controls that enable the system to be operated at less than the required minimum ventilation rate. Furthermore, the 1995 National Building Code of Canada only mentions specifically in its Table 9.32.3.A the same minimum ventilation rates as are indicated in Table 1 of the CAN/CSA-F326-M91 standard which are listed in Table 1 of this report. Considering the apparent lack of clear consensus, the minimum room-by-room ventilation rates listed in Table 1 of both this report and the

CSA standard were applied directly to the designs for the test ventilation system configurations in the research house.

The selection of locations for the passive inlet vents in the local exhaust system approach (Configuration B) was based on trying to deliberately distribute the passive supply of make-up air to each closed bedroom and to the rest of the house via the ground floor. An earlier experimental project in the research house [7] had indicated that mechanical exhaust at the rate of 65 L/s could raise the neutral pressure level in the house (with and without distributed deliberate openings [8]) to a level which might permit these second storey vents to serve successfully as air inlets. The Configuration B tests were expected to reveal the success or failure of this distributed passive supply venting strategy.

The partially distributed exhaust system approach with its single inlet vent (Configuration D) was intended to test the strategy of distributed exhaust pick-up with centralized passive supply delivery. The location of the single inlet was selected to provide a relatively centralized delivery of make-up air. The earlier experimental project had indicated an exhaust flow rate of 70 L/s should sufficiently raise the neutral pressure level to allow this single vent located at the elevation of the second storey's floor to successfully serve as an air inlet. The Configuration D tests were expected to reveal the success or failure of this centralized passive supply venting strategy.

The extra exhaust of 5 L/s for the second approach (Configurations C and D) is the consequence of the discrepancy between the minimum exhaust capacity of 10 L/s required for each bathroom in the CSA standard and the minimum ventilation requirement for each bathroom of 5 L/s. When the ventilation requirement for the bedrooms was transferred to the partially distributed exhaust system, the exhaust fan in the second storey bathroom was left to provide only the bathroom's ventilation needs of 5 L/s, but was required by the standard to provide a minimum of 10 L/s of exhaust.

Consequently, the total mechanical ventilation provided by Configurations C and D was 70 L/s, rather than the 65 L/s for the other three test configurations.

7. MEASURED AIRTIGHTNESS CHARACTERISTICS OF THE VENTILATION SYSTEM CONFIGURATIONS

The airtightness characteristics of the whole house envelope for each of the test configurations were measured using the fan depressurisation technique [9]. This information was needed to set the context of the ventilation systems and of the house in the broad spectrum of building envelope leakage typical in Canadian houses. The measured flow coefficient, flow exponent, Equivalent Leakage Area and Normalised Leakage Area values for each test configuration are listed in Table 2.

Table 2
MEASURED AIRTIGHTNESS CHARACTERISTICS
FOR EACH TEST CONFIGURATION

Config ID	Flow Coeff.* C [L/s Pa^n]	Flow Exp.* n	ELA_{CGSB} ** @10 Pa [cm^2]	NLA*** [cm^2/m^2]
A	21.59	0.656	393	1.34
B	60.15	0.582	922	3.15
C	22.53	0.650	404	1.38
D	105.66	0.611	1731	5.92
E	21.83	0.654	396	1.35
F,G	24.33	0.636	423	1.45
*Air leakage curve Q[L/s] = C[L/s Pa^n] • (ΔP[Pa])^n , ref. [9].				
**ELA calculated according to standard CAN/CGSB-149.10-M86, ref. [9].				
***Total exterior above grade envelope area A = 292.54 m^2, NLA = ELA/A.				

As expected, the ELA values of Configurations A, C and E are virtually identical since the envelope conditions were identical; all the fan outlets and inlets were sealed for these measurements. Despite the fact that all the casement window panels were closed for Configurations F and G, their increased ELA 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 the opened 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.

The measured airtightness of the house indicates that it is very airtight, comparable with low-energy houses of the R-2000 type [10,3,11]. With the Configuration B vents open, the envelope leakage is equivalent to the leakiest of modern tract-built Canadian houses, and construction of the 1960s and 1970s in the Prairie provinces. With the Configuration D vent open, the envelope is as leaky (albeit in one well defined location) as pre-1945 Prairie houses.

8. DESCRIPTION OF THE INSTRUMENTATION SET-UP

Tracer gas techniques were used to measure air change rates and air distribution patterns in the two-storey research house for the seven test 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 which allowed hands-off operation of each test once the test conditions were set up and the test was started. A more detailed description of the tracer gas measurement system is contained in a following section.

The ambient test conditions, such as flow rates through ventilation system components, temperature distributions in the various zones throughout the house, the envelope pressure distribution, and outside weather conditions, were continuously monitored and recorded during each test to establish the complete experimental context for each test's results. These data were automatically measured and recorded by another computerized data acquisition system. A more detailed description of these measurements and the measurement instrumentation is contained in a subsequent section.

8.1 TRACER GAS CONCENTRATION MEASUREMENT

The two tracer gases used in these tests were nitrous oxide (N_2O) and sulphur hexafluoride (SF_6). A Beckman Model 865 absorptive infrared analyzer was used to measure the concentrations of N_2O in the range of 0-200 ppm. A Varian Model 3400 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 0-200 ppb range. Air samples were drawn from central locations in each room by sampling pumps which were located in those rooms and connected to a 16-position sampling valve whose outlet was connected through a tee fitting to the analyzers' inlets by flexible plastic tubing. This arrangement maintained a positive pressure in the sampling lines ensuring that any leaks in the tubing would not corrupt the air sample. The gas analyzers, sampling valve and controller, associated hardware and plumbing, and computerized data acquisition and control systems were located in the kitchen and dining rooms. The waste heat from the electronic devices provided a useful simulation of warmer temperatures especially in the kitchen typical in many homes. Rather than discharging the tracer gas samples into the dining room and kitchen areas, each sample line's gas flow was redirected to its source room through a return tube which included a flow restriction when not being directly sampled by the analyzers. This constant flow through the sampling lines also ensured that samples provided to the analyzers were as fresh as possible. The system's concentration measurement sampling rate was approximately 45 seconds per sample, so a complete cycle of the 16 valve positions occurred every 12 minutes. This system was capable of measuring, and recording in data files on the computer's hard disk, concentrations of either one or both tracer gases with no variations in the sampling rate.

8.2 FLOW RATE, TEMPERATURE AND PRESSURE MONITORING

Forty-two pressure taps for measuring pressure differences across the envelope were installed in the four exterior walls. Pressure transducers and an automated data acquisition and control system allowed up to 32 pressures to be monitored simultaneously. Temperatures at up to 32 locations could also be measured simultaneously.

The exhaust duct of each of the three exhaust fans was instrumented with an averaging tube device to measure precisely the flowrate through each fan. Each of the four pick-up branches of the partially distributed exhaust system (Configurations C and D) was similarly instrumented to measure the individual exhaust flowrates in each branch. Each of the thirteen supply branches of the minimal ducted supply system (Configuration E) were also instrumented with averaging tubes to measure the individual supply flowrates in each branch. One pressure transducer (and one data acquisition system transducer channel) was required for each flowrate measurement, thereby reducing the number of envelope pressure tap locations that could be monitored during any particular test. For tests on ventilation system Configurations A and B, only three exhaust flow rates were monitored. Seven exhaust flowrates were monitored for tests on systems C and D. For system E tests, three exhaust flowrates and thirteen supply flowrates were monitored.

This automatic flowrate measurement facility was very useful for the initial commissioning adjustment of each ventilation system. In addition, each relevant flowrate was monitored and recorded continuously for each test, to provide a check on the operation of the ventilation systems. The recorded flowrate data were analyzed after each test and verified that each ventilation system performed according to design specifications for all tests. Any departures from precise design flowrates were due to the influences of weather. The real-time display capability of the flowrate monitoring system was useful during experiments as a check to ensure that the ventilation system components were functioning properly and set correctly.

Temperatures 15 cm below the ceiling and 15 cm above the floor in each of the habitable rooms were measured continuously during each test using Type-T thermocouples connected to specialized isothermal plate thermocouple circuit boards in the data acquisition system and mounted on pipe "trees" located reasonably near to the centroids of each room (with due regard for safety, traffic flow and the protection of the sensors). In addition, the same data acquisition system continuously measured the outdoor temperature using a shielded Type-T thermocouple during each test.

There were a total of 28 pressure transducers available to measure either flow rates or envelope pressures. Three pressure transducers were located in the basement and committed to measurement of the three basement supply flow rates of Configuration E. Since the flow rate monitoring required 3, 7 or 16 transducers, depending upon the ventilation system configuration being tested, 22, 18 or 9 transducers were available to monitor envelope pressures.

Weather conditions including barometric pressure, relative humidity, solar radiation, precipitation, and wind speeds and directions at three elevations 6 m, 10 m and 20 m, were also automatically monitored on-site.

9. DESCRIPTION OF THE EXPERIMENTAL PROCEDURES

Each ventilation system configuration was tested using both single and multiple tracer gas techniques. The decay method was used for all tests–a single dose of tracer gas was quickly injected or released into the whole house or a specific zone and the decay of its concentration with time was measured at several sampling locations. The single tracer gas technique, using either N_2O or SF_6, was used to measure the local air change rate in each zone or room in the house. The multiple tracer gas technique using the two tracer gases was used to determine the air flow patterns between the closed master bedroom and the rest of the rooms in the house.

The general test procedure was composed of the following steps: tracer gas injection, mixing period, and monitoring the concentration decay in zones of interest. First, conditions were set in the house and the furnace fan and forced-air delivery system for the tracer gas injection and mixing stage. Second, the concentration measurement system was started and the tracer gas dose was injected. Third, the tracer gas was allowed to be distributed to all rooms and then mixed thoroughly throughout the house to a uniform concentration by operating the furnace fan. At the end of the mixing period, the mixing equipment (furnace fan) was stopped and its supply and return grilles were sealed and the ventilation system configuration to be tested was set in operation. Subsequently, the changes in tracer gas concentrations were measured and recorded for an appropriate duration. At the end of the test, the data acquisition system was stopped and the ventilation system operation was then stopped. The raw data files could then be downloaded from the computer for later processing and analysis. Each ventilation system configuration involved continuous operation of its various fans. The flow rates through each active ventilation system component were monitored and recorded automatically throughout each test. These flow rate records were reviewed after each test to confirm that the mechanical movement of air had been constant and at design flow rates throughout the test. More details of the various test procedures are described in subsequent sections.

Initially, tracer gas concentrations were measured only in the habitable rooms as defined in the CSA F326 standard; i.e., in rooms having specified ventilation requirements. Concentrations in other spaces such as the hallways were not measured for the first several tests. When preliminary analysis of the early test results suggested that all the fresh air supply to the house had not been accounted for, the sampling configuration was changed to measure tracer gas concentrations in the hallway spaces on the first and second storeys since the volumes of their individual and combined enclosed space was similar to the volumes of many of the habitable rooms in the house. Table 3 lists the sampling locations before and after this change to the sampling configuration which was made late on January 18, 1994, after the completion of that day's tests.

Table 3
SAMPLING VALVE POSITION ASSIGNMENTS
FOR EACH SAMPLING CONFIGURATION

Prior To and On 940118		After 940118	
Valve Position	Sampling Location	Valve Position	Sampling Location
1	Utility Room (UT)	1	Utility Room (UT)
2	Basement (BT)	2	Basement (BT)
3	Dining Room (DR)	3	Dining Room (DR)
4,8,12,16	Master Bedroom (MBR)	4,8,12	Master Bedroom (MBR)
5,13	Kitchen (KT)	5	Kitchen (KT)
6	Living Room (LR)	6	Living Room (LR)
7,15	Family Room (FR)	7	Family Room (FR)
9	Powder Room (PR)	9	Powder Room (PR)
10	Bedroom 2 (BR2)	10	Bedroom 2 (BR2)
11	Bedroom 3 (BR3)	11	Bedroom 3 (BR3)
14	2nd Floor Bath (2B)	13	N_2O Zero Check
		14	2nd Floor Bath (2B)
		15	2nd Floor Hall (H2)
		16	1st Floor Hall (H1)

9.1 SINGLE TRACER GAS TESTS

The single tracer gas tests were intended to measure the local air change rate in each zone of interest in the house–initially only the "habitable" rooms and later including the hallway spaces. The general test strategy was to inject the single tracer gas and mix it to a uniform concentration throughout the house interior, and then monitor its concentration decay in each room. The resulting data curves for each room describing the decay with time were mathematically fitted with single exponential curves, whose resulting exponent coefficient was interpreted as the air change rate in the room. When multiplied by the room volume, in appropriate units, the calculated result was the effective ventilation supply flow rate of outdoor (dilution) air to that room. More details of the test procedures appear in the following sections.

9.1.1 Injection, Distribution and Mixing

The forced-air furnace and its air-delivery duct system were used as the principal means of mixing the tracer gas to a uniform concentration throughout the house as the starting condition for the single tracer gas tests. All the interior doors were opened wide to facilitate the mixing process. All the exterior doors and windows were tightly closed and locked to reduce as much as possible the premature loss of tracer gas by air leakage. The concentration measurement system was started and calibration checks of the gas analyzers were done and recorded by the data acquisition system. The tracer gas dose was injected into the return air plenum of the furnace after the furnace fan was switched on in continuous mode operation. Preliminary tests had indicated that this simple approach did not distribute the tracer gas dose evenly within the house, unnecessarily lengthening the mixing time required. Trial and error led to a strategy of partially obstructing certain supply air registers during the first part of the mixing period to solve this distribution problem. Several portable box fans were placed in some of the open interior doorways to assist the mixing. At the end of this distribution phase, the partial obstructions of the supply air registers were removed for the balance of the mixing period to allow the full force of the forced-air delivery to mix the tracer gas thoroughly in each room. The total time required for injection, distribution and mixing to a uniform concentration was 30 minutes in this house.

9.1.2 Ventilation System Operation and Building Conditions

Prior to the tracer gas injection, all the exterior doors and windows were closed tightly and locked. The normal test conditions included keeping them closed tightly (except for those window panels which had to be opened to unseal passive inlet vents or ventilation fan inlets or outlets for all tests) to measure only the air distribution due to accidental air leakage and the deliberate action of the tested ventilation system. At the end of the mixing period, the furnace fan was switched off and its supply and return air registers were all sealed to ensure that the forced-air duct system did not offer flow paths between rooms. (Such errant flow paths could confound the test results and provide misleading indications of the internal air flow patterns and air distribution performance of the tested ventilation system configuration.) The various components of the ventilation system being tested were then put into operation. This involved unsealing the openings for exhaust fan outlets and/or supply fan inlets and/or opening the casement window panels covering passive inlet vent openings. The portable mixing-assist fans were switched off and removed from their doorways and the interior doors to the bedrooms, bathrooms and the basement rooms were closed. Finally, the fans of the ventilation test configuration were then switched on, and their flow rates were verified using the real-time display of the flow/temperature/pressure data acquisition system. All these start-of-test procedures were carried out as quickly as possible to minimize the departure from the well-mixed initial condition before the test ventilation configuration was fully operational. Detailed check lists of the instrumentation start-up and ventilation set-up procedures for each test configuration were assembled and followed closely to prevent discrepancies in any of the many test conditions.

With the ventilation system being tested in operation, the concentration data acquisition system monitored and recorded the tracer gas concentration in each sampled room or zone for at least two hours, to provide at least ten concentration data points per decay curve (one curve per room or zone) and ensure enough data to support accurate curve fitting. During the test, access and egress to the research house was restricted to a minimum to avoid corruption of the test results. At the end of the test, the calibration of the gas analyzers was checked and recorded, the data gathering was stopped, and the ventilation configuration's fans were switched off and the vent and fan inlet and outlet openings were closed.

A single tracer gas test typically required approximately three and one half hours from start to finish once the set-up procedures were fully developed–one half hour for set-up, 30 minutes mixing period, two hours of decay and one half hour to shut down and wrap up, download data files and secure the research house. The ability to use either tracer gas interchangeably avoided the need to purge the house of tracer gas from one test before a second test could be conducted. This allowed two single tracer gas tests (each using a different tracer gas) to be carried out in one day. Normal air leakage under typical weather conditions during the heating and shoulder seasons usually was sufficient for all the tracer gases from one day's tests to have dissipated before the start of the next day's testing.

9.2 MULTIPLE TRACER GAS TESTS

The multiple tracer gas tests were intended to determine the air flow patterns between the closed master bedroom and the rest of the house interior. The general strategy included injecting one tracer gas (SF_6) into the master bedroom and the other tracer gas (N_2O) into the rest of the house, allowing the two tracer gases to mix thoroughly within their respective spaces, and then putting the test configuration into operation and monitoring the concentrations of both gases as the ventilation equipment moved the air into, within and out of the house. Some test conditions lent themselves to attempts to quantitatively analyze the measured results to determine actual interzonal flow rates, while other conditions only allowed qualitative interpretation of the measured data.

9.2.1 Injection, Distribution and Mixing

The objective of the multiple tracer gas injection, distribution and mixing process was to create a uniform concentration of each tracer gas only in its dose or source zone–SF_6 in the master bedroom and N_2O in the rest of the house–with zero concentration of each gas in their respective target zones–the master bedroom for N_2O and the rest of the house for SF_6. To accomplish this, the two zones had to be sealed from one another. This was effected by sealing the supply and return registers of the forced-air system in the master bedroom and closing and sealing with duct tape the edges and bottom undercut of the master bedroom door. In addition, all the openings of the partially distributed exhaust system's pick-ups and of the minimal ducted supply system's supplies were sealed with duct tape to prevent tracer gas leakage through these ducts. The furnace fan could then be used to distribute and mix the N_2O in the rest of the house in the same manner as described for the single tracer gas test procedure. The SF_6 dose was delivered to the master bedroom via a line of plastic tubing leading from the dining room (control centre) to a small pump located in the master bedroom. This arrangement maintained a negative pressure in this dosing line during the SF_6 injection to prevent leakage of the SF_6 into the rest of the house. Despite this precaution, the SF_6 gas proved very difficult to contain in the master bedroom in preliminary testing of this injection strategy. SF_6 gas generally exhibits a very large apparent molecular diffusivity which helps it mix very quickly throughout an enclosed space. Taking advantage of this property, the SF_6 injection strategy was modified by delaying its injection until just 5 minutes before the end of the N_2O mixing period. To help ensure the complete mixing of the SF_6 in the master bedroom, two box fans were located in that room. Both these mixing fans and the dosing pump were switched on and off remotely using electrical extension cords. Except for the special treatment of the master bedroom, the injection, distribution and mixing of the N_2O followed the same procedure as described for the single tracer gas tests in an earlier section. As for the single tracer gas tests, the total time required for the injection, distribution and mixing of the two tracer gases for a multiple tracer gas test was 30 minutes.

9.2.2 Ventilation System Operation and Building Conditions

Prior to the injection of the tracer gases, all the exterior doors and windows were closed tightly and locked, with some exceptions for specific ventilation system configuration tests. For Configuration B tests, the master bedroom casement window panel, through which that room's passive inlet vent opens to outdoors was opened. A cord was attached securely to the flexible magnetic plate (the secondary seal) covering the orifice plate of the passive inlet vent and its other end was passed underneath the master bedroom door into the hall. This provided a means of opening the master bedroom's passive inlet vent at the end of the mixing period without opening the bedroom's door. When the test monitoring stage was begun at the end of the mixing period, the tape seal of the master bedroom door was removed, and the cord was pulled until the magnetic seal of the inlet vent fell away free, fully exposing the vent opening. For Configuration C and D tests, the two pick-up inlet openings of the partially distributed exhaust (PDE) system in the master bedroom were rigged with duct tape seals that had similar cords attached that were passed under the door before its tape seal was installed. At the start of the monitoring stage, just before the PDE ventilation system was powered on, these tape seals were removed remotely without opening the door by pulling on the cords until the seals fell away. For Configuration E tests, similar cord tape seals were added to the minimal ducted supply system's two supply outlet openings in the master bedroom which allowed them to be remotely unsealed immediately prior to the monitoring stage. For Configuration G tests, cords were similarly attached to the flexible magnetic seals of the forced-air system's supply and return grilles in the master bedroom. At the start of the monitoring stage, these cords were pulled to open these grilles at the same time that the tape seal was removed from the closed master bedroom door.

At the end of the mixing period for both the tracer gases, the furnace fan was switched off and the forced-air system's supply and return grilles were sealed. The mixing fans and dosing pump in the master bedroom were unplugged (remotely switched off). The tape seal of the master bedroom was removed and the remote seals were removed by pulling on the appropriate cords. The mixing-assist fans in any interior doorways were removed and switched off. The vents and fans, and supply or pick-up openings as appropriate, of the test ventilation configuration were opened or unsealed, and doors to the bedrooms, bathrooms and basement were closed. Finally, the fans of the test ventilation configuration were powered on, and the flow rates of the ventilation system were verified using the real-time display of the flow/temperature/pressure data acquisition system. The start-of-test procedures were carried out as quickly as possible, following detailed check-list procedures, to minimize departure from uniform concentrations of each tracer gas in their respective source zones.

The concentrations of the two tracer gases were continuously monitored and recorded automatically at each sampling location (listed in Table 3) at the rate of one sample concentration measurement every 45 seconds, for a sampling frequency at any one sampling location of one per 12 minutes. Automatic concentration monitoring for multiple tracer gas tests usually continued for at least 6 hours. This time was required to obtain substantial decay of the tracer gases in their target zones, where initially the concentrations would typically first increase, reach a peak depending on the interzonal airflow rates and then decay, while the gases' concentrations in their respective source zones would steadily decay. During the test, access and egress to the research house was restricted to a minimum to prevent corruption of the test results.

10. GENERAL DESCRIPTION OF THE TESTS

10.1 NUMBERS OF TESTS, TEMPERATURE RANGES AND DATES

The tracer gas tests began in late autumn 1993 and ended in late spring 1994. The intention of scheduling the tests thus was to capture test conditions representing the full range of weather conditions typical of the heating season and the shoulder seasons in Canada. The 99% winter dry bulb design temperature for Ottawa is -27°C [Table 2, p.24.17 ref.14]. Due to the design and construction of the experimental set-up, any ventilation system configuration could be selected arbitrarily for any test. This allowed an approximately cyclic selection of test configurations throughout the overall test period, so each configuration would be tested for a broad range of weather conditions. At least ten single tracer gas tests and four multiple tracer gas tests were conducted on each of the seven ventilation system configurations. Tables 4 and 5 list the earliest and latest dates, the range of outdoor air temperatures and the number of tests for each configuration for single and multiple tracer gas tests. The average outdoor air dry bulb temperatures for each single tracer gas test are indicated in the tables in Appendix B which report individual measured results for each ventilation system configuration. The average outdoor temperatures for each multiple tracer gas test are listed in Table 9 later in this report, along with measured results from individual tests.

Table 4
SUMMARY OF SINGLE TRACER GAS TESTS' CONDITIONS

		Test Period		Temperature Range	
System Config	Number of Tests	Start Date	End Date	Coldest OAT [°C]	Warmest OAT [°C]
A	12	Nov. 18/93	June 1/94	-23.0	+17.1
B	10	Nov. 23/93	April 18/94	-24.4	+11.2
C	12	Nov. 24/93	June 3/94	-19.3	+19.3
D	12	Dec. 2/93	May 26/94	-23.4	+14.9
E	10	Dec. 1/93	May 11/94	-14.0	+11.9
F	11	Nov. 17/93	May 18/94	-16.4	+14.6
G	10	Nov. 18/93	May 10/94	-18.6	+14.4

Table 5
SUMMARY OF MULTIPLE TRACER GAS TESTS' CONDITIONS

		Test Period		Temperature Range	
System Config	Number of Tests	Start Date	End Date	Coldest OAT [°C]	Warmest OAT [°C]
A	4	Dec. 13/93	Mar 1/94	-26.0	0
B	4	Dec. 8/93	May 4/94	-26	+16
C	5	Jan 19/94	Apr. 20/94	-24	+5
D	4	Dec. 14/93	May 5/94	-19	+17
E	4	Dec. 15/93	Mar 22/94	-9	+9
F	4	Jan 20/94	May 3/94	-16	+11
G	5	Dec. 9/93	May 12/94	-18	+8

10.2 TEST IDENTIFIERS

Tests were labelled according to their date, ventilation system configuration and whether they used single or multiple tracer gases, using the format yymmddx, where yy, mm, dd are the numerical identifiers for the year, month and day and x is the configuration identifier. The prefix M was added to the test label if it was a multiple tracer gas test. For example, test M931214D was a multiple tracer gas test of Configuration D conducted on December 14, 1993. Because the test period did not span more than 12 consecutive calendar months, the year identifier is redundant, and was sometimes dropped where additional characters were needed for other purposes, for example in identifying data files of concentrations measured at specific locations, using eight character filenames in the computer's MS-DOS operating system environment. Since multiple tracer gas tests required one entire day, even the prefix M could be dropped in such situations. The same example test could therefore be unambiguously labelled 1214D.

11. DISCUSSION OF THE SINGLE TRACER GAS TESTS' RESULTS

This discussion begins with some preliminary general comments. Those are followed by subsections which address the results from tests on individual ventilation system configurations. The discussion is completed by summary comments and general conclusions.

11.1 GENERAL COMMENTS

In general, the measured decay of tracer gas concentration in each room or zone was curve fitted with a single exponential curve of the form:

$$C(t) = C_0 \bullet \exp(-I \bullet t) \qquad [11.1]$$

where: $C(t)$ is the concentration in the zone, [ppm or ppb]
C_0 is the "initial" concentration in the zone, [ppm or ppb]
I is the air change rate in the zone, [ac/h]
t is the time, [h].

Non-linear regression was used to calculate the curve fit, from which the apparent air change rate in each zone, I, was determined. When the air change rate was multiplied by the room volume, the calculated result was the apparent supply flow rate of outdoor (dilution) air to that room. This analysis assumed that flow conditions were steady, and that the concentration of the tracer gas in the outdoor air was zero.

This physical model used as the basis for the data analysis is usually applied to single zone situations where the single zone is well mixed. Its application to a multizone situation attempts to calculate the effective outdoor air change rate in each zone. This approach is expected to be effective in zones where the dominant inflow is direct from outdoors. It may not be so effective, or accurate, in zones where the dominant inflow is from other interior zones where the tracer gas concentration is non-zero. From the earlier discussion of the general theories about interior air flow patterns, zones affected most adversely might be expected to be the second storey rooms in cold weather, while ground floor rooms where most of the inward air leakage occurs should yield results which fairly represent the actual outdoor air supply rates. The mechanism may be especially important where the tracer gas concentration in lower storey rooms is changing (decaying steadily) and thereby the apparent amount of fresh air contained in the flow from these zones into upper storey rooms (when stack effect may dominate the interior airflow patterns), which represents the effective fresh air (diluting) flow into those upper storey rooms, would appear to increase (i.e., non-steady flow conditions). With this limitation in mind, Eq.11.1 was fitted to the concentration decay data in each zone measured in the single tracer gas tests. The numerical results of this curve fitting form the basis for the discussions in the conclusions later in this report.

The complete set of analyzed results from the single tracer gas tests on each configuration are listed in Appendix B. To facilitate the comparison of the ventilation air distribution performance of each ventilation system configuration, whole house, floor-by-floor, and room-by-room averages of the ventilation rates measured during the single tracer gas tests were calculated and are listed in Tables 6, 7, and 8. For each configuration and zone of interest there are two table entries: the average of the measured results for all tests of that configuration (excluding obvious outliers) and the upper and lower bounds of the range of those results expressed as percentages of the requirement for that zone or room.

In Table 6, the ventilation rates listed under Total* are the sum of the ventilation rates measured only in the "habitable" rooms (as defined in the CSA F326 standard, i.e., not including the hallways or the storage room). Similarly, the ventilation rates listed under 2nd Floor* and 1st Floor* also exclude these non-habitable spaces.

Despite the fact that the flow rates of all the exhaust (and supply) fans were measured during each test and the measurements confirmed that those flow rates summed to 65 L/s (for Configurations A, B, and E--both total supply and total exhaust) or 70 L/s (Configurations C and D), many tests' tracer gas results indicated that the Total* ventilation rates were less than these numbers.

The ventilation rates in the hallway spaces were only measured for the later tests (after January 18, 1994) and were excluded from the table entries because they were not measured for all tests. The combined total volume of the hallway spaces represents a significant portion of the total internal volume of the house, certainly more than some "habitable" rooms. For the later tests, the measured hallway ventilation rates showed that some of the apparently missing ventilation air supply could be accounted for by the effective ventilation happening in these hallway spaces (cf. Appendix B).

The house total ventilation rates listed in Table 6 suggest that Configurations B, D and E satisfy the CSA F326 requirements on average for the house considered as a whole. While Configurations A and C fall below 60 L/s on average, C was measured to meet the total requirement in some tests, and both A and C greatly exceeded the air supplied through natural air leakage as measured for Configurations F and G. Therefore, from the point of view of the total ventilation air supply to the house as a whole, the partially distributed exhaust systems, Configurations C and D, show some promise, especially D which includes a passive air inlet. The local exhaust system with passive air inlets, Configuration B, actually provides excess ventilation, and the minimal ducted supply system, Configuration E, provides the required ventilation rate. Local exhaust fans alone without passive air inlets, Configuration A, do not seem to provide the necessary ventilation.

Table 6
AVERAGE ZONAL MEASURED VENTILATION RATES

	Average Ventilation Rates in Habitable Rooms*							
Config ID	Total* (65 L/s)**		2nd Floor* (25 L/s)**		1st Floor* (25 L/s)**		Basement (15 L/s)**	
	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]
A†	50.7	68-89	8.15	26-39	22.0	78-110	20.5	111-160
B†	74.7	92-158	17.4	38-100	42.2	123-253	15.1	72-145
C†	59.7	82-102	13.3	43-63	24.7	85-117	21.7	103-192
D†	62.9	84-127	17.0	59-78	31.0	104-169	14.8	72-144
E‡	65.1	91-119	21.2	81-94	20.7	72-97	23.2	133-198
F	20.3	19-59	2.40	5-15	7.81	16-65	10.1	45-123
G	19.1	17-43	6.16	15-37	5.75	14-34	7.20	24-68

*Habitable Rooms do not include hallways or storage closets (CSA F326 standard).

**Total zonal ventilation requirements shown in parentheses.

†Total exhaust flow rates for A, B, C and D were directly measured and confirmed at design rates for all tests.

‡Total supply and exhaust flow rates for E were directly measured and confirmed at design rates for all tests.

On a floor-by-floor comparison, Configurations A through E all met or exceeded their total zonal ventilation requirements for the basement and the first (ground) floor. However, for the second floor all the systems demonstrated some apparent ventilation deficit. Even for Configuration E, the minimal ducted supply system where fresh ventilation air was deliberately delivered to all "habitable" rooms at their specified rates–confirmed by direct flow rate measurements–the tracer gas measurements indicated, on average, an almost 15 percent shortfall in the total ventilation supplied compared to the total zonal requirement for the second floor. Only Configuration B was measured in one test to just meet this second floor total requirement. However, if the air distribution performance of Configuration E is taken as the reference standard, since flow rate measurements confirmed that it delivered the required flow rates of fresh air to all "habitable" rooms, then Configurations B and D show a second storey deficit of only 18-20 percent on average. Configuration C then would still show a deficit of almost 40 percent and Configuration A a deficit of more than 60 percent. The floor-by-floor comparison indicates that the second floor poses the greatest challenge to the ventilation systems. Some of the apparent ventilation shortfall in these upper storey rooms may be a result of the limitation on the single tracer gas technique mentioned earlier, the consequence of which seems to be that the grouped or multizone single tracer gas technique applied here underestimates the ventilation air supply in rooms where much of the inflow is interior air from other rooms.

The results measured for the basement illustrate that the deliberate passive air inlets of Configurations B and D were very effective at providing the make-up air for their exhaust fans. For those two configurations, the average ventilation rates measured in the basement were in close accord with the standard requirements. The other two exhaust-only ventilation systems, Configurations A and C, obviously relied on air leakage into the basement for a significantly greater portion of their make-up air supply as illustrated by their larger measured ventilation rates in the basement. The minimal ducted supply system, Configuration E, which was a balanced approach where total mechanical supply and exhaust flow rates were equal, would not have affected the distribution of pressure differences acting across the building envelope or the natural air leakage patterns driven by those pressures. Therefore, the larger apparent ventilation rates measured in the basement rooms for Configuration E probably represent the mechanically supplied ventilation air supplemented by the infiltration of outdoor air through leaks in the basement walls. (A suspected major site of air leakage in typical Canadian house construction is the joint between the foundation wall and the sill plate.)

Tables 7 and 8 list the averages of the tracer gas measurements of the ventilation rates in the "habitable" rooms on the second floor and the first floor, respectively. The average measured ventilation rates in the “habitable” basement rooms are also listed in Table 7. These results illustrate in a more detailed way the same general behaviour indicated in the collective floor-by-floor comparison reported in Table 6.

The ventilation rates measured in the second floor rooms, whose doors were all closed during all the tests, are generally less than the requirements specified in the CSA F326 standard. Configuration E ventilation rates are very close to the requirements, and Configurations B and D provide, on average, more than half the requirements. However, the flow rates of outdoor air supplied mechanically by Configuration E to each of the second storey bedrooms were measured directly, and these measurements confirmed that 10 L/s was consistently provided to the master bedroom and 5 L/s to each of the other two bedrooms and to the bathroom, indicating that the single tracer gas technique used here underestimates the amount of fresh dilution air provided to these rooms. If the measured bedroom air change rate performance of Configuration E is again taken as the reference, then Configuration C also provides on average more than half, and Configurations B and D provide approximately 75 percent, of the ventilation required. Configuration A in most of the second floor rooms performs little better than Configuration G, suggesting that kitchen and bathroom exhaust fans alone, without deliberate make-up air inlets are not suitable for providing adequate ventilation for second storey zones.

The ventilation rates for Configurations A through E measured in the first floor rooms generally exceed the requirements, on average. Configuration E most closely matches the requirements of 5 L/s per room, with a slight deficit of 4 percent or less in some rooms. Configuration B displays the largest ventilation rates for these rooms, with Configuration D the next largest. This was expected since the distribution of Configuration B's deliberate leakage area placed more than half in first floor rooms. The single centralized passive air inlet opening of Configuration D, which opens into the stairwell between the two storeys provided less effectively distributed deliberate leakage area for stack effect driven infiltration than Configuration B. By providing its incoming airflow into the stairwell, that make-up outdoor air was not directly supplied into first floor rooms for Configuration D.

Table 7
AVERAGE MEASURED VENTILATION RATES IN SECOND FLOOR ROOMS

Config ID	Average Ventilation Rates in Habitable Rooms* on Second Floor and Basement Levels											
	Master Bedroom (10 L/s)**		Bedroom 2 (5 L/s)**		Bedroom 3 (5 L/s)**		2nd Floor Bath (5 L/s)**		Basement Area (10 L/s)**		Utility Room (5 L/s)**	
	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]
A	3.6	23-47	1.47	16-46	1.02	15-26	2.06	35-45	13.36	110-155	7.15	110-178
B	6.77	38-140	3.61	26-176	3.6	24-115	3.45	51-93	10.21	72-148	4.85	67-139
C†	6.06	49-74	2.72	43-69	2.18	33-60	2.33	39-56	13.88	104-183	7.79	99-213
D†	7.42	64-84	3.26	58-74	3.12	52-73	3.24	55-75	9.97	71-160	4.85	72-142
E‡	9.81	94-104	4.5	86-106	4.24	80-98	2.61	46-58	15.26	134-184	7.96	128-226
F	0.89	2-20	0.37	2-17	0.32	2-13	0.39	2-11	6.80	41-129	3.25	42-111
G	3.14	19-47	1.28	15-38	0.99	11-29	0.75	8-22	4.64	24-68	2.56	24-70

*Habitable Rooms do not include hallways or storage closets (CSA F326 standard).

**Room ventilation rate requirements shown in parentheses, verified by measurement where applicable as indicated below.

†Bedroom , bathroom and kitchen exhausts measured and verified for PDE tests (Configurations C and D).

‡Supply rates to all rooms and all exhaust rates measured and verified for MDS tests (Configuration E).

Table 8
AVERAGE MEASURED VENTILATION RATES IN FIRST FLOOR ROOMS

	Average Ventilation Rates in Habitable Rooms* on Ground Floor									
Config ID	Kitchen (5 L/s)**		Dining Room (5 L/s)**		Living Room (5 L/s)**		Family Room (5 L/s)**		Powder Room (5 L/s)**	
	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]	Avg. [L/s]	Range [%]
A	5.20	87-130	5.47	98-137	5.46	92-137	5.21	88-131	0.70	11-18
B	10.1	145-319	11.7	181-352	9.85	136-278	9.33	128-277	1.22	17-36
C	5.88	99-147	6.16	107-151	6.12	103-143	5.77	100-133	0.79	13-19
D	7.98	127-201	8.27	133-206	7.14	94-214	6.65	83-199	0.98	14-26
E‡	4.80	84-108	4.87	84-110	5.26	93-128	4.97	87-123	0.80	13-18
F	1.81	19-76	1.84	20-78	1.99	21-83	1.86	19-76	0.32	3-10
G	1.37	16-40	1.37	17-39	1.47	18-44	1.36	17-41	0.19	2-5

*Habitable Rooms do not include hallways or storage closets (CSA F326 standard).

**Room ventilation rate requirements shown in parentheses.

‡Supply rates to all rooms and all exhaust rates measured and verified for MDS tests (Configuration E).

The tracer gas measurements of the ventilation rates in the bathroom on the second floor and in the powder room on the first floor were consistently smaller than their room requirements, especially so for the powder room. This was likely caused by their local exhaust fans' inlet flow patterns, and especially in the case of the powder room, their small room sizes which together probably created significantly non-uniform tracer gas concentrations in these rooms. The tracer gas method depends upon good mixing and uniform concentrations of the gas in the zone of interest to accurately measure the air change rate. To have a uniform concentration practically requires that the mixing rate in the zone be substantially faster than the overall air change rate. This may have not been the case in these small rooms with strong exhaust flow rates. The flow rates through all exhaust fans were continuously monitored during all tests, and maintained a steady 10 L/s in the powder room and either 25 L/s (A, B and E) or 10 L/s (C and D) in the second floor bathroom.

11.2 CONFIGURATION SPECIFIC DISCUSSIONS

Configuration F tests provided the reference case for the house as-is with no mechanical ventilation. These tests' results are presented and discussed first to provide the context for the subsequent discussion of the results of the other test configurations. Configuration G was expected to provide the reference case for the best-mixed configuration, but with no mechanical air exchange with outdoors.

11.2.1 Configuration F - Reference Case Without Circulation

The average ventilation rates for the whole house and each storey listed in Table 6 indicate that natural air leakage in the research house provides only 25 percent of the required total ventilation, as little as 10 percent for the second floor, 30 percent for the ground floor and as much as 67 percent for the basement. 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. Figures 7 and 8 report the multi-room single tracer gas decay curves measured for two Configuration F tests at average outdoor air temperatures of -13°C (Test 940111F) and +8°C (Test 931117F). These two figures illustrate that, for a broad range of temperature, the natural air exchange can cause the individual storeys to behave as distinct well-mixed zones. (The powder room seems to behave as if it is part of the basement zone rather than the first floor zone.) This general behaviour pattern can be distorted significantly by windy conditions, especially at milder outdoor temperatures, where stack effect is not so strong. This is illustrated in Figure 9 where the results of a test at +12°C (Test 940518F) show that only the ground floor rooms still behave as a single well-mixed zone, other rooms behave individually.

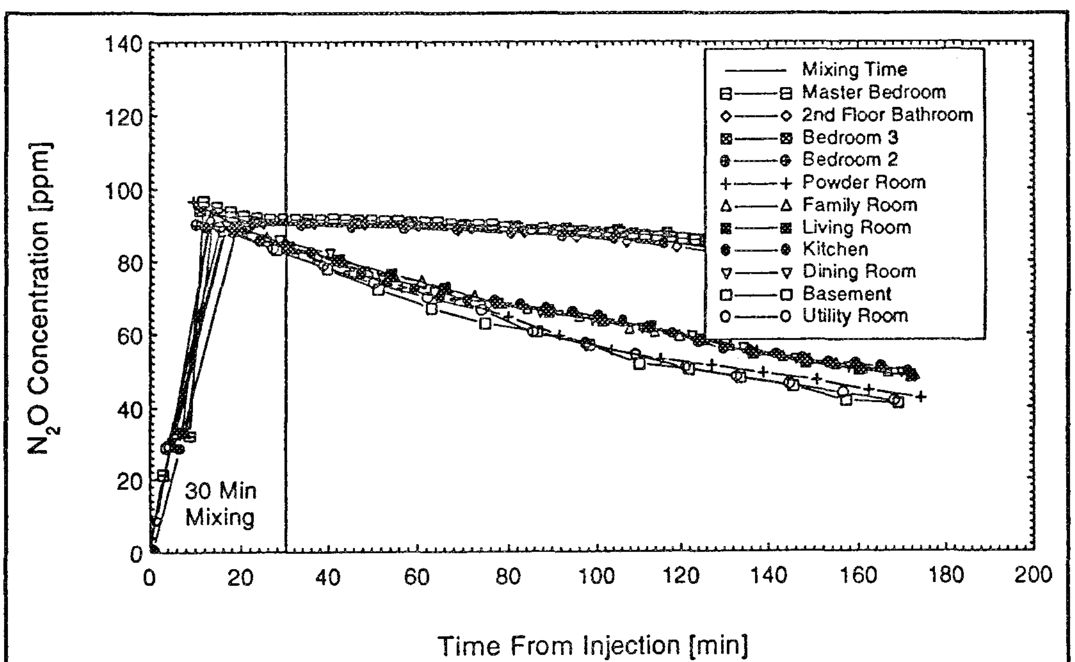

Figure 7 - Single Tracer Gas Measurements for Test 940111F at -13°C

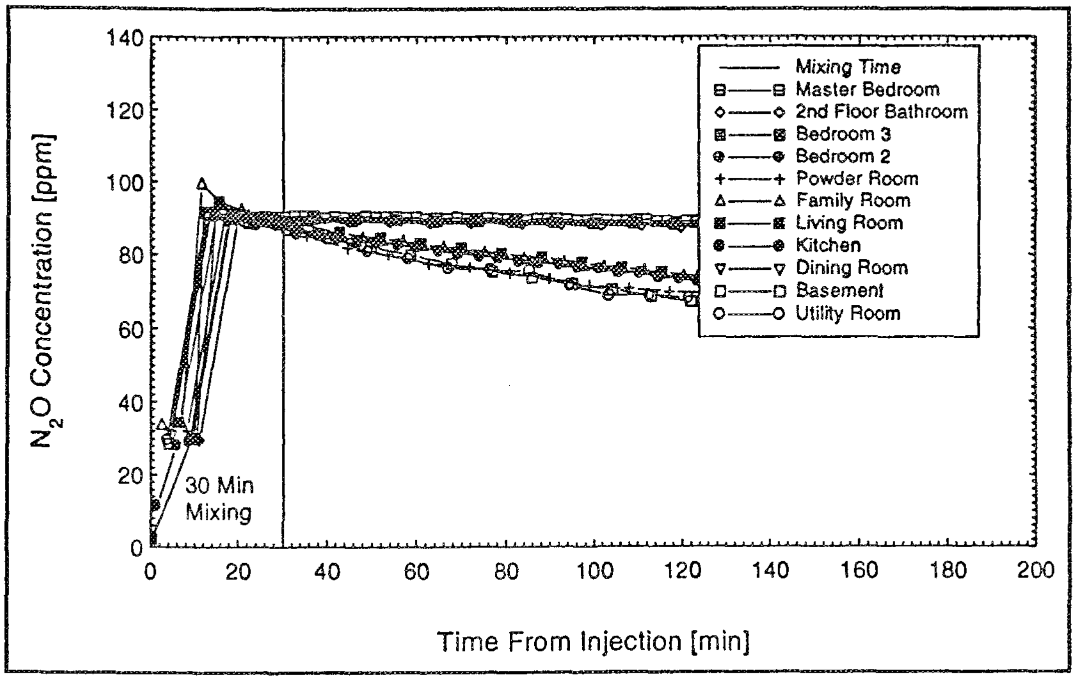

Figure 8 - Single Tracer Gas Measurements for Test 931117F at +8°C

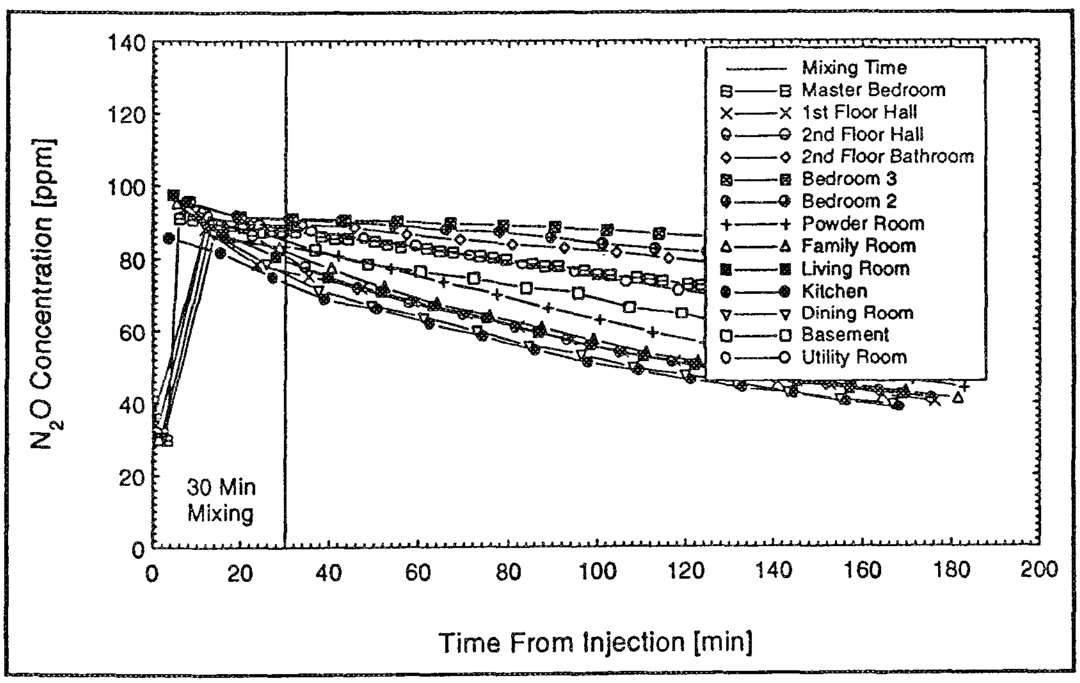

Figure 9 - Single Tracer Gas Measurements for Test 940518F at +12°C

11.2.2 Configuration G - Reference Case With Circulation

The average whole house ventilation rate for Configuration G listed in Table 6 is very similar to that for Configuration F. This is in accord with expectations, since for both configurations, accidental air leakage is the only source of ventilation air, and both groups of tests' conditions included similar temperature ranges (see Table 4 and Appendix B for details). The mechanical recirculation during these tests however, distributed the outdoor air supply more evenly among the zones in the house as indicated by the average ventilation rates reported in Table 6 for each storey. These zonal average ventilation rates are still very much less than required. Figures 10 and 11 report the multi-room single tracer gas decay curves measured for two Configuration G tests at average outdoor temperatures of -19°C (Test 940209G) and +11°C (Test 940510G). These two figures illustrate that the mechanical recirculation caused by continuous furnace fan operation creates a very well mixed condition throughout the house. This results in virtually equal air change rates in each room in the house which translate into different ventilation rates when converted using the volumes of each individual room. These tests indicated the effectiveness of the forced-air heating system at evenly distributing the ventilation air throughout the house, despite the closed doors to the bathrooms and bedrooms and the inadequate total supply of outdoor air to the house. They also indicate that door undercuts sized according to the CSA F326 standard do not hinder the good air circulation of the forced-air system to bedrooms and bathrooms with closed doors. Therefore, the door undercuts should not impede the smaller flow rates of the individual room ventilation requirements.

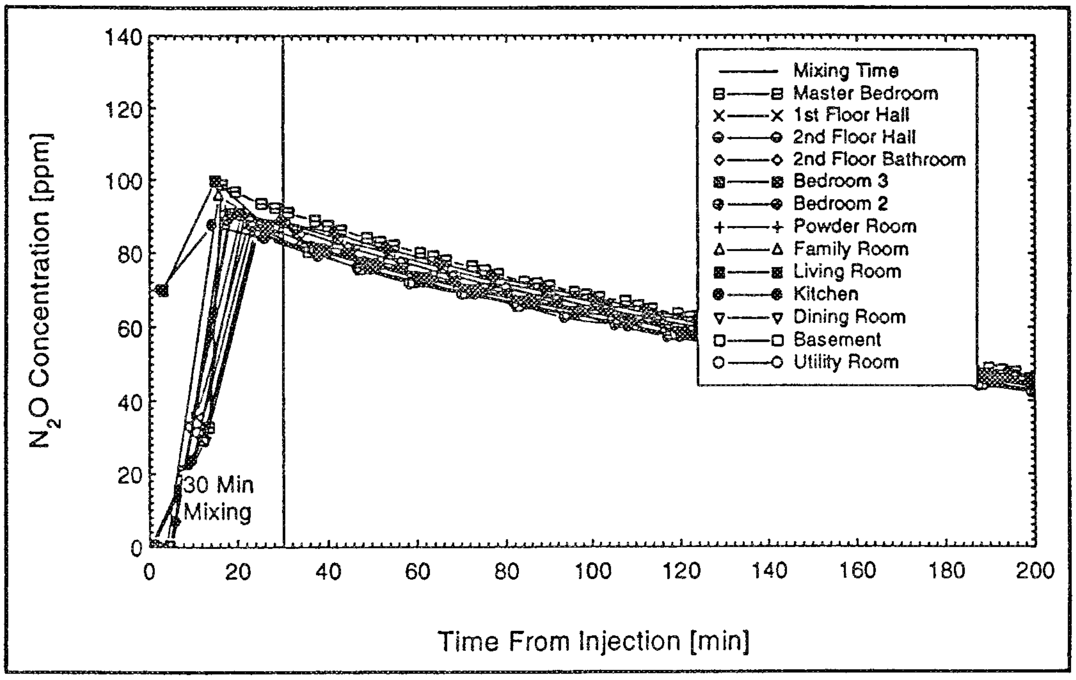

Figure 10 - Single Tracer Gas Measurements for Test 940209G at -19°C

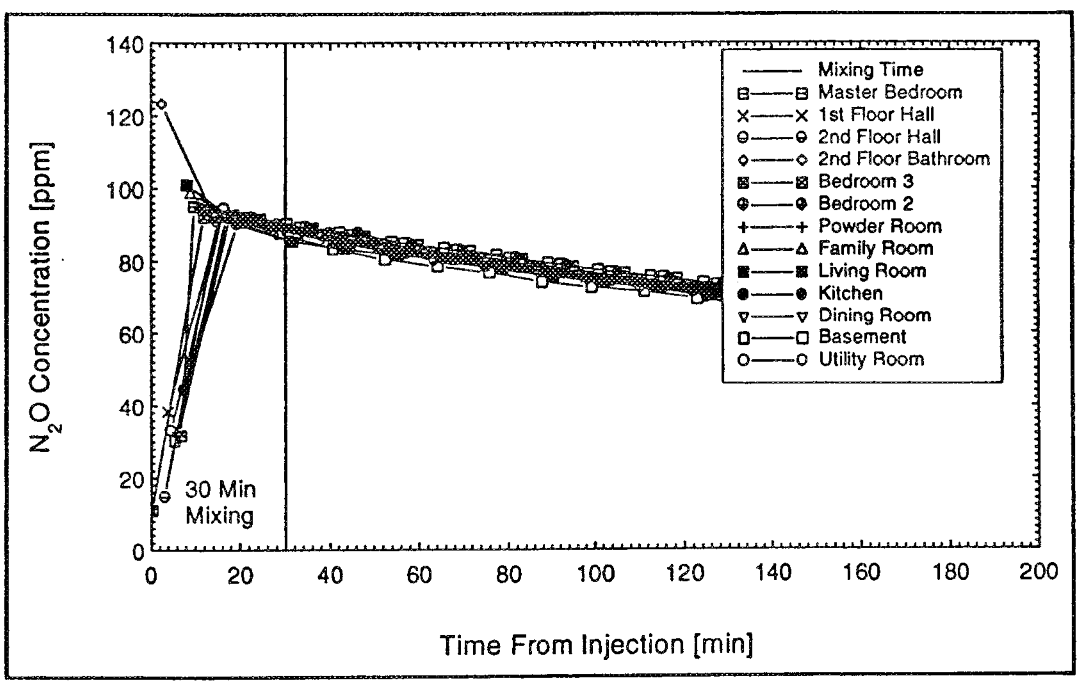

Figure 11 - Single Tracer Gas Measurements for Test 940510G at +11°C

11.2.3 Configuration A - Local Exhaust System.

The tracer gas test results reported in Table 6 indicate that Configuration A, on average, provides about 20 percent less ventilation than the whole house requires, and that this ventilation air is not particularly well distributed. The flow rates through all three exhaust fans were measured continuously throughout each test, and these measurements confirmed that the flow rates were consistently in accord with design specifications. This suggests that the single tracer gas method used here underestimates the actual total fresh air supply rate. The zonal average ventilation rates indicate that Configuration A provides only about 30 percent of the second floor's requirement while almost meeting the first floor's requirement and consistently overventilating the basement by about 35 percent. This preferential supply of fresh air to the lower floors at the expense of the upper floor is most severe for the lowest outdoor temperatures, and becomes least distinct at the warmest test temperatures (cf. Appendix B). This general distribution of the ventilation air supply is consistent with air infiltration, principally dominated by stack effect, substantially influencing both the locations of outdoor air supply to the building interior (through leaks in the lower part of the building envelope) and the internal air flow patterns, from lower floors to upper floors.

The impact of this temperature dependant air distribution behaviour is illustrated by comparing Figures 12 and 13 in which the multi-room single tracer gas decay curves are reported for two Configuration A tests, Test 940210A at -23°C and Test 940425A at +11°C. In Figure 12, at a very cold outdoor temperature, the three bedrooms behave as almost one well-mixed zone, with a very low air change rate (shallow decay curve) compared to the much larger air change rates (steeper decay curves) for the rest of the zones and rooms in the house, including the second floor bath. However, in Figure 13, at much milder conditions, the decay curves of the bedrooms have spread out and steepened slightly while the decay curves for the lower floors' rooms have become shallower and grouped closer to each other and to the decay curves for the bedrooms. At the milder temperatures, the air change rates in all the rooms in the house become closer together in value. At the milder temperatures, the basement and ground floor rooms are not overventilated, but the second storey bedrooms are still significantly underventilated.

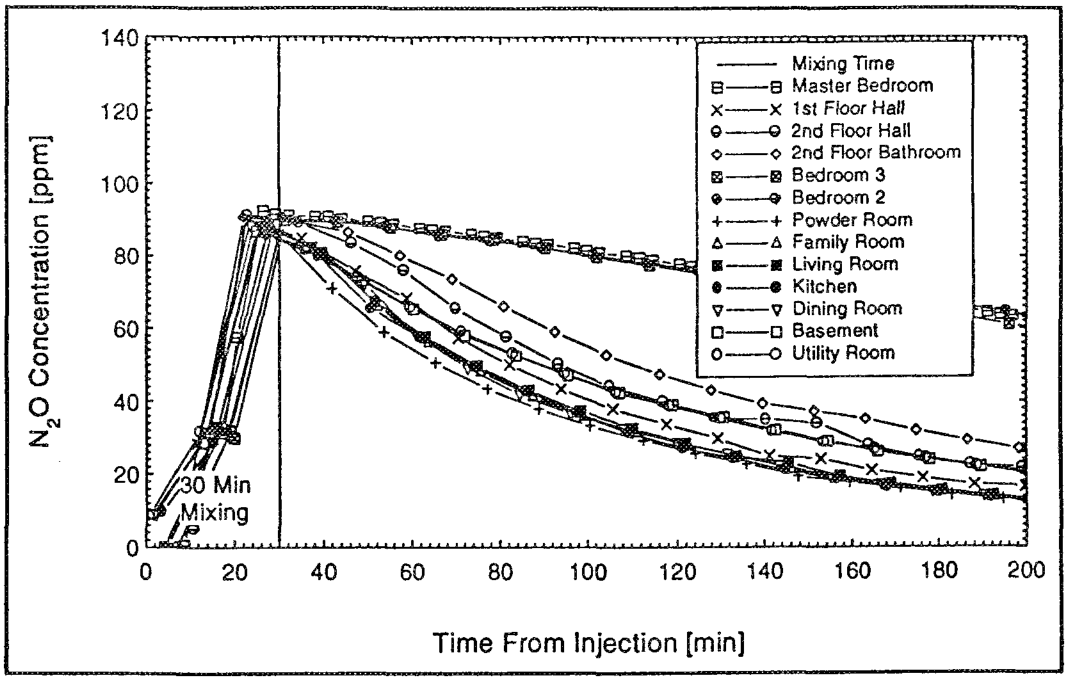

Figure 12 - Single Tracer Gas Measurements for Test 940210A at -23°C

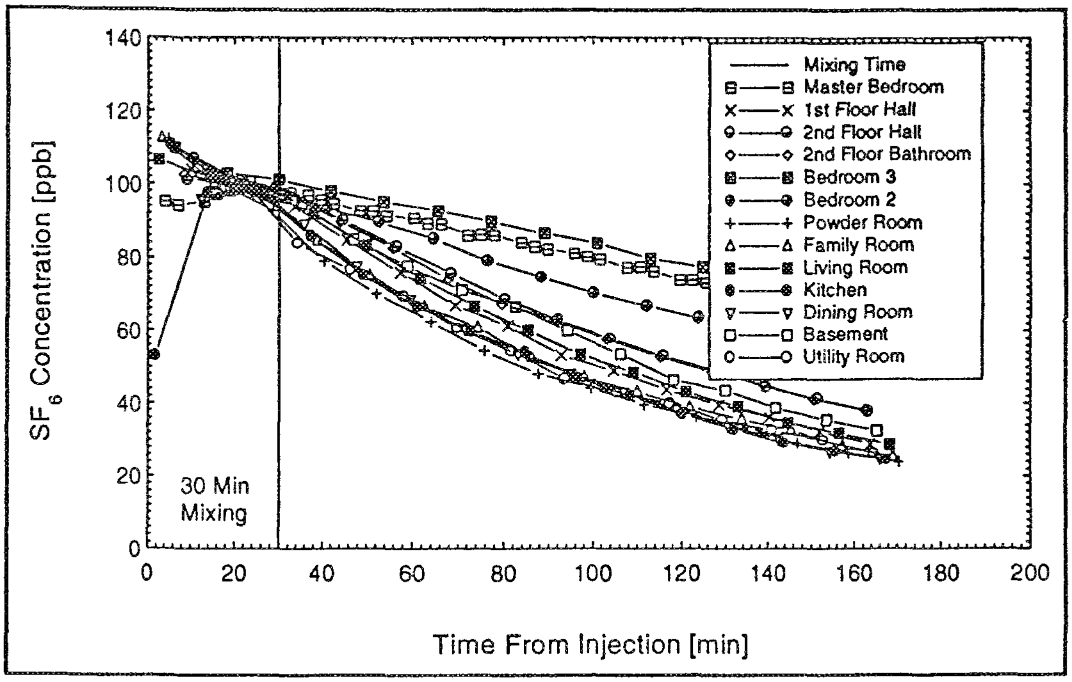

Figure 13 - Single Tracer Gas Measurements for Test 940425A at +11°C

11.2.4 Configuration B - Local Exhaust System with Vents.

The Configuration B tests' results reported in Table 6 indicate that, on average, Configuration B overventilates the house overall by 15 percent, meeting or exceeding the whole house ventilation requirements consistently. This suggests that the provision of deliberate vent openings in this configuration have been effective at increasing the overall ventilation rate. However, that increased ventilation air supply is not well distributed. The floor-by-floor average ventilation rates indicate Configuration B provides only 67 percent of the second floor's total requirement, meets the basement's total requirements, and consistently overventilates the first floor by 65 percent, on average. Results in Table 7 indicate that each of the second floor rooms are underventilated by between 30 and 35 percent. The room-by-room results in Table 8 indicate that most rooms on the ground floor are overventilated by almost 100 percent or more. These observations are consistent with stack effect dominance of the interior air flow patterns, and suggest that the deliberate openings distributed on the first and second floors have "opened the flood gates" for stack effect to increase dramatically the overall air change rate for the house by supplementing the mechanical exhaust with a substantial amount of air infiltration through the ground floor vents and air exfiltration through the bedroom vents. The deliberate openings in each of the bedrooms are apparently not serving as air inlets, but as outlets for air exfiltration.

When compared to the results for Configuration A in Table 6, it is also interesting that, while the whole house, second floor and first floor average ventilation rates all increased for Configuration B's opened vents, the basement's average total ventilation rate decreased to closely match its total standard requirement. This suggests that as deliberate (make-up air) vents are provided, the accidental openings, especially leaks in the basement envelope, become less important to the overall air change rate and internal air flow patterns. These observations are illustrated in Figures 14 and 15, where multi-room single tracer gas decay curves measured for a very cold temperature -24°C (Test 940208B) and a mild temperature +11°C (Test 940418B) are graphed. The air change rates and ventilation rates in the basement rooms decrease the most dramatically for the increase in outdoor temperature, becoming the least of all the zones in Figure 15, even smaller than in all the bedrooms. In fact the ventilation rates in the basement rooms fall below their requirements for the warmest temperatures (cf. Appendix B). In general, as the outdoor air temperature (OAT) increased and stack effect decreased, the first floor's ventilation decreased and the second floor's increased bringing the upper two storeys of the house closer to a well-mixed state.

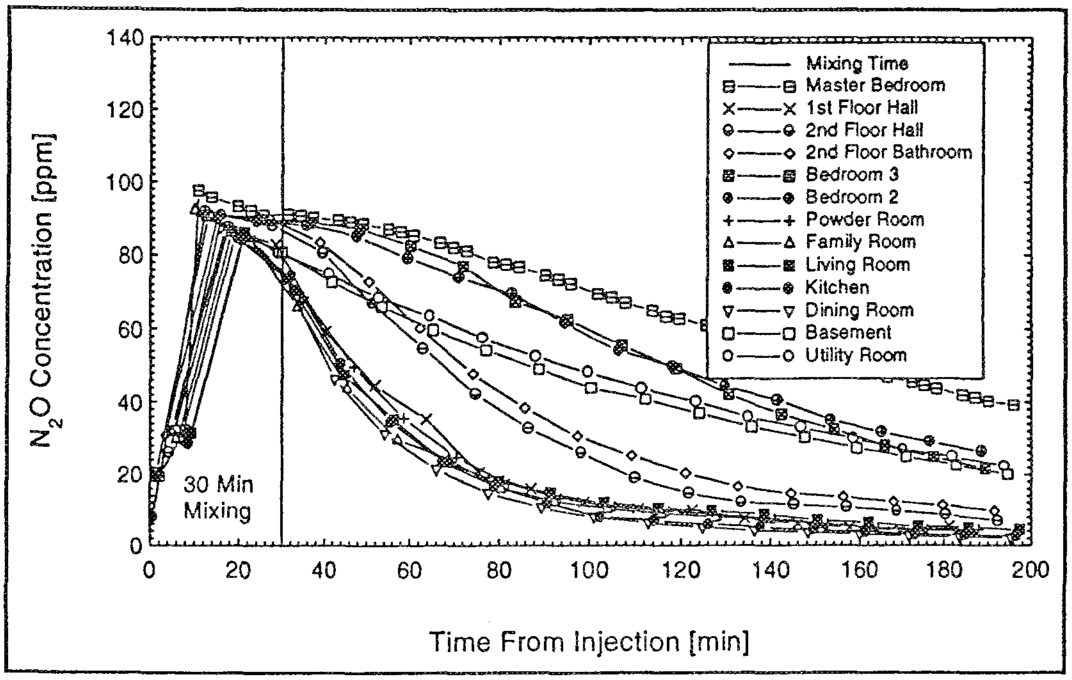

Figure 14 - Single Tracer Gas Measurements for Test 940208B at -24°C

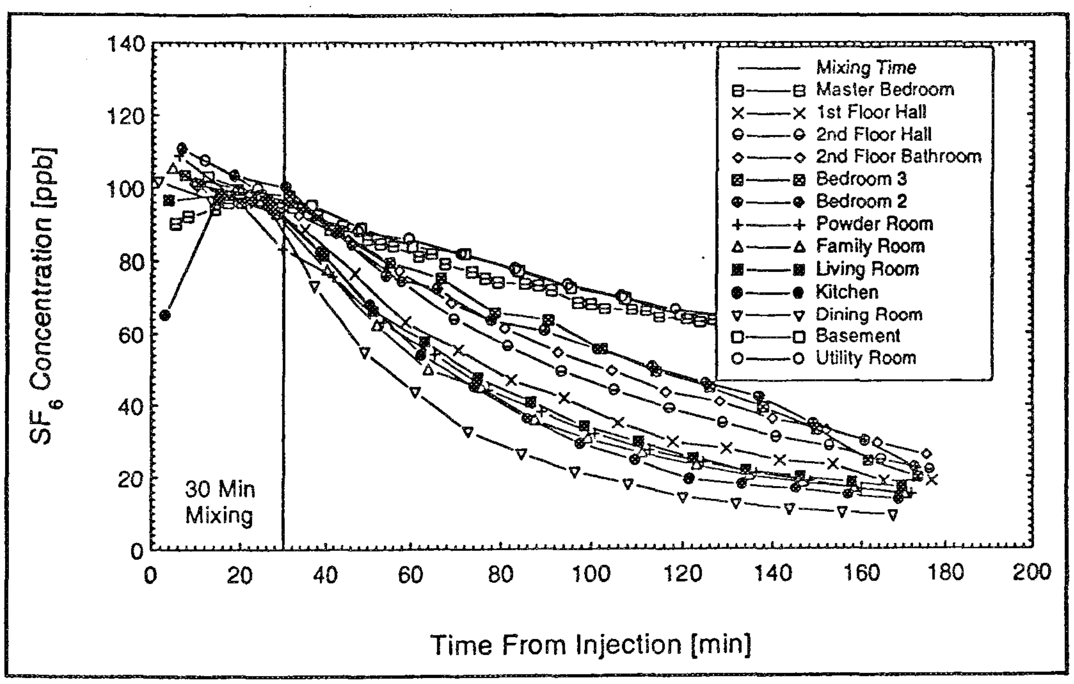

Figure 15 - Single Tracer Gas Measurements for Test 940418B at +11°C

11.2.5 Configuration C - Partially Distributed Exhaust System.

Results in Table 6 indicate that, on average, Configuration C slightly underventilates (by less than 10 percent) the whole house overall. Relying only on accidental leakage for make-up air like Configuration A, Configuration C provides only 53 percent of the second storey's zonal ventilation requirement while meeting the first floor's requirement and overventilating the basement zone by almost 45 percent, on average. Individual room results in Table 7 indicate that the partially distributed exhaust (PDE) system's distributed pick-up (and the extra 5 L/s of total mechanical exhaust rate for the second floor) seems to have been somewhat successful in better distributing the supply of outdoor ventilation air to the second floor rooms–it almost doubled the ventilation rates for all the bedrooms compared to the local exhaust system of Configuration A. The flow rates through each branch of the PDE, i.e. the rates at which air was exhausted mechanically from each bedroom, were continuously measured for each test and the analysis of those measurements verified that 10 L/s was exhausted from the master bedroom and 5 L/s from each of the other two bedrooms consistently. In addition, the flow rates through the kitchen and bathroom fans were continuously measured and found to consistently match design requirements. Therefore, the single tracer gas technique applied here has underestimated the ventilation rate for the whole house by up to 15 percent, on average. The individual results for the bedrooms also indicate that some of the make-up air flowing into them is interior air rather than fresh outdoor air.

The floor-by-floor variations in zonal ventilation rates for Configuration C are also consistent with stack effect significantly influencing the interior air distribution patterns. Figure 16 (Test 940106C at -19°C), when compared to Figure 12 illustrates the impact of the PDE system's distributed pick-up to reduce the concentrations in all of the bedrooms while stack effect dominance still clearly distinguishes the three storeys as separate zones and better ventilates the ground floor than the basement. Figure 17 (Test 940425C at +11°C) illustrates a diminished influence of stack effect for the milder

OAT, thereby reducing the air change rates on the lower floors 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 ventilation air to the bedrooms compared to Configuration A (as illustrated in Figure 13 for the same OAT).

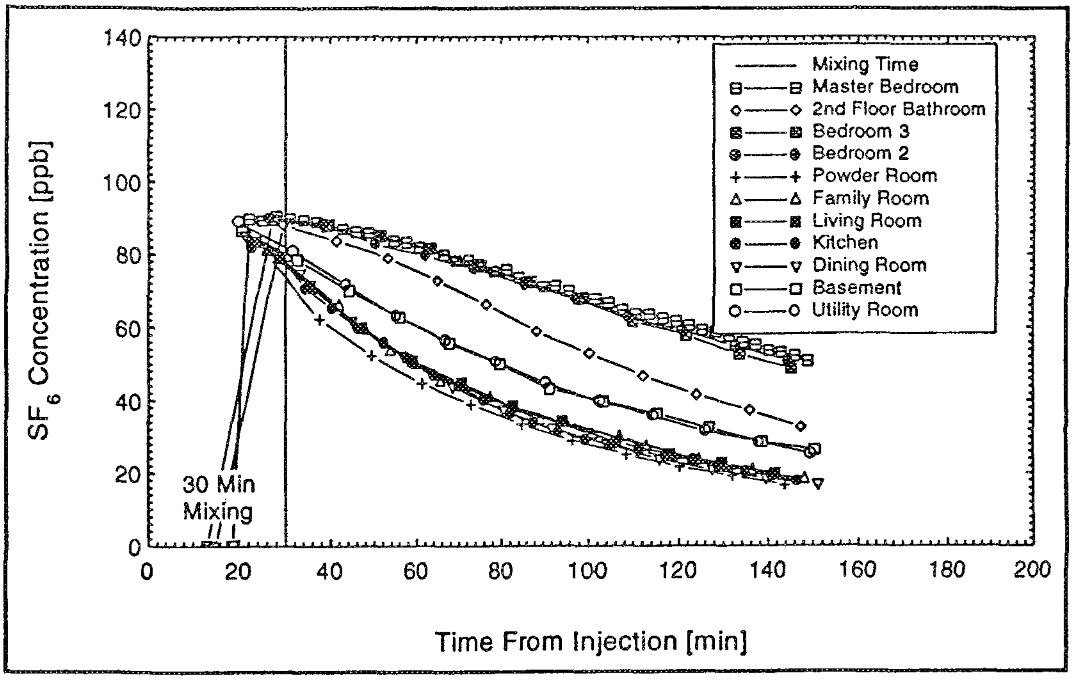

Figure 16 - Single Tracer Gas Measurements for Test 940106C at -19°C

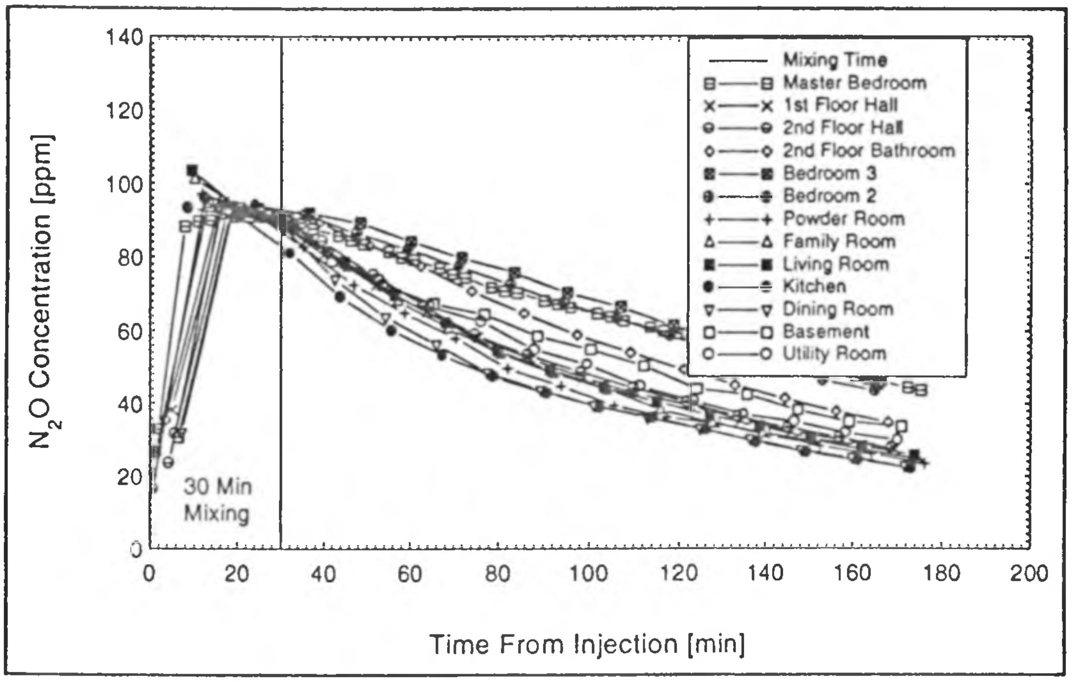

Figure 17 - Single Tracer Gas Measurements for Test 940425C at +11°C

11.2.6 Configuration D - Partially Distributed Exhaust System with Vent

The results listed in Table 6 indicate that Configuration D on average provided 97 percent of the overall ventilation requirement for the whole house. On a floor-by-floor zonal view, this configuration generally met the total ventilation requirements for the basement level, overventilated the first floor by an average of almost 25 percent and provided only 68 percent of the second storey's requirement. All the flow rates in the mechanical ventilation system's components were measured, as described for Configuration C, and those measurements verified that the design flow rates were maintained consistently by the ventilation system. Therefore, the apparent slight shortfall in the whole house's ventilation rate measured using the tracer gas method reflects the shortcoming of the tracer gas technique. The apparent underventilation of the second storey rooms indicates that a portion of the make-up air flowing into those directly exhausted rooms was interior air, not outdoor air. Table 7 indicates that

Configuration D provided better ventilation than Configuration C for each of the bedrooms and the second floor bathroom. Table 8 indicates that Configuration D also provided more ventilation air to each main floor room. These results suggest that the centralized passive air inlet of Configuration D was effective at improving the supply of ventilation air to all rooms in the main living areas of the house.

Concentration profiles from a very cold test of Configuration D (Test 940106D at -23°C) are graphed in Figure 18. It shows that the three storeys definitely behave as three distinct zones, with the ground floor well-mixed and best ventilated, and the second storey least well ventilated, not dissimilar to Figure 16 for cold OAT. Figure 19 shows results for a mild OAT (Test 940419D at +12°C) where the rooms on the first floor behave separately (much less like a cohesive single zone) and the basement becomes the least well ventilated zone in the house. When compared with Configuration C results at a similar mild OAT, second floor rooms are similarly ventilated, while the first floor rooms are better ventilated by Configuration D. However, the basement is much more poorly ventilated by Configuration D than Configuration C, suggesting, as in the comparison between Configurations A and B, that when deliberate air inlet vents are provided, the accidental air leakage into the basement actually decreases and represents a less significant contribution to whole house ventilation air supply especially as OAT increases and stack effect is diminished.

The equivalent leakage areas listed in Table 2 help illustrate another advantage of Configuration D. The extra equivalent leakage area provided by the single vent of Configuration D is almost three times the extra ELA provided by the distributed vents of Configuration B, and Configuration D's total leakage area is double that of Configuration B. In addition, the total mechanical exhaust from the house for Configuration D is 5 L/s more than that for Configuration B. Despite all these factors, Configuration D does not experience the overventilation that Configuration B did. This suggests that the centralized single vent of Configuration D did not leave the house susceptible to stack effect dominance of its air change rate and interior air flow patterns, as did the distributed vents of Configuration B. The location of this single intake vent just above the mid-plane of the building may also have succeeded in placing it near the neutral pressure level of the stack effect pressure distribution, thereby minimizing its role in stack effect-driven infiltration and exfiltration. Better control over the total ventilation air supply and its distribution seems to be provided by using a single centralized inlet vent. The single centralized vent would also make it easier to install a motorized damper to close it when the ventilation system is not in use.

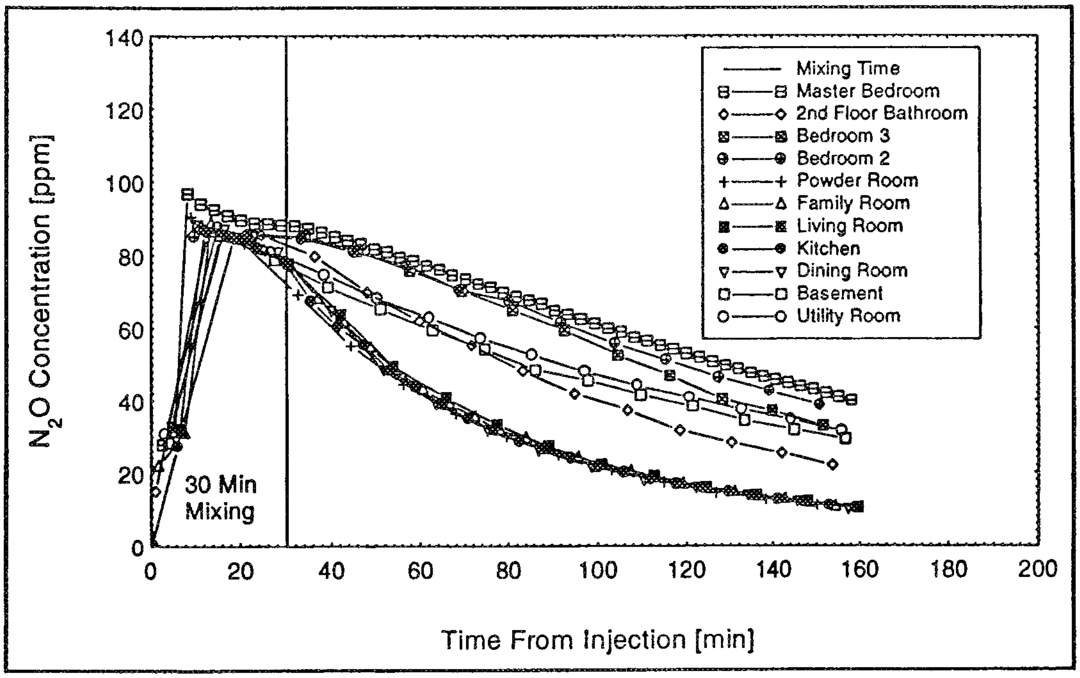

Figure 18 - Single Tracer Gas Measurements for Test 940106D at -23°C

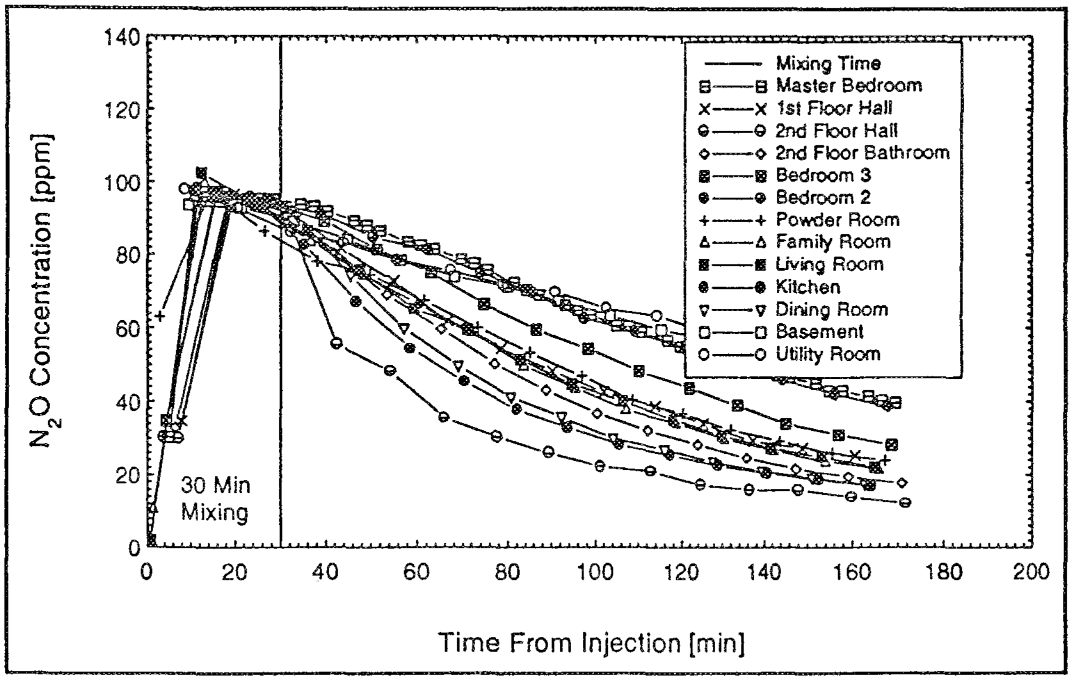

Figure 19 - Single Tracer Gas Measurements for Test 940419D at +12°C

<u>11.2.7 Configuration E - Minimal Ducted Supply System</u>

The results listed in Table 6 indicate that the minimal ducted supply system (MDS) of Configuration E most closely provides the total ventilation requirement for the whole house overall, on average. It is the best configuration at providing the second floor's total zonal ventilation requirement (85 percent on average). The basement is overventilated by an average of 55 percent and the main floor receives only 83 percent of its zonal requirement. Table 7 confirms that Configuration E is the best at meeting the room-by-room ventilation requirements for the closed bedrooms (albeit with an apparent slight deficit), and Table 8 indicates that Configuration E most precisely meets, on average, the room-by-room requirements on the first floor as well.

It is interesting that this configuration does not appear to do the best job at meeting the ventilation requirements for the two bathrooms. This measurement calculation result is primarily due to the small room volume, particularly for the powder room, since Figures 20 and 21, in which Configuration E single tracer gas test measurements for cold (Test 940110E at -14°C) and mild (Test 940511E at +12°C) conditions are graphed, indicate that the powder room consistently displayed the largest air change rates of any room in the house. These two figures also indicate the whole house, with the exception of the powder room, is generally well-mixed by Configuration E, to a lesser extent than by Configuration G however, and that the results are not significantly influenced by the outside air temperature. This may in part be due 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 passive air vent openings for this configuration. The powder room results probably illustrate a design shortcoming in deliberately providing supply air to small rooms which are also principal exhaust sites. This situation probably leads to ventilation air short-circuiting in these small rooms, and the strong flows into and out of duct ends rendering invalid the well-mixed room assumption on which the tracer gas measurement technique is based. The supply air flow rates in each delivery branch of this ducted supply system and the flow rates through each exhaust fan were monitored continuously during each test, and review of those measured flow rates confirmed that the design flowrates were in fact consistently provided throughout each MDS test. Therefore, apparent shortfalls in supplied ventilation rates as determined from the single tracer gas tests of Configuration E probably indicate a shortcoming in this measurement approach. (In tests where the air change rates, and hence apparent ventilation rates, were measured in the hallway spaces, the overall house and floor-by-floor ventilation shortfalls were mostly accounted for in these spaces.)

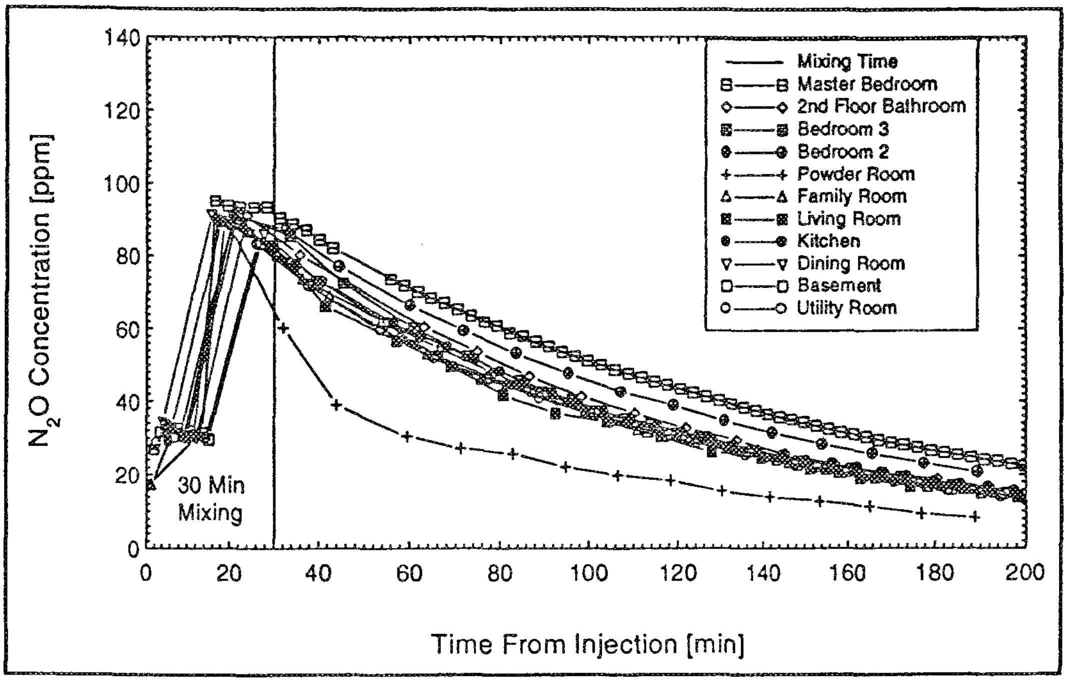

Figure 20 - Single Tracer Gas Measurements for Test 940110E at -14°C

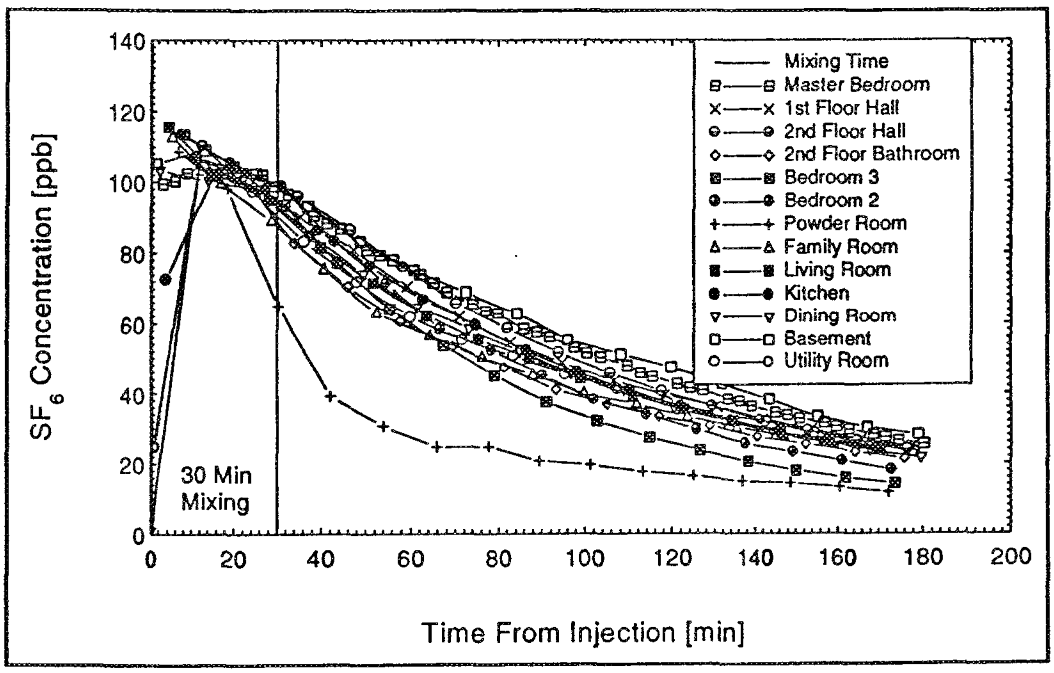

Figure 21 - Single Tracer Gas Measurements for Test 940511E at +12°C

11.3 SUMMARY DISCUSSION

Taken together, the results of the single tracer gas tests indicate that the minimal ducted supply system (Configuration E) is most consistent at meeting the CSA F326 standard's ventilation requirements for the whole house, floor-by-floor and room-by-room. Next best are the partially distributed exhaust and the local exhaust systems which include deliberate make-up air inlet openings (Configurations D and B), although they both seem to overventilate the lower rooms and underventilate the bedrooms (by up to 30 percent). Configuration B also seems to overventilate the house as a whole by up to 15 percent on average and seems to be dominated by stack effect, seriously overventilating the 1st floor. The partially distributed exhaust system without deliberate make-up air provisions (Configuration C) does show its effectiveness at helping distribute evenly the ventilation air to the bedrooms, despite its more than 40 percent ventilation deficit for the second storey as a zone. The local exhaust strategy without make-up air inlets (Configuration A) does not seem to provide adequate ventilation to the second storey. The passive inlet vents of Configurations B and D do seem to be effective at supplying the make-up air for the mechanical exhaust, as indicated by reduced basement leakage for those configurations. The door undercuts, sized according to the CSA F326 standard, seem to be adequate to allow air circulation to the closed bedrooms and bathrooms driven by the forced-air heating system. The deliberate supply of ventilation air to rooms which are directly exhausted, especially small rooms like a powder room or bathroom, seems to be ineffective which may be due to short-circuiting of the supply air directly into the exhaust flow without adequately mixing with room air and diluting airborne pollutants.

12. DISCUSSION OF THE MULTIPLE TRACER GAS TESTS' RESULTS

There are a total of 13 distinct zones in the house. Theoretically, 13 separate tracer gases (and the capability to measure the concentration of each gas) would be required to resolve the complete set of interzonal flow rates among these zones and the outdoors. Such resources were not available for this project, and even if they were, their successful practical application would be anything but certain [12,13]. The main objective of the two tracer gas approach was to identify qualitatively the air flow patterns between the closed master bedroom and the rest of the house. The master bedroom was selected as the focus of these multiple tracer gas tests for two reasons. First, it is one of the second storey rooms with a closed door, which discussions earlier in this report have indicated present the greatest challenge to effective distribution of fresh ventilation air. Second, its standard ventilation air supply requirement is double that of the other bedrooms, and so presents a more rigorous air distribution challenge. For these reasons, the master bedroom was used to provide the best basis for distinguishing between the ventilation performance of the various tested configurations.

12.1 INTERZONAL FLOWRATES FOR CONFIGURATION G

The Configuration G tests, where the continuous operation of the furnace fan caused the rest of the house to be well mixed, did present a two-zone situation which might lend itself to a quantitative calculation of the flow rates between the master bedroom, the rest of the house (treated as a single zone) and the outdoors. An example of the tracer gas concentration measurements for such a multiple tracer gas test (Test M940125G at -18°C) is shown in Figures 22 and 23, multizone graphs of the target and source zone behaviours respectively. The interzonal flowrate solution method for a two-zone system [12] was used to calculate the six flow rates as functions of time. The concentrations measured in the Family Room zone were used to represent the Rest-of-House zone. These solutions are plotted in Figure 24, where:

F10 - flowrate from MBR to Outdoors
F01 - flowrate from Outdoors to MBR
F20 - flowrate from Rest-of-House to Outdoors
F02 - flowrate from Outdoors to Rest-of-House
F12 - flowrate from MBR to Rest-of-House
F21 - flowrate from Rest-of-House to MBR.

Unfortunately, two singularities occurred in the solutions to the interzonal flowrate equation set for these results and no obvious converged correct solution set emerged. This was common to the attempts to solve the interzonal flowrate equations for all the other multiple tracer gas tests of Configuration G. These attempts were regarded as unsuccessful.

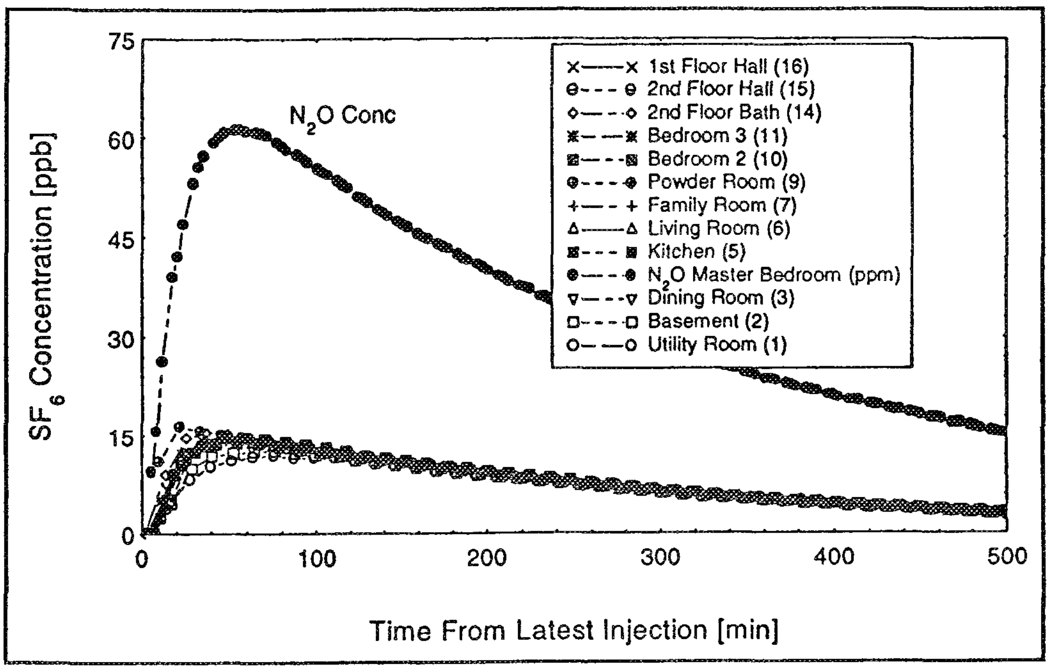

Figure 22 - Target Zone Tracer Gas Measurements for Test M940125G at -18°C

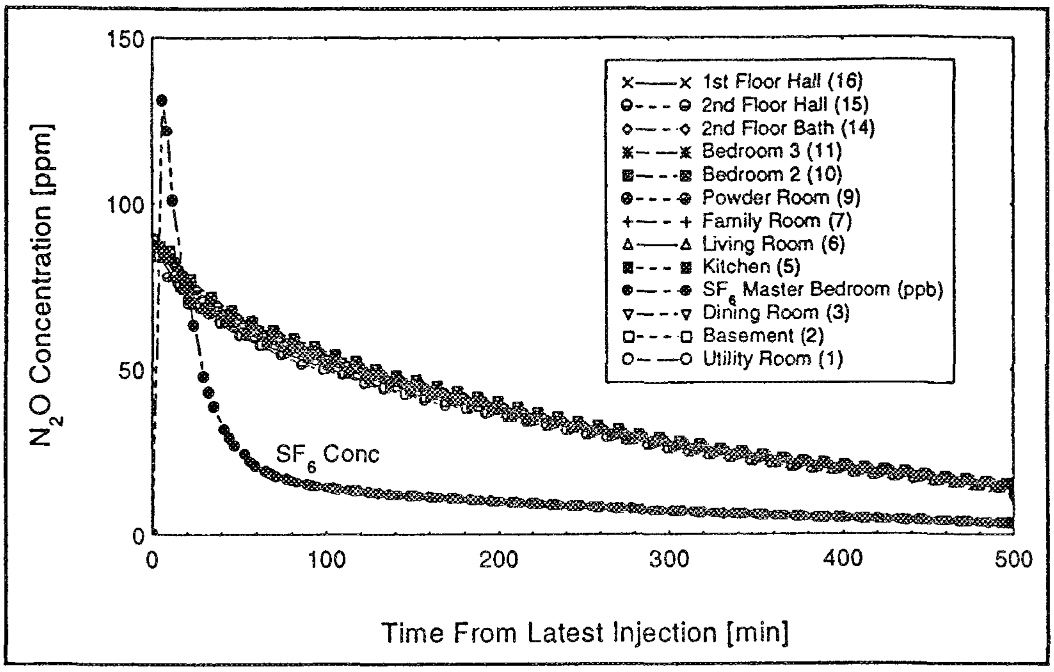

Figure 23 - Source Zone Tracer Gas Measurements for Test M940125G at -18°C

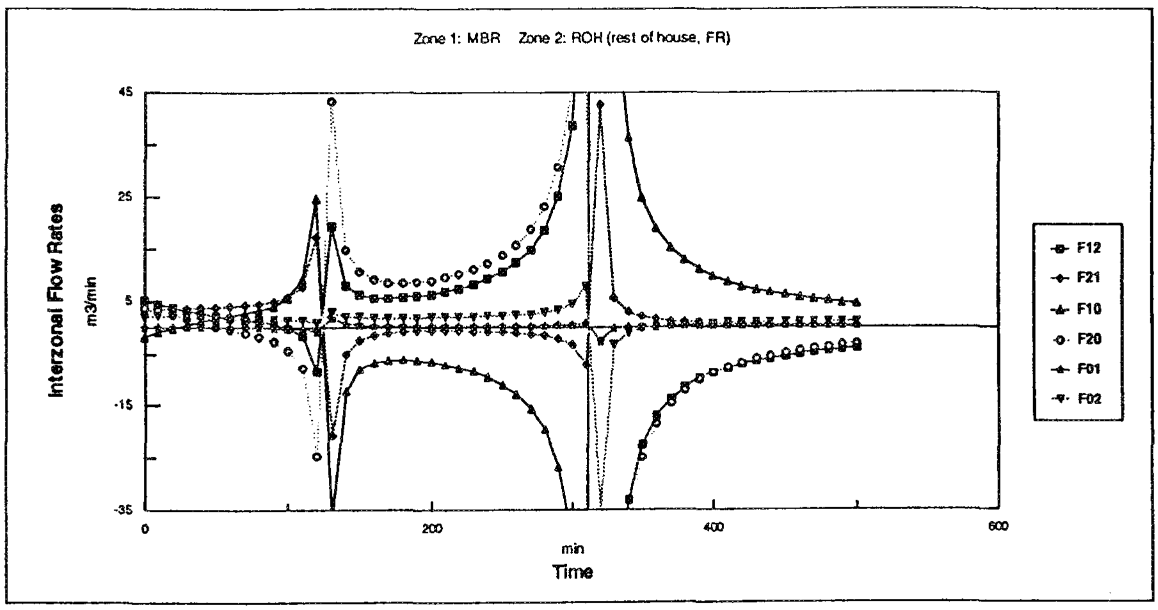

Figure 24 - Interzonal Flowrates Calculated for Test M940125G at -18°C
Treated as Two Zones: MBR and Rest-of-House (FR)

12.2 AIR CHANGE RATES IN THE MASTER BEDROOM

The multiple tracer gas tests do provide one quantitative analysis opportunity. As mentioned in an earlier section, the single tracer gas approach to measure air change rates in multiple zones suffers the disadvantage that its underlying assumption of constant flow conditions within zones which receive a substantial inflow from adjacent zones may be invalid. In the single tracer gas tests, the concentration of the tracer gas was mixed to a uniform concentration throughout the entire house for the start of the actual ventilation system test period. Therefore, before the interior flows from lower rooms into upper rooms can dilute the tracer gas concentrations in those upper rooms, the concentration in the lower rooms must first be diluted by the outdoor air flowing directly into the lower rooms. In the multiple tracer gas tests, SF_6 gas was dosed only into the master bedroom, so its decay there should be relatively uncorrupted by changing concentrations in the flows from lower rooms into the master bedroom. Therefore, the decay of SF_6 in the MBR and the apparent 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 very little or no SF_6 content and outdoor air via direct air leakage, deliberate inlet venting or mechanical supply.

The results of fitting a single exponential curve to the decay of SF_6 in the master bedroom for all the multiple tracer gas tests are listed in the Source Zone section of Table 9. Also listed there are the converted supply flow rates to the master bedroom calculated by multiplying its air change rates by its internal volume. The air change rates are quite uniform for each ventilation system configuration and the average values for each configuration are also included in the table. Configuration B results exhibited the greatest relative scatter in the ventilation rates of the master bedroom, possibly reflecting the most susceptibility to stack effect and wind due to the additional deliberate leakage which is vertically well distributed. Both the partially distributed exhaust system and the minimal ducted supply system (Configurations C, D and E) provided average ventilation rates in the master bedroom of approximately 12 L/s. The local exhaust strategy without deliberate vent openings (Configuration A) provided an average 4.6 L/s ventilation in the master bedroom, little more than the average 4 L/s ventilation provided by the totally natural air infiltration patterns of Configuration F, although the ventilation rates for the mechanical ventilation were more consistent. The local exhaust with deliberate vents strategy (Configuration B) provided a variable ventilation rate which averaged 8 L/s. Of course, the large recirculation flow rates of Configuration G, with the furnace fan operating continuously, provided the largest ventilation rate, on average 34 L/s. The relatively uniform concentrations observed in Configuration G results is consistent with the argument that the bedroom door undercuts were sufficiently large to not pose a barrier to interior air distribution for a forced-air heating system.

Table 9
SUMMARY OF MULTIPLE TRACER GAS TESTS' RESULTS

		Source Zone				Target Zones***																				
		MBR - SF6*				MBR - N2O**			BR2 - SF6			2B			BR3			KT(/DR)			PR			LR/FR		
Test ID	O.A.T.	Co	I	I	Qin	Tpeak	Cmax	Cmax/Co	Tpeak	Cmax	Cmax/Co	Tpeak	Cmax	Cmax/Co	Tpeak	Cmax	Cmax/Co	Tpeak	Cmax	Cmax/Co	Tpeak	Cmax	Cmax/Co	Tpeak	Cmax	Cmax/Co
	[C]	[ppb]	[ac/min]	[ach]	[L/s]	[min]	[ppm]	[%]	[min]	[ppb]	[%]	[min]	[ppb]	[%]	[min]	[ppb]	[%]	[min]	[ppb]	[%]	[min]	[ppb]	[%]	[min]	[ppb]	[%]
M940126A	-26	132.8	0.003674	0.2204	4.43	128	19.3	22.7	280	11.7	8.8	75	9.5	7.2	390	2.4	1.8	175	1.2	0.9	180	1.1	0.8	180	1.2	0.9
M940223A	-13	84.89	0.003809	0.2285	4.60	158	17.7	19.7	220	6.5	7.7	50	7.4	8.7	245	2.9	3.4	70	1.4	1.6	38	1.25	1.5	85	1.25	1.5
M940301A	-8	144.8	0.003400	0.2040	4.10	168	18.2	20.2	290	11.4	7.9	75	11.8	8.1	415	3.15	2.2	100	2.3	1.6	165	1.55	1.1	160	1.5	1.0
M931213A	0	141.2	0.004019	0.2411	4.85	160	14.7	17.3	224	10.5	7.4	82	10	7.1	316	3.5	2.5	136	3.8	2.7	130	2.6	1.8	180	2.1	1.5
Averages					4.5	154	17.5	20.0	254	10.0	7.9	71	9.7	7.8	342	3.0	2.5	120	2.2	1.7	128	1.6	1.3	151	1.5	1.2
M940127B	-26	127.9	0.010020	0.6012	12.09	47	34.8	36.6	80	3.7	2.9	38	2.2	1.7	90	0.78	0.6		0			0			0	
M940302B	-15	134.8	0.006416	0.3850	7.74	70	30.7	34.1	210	5.4	4.0	200	4.1	3.0	235	2.4	1.8		0			0			0	
M931208B	3	173.7	0.004525	0.2715	5.46	123	28.3	29.5	190	17	9.8															
M940504B	16	157	0.005717	0.3430	6.90	155	17.7	19.0	155	7.9	5.0	110	17.7	11.3	120	2.15	1.4	255	1.3	0.8	260	1.06	0.7	230	1.17	0.7
Averages					8.0	99	27.9	29.8	159	8.5	5.4	116	8.0	5.3	148	1.8	1.3	255	0.4	0.8	260	0.4	0.7	230	0.4	0.7
M940119C	-24	148.9	0.010330	0.6198	12.46	80	32.3	38.0	90	4.5	3.0	65	4	2.7	130	0.8	0.5	60	0.52	0.3	80	0.425	0.3	90	0.42	0.3
M940131C	-19	126.1	0.009986	0.5992	12.05	85	32.8	38.6	95	4.2	3.3	60	3.65	2.9	120	0.75	0.6		0			0			0	
M940303C	-4	145.3	0.009935	0.5961	11.99	105	34.0	35.8	105	4.2	2.9	70	3.3	2.3	135	0.83	0.6	75	0.5	0.3		0			0	
M940221C	2	133.7	0.009795	0.5877	11.82	90	29.0	30.2	95	4.1	3.1	65	3.7	2.8	130	0.91	0.7	0	0.5	0.4	30	0.45	0.3	20	0.46	0.3
M940420C	5	157.1	0.010090	0.6054	12.17	98	30.5	32.1	115	4.5	2.9	85	3.8	2.4	130	1.05	0.7	40	0.54	0.3		0			0	
Averages					12.1	92	31.7	34.9	100	4.3	3.0	69	3.7	2.6	129	0.9	0.6	44	0.4	0.4	55	0.2	0.3	55	0.2	0.3
M940201D	-19	138.2	0.011270	0.6762	13.60	65	30.8	34.2	78	3.95	2.9	70	3.5	2.5	125	0.61	0.4		0			0			0	
M940308D	1	158.5	0.010310	0.6186	12.44	80	27.8	30.9	90	4.5	2.8	60	3.55	2.2	140	0.66	0.4	100	0.53	0.3	90	0.44	0.3	75	0.47	0.3
M931214D	6	157.5	0.010220	0.6132	12.33	65	24.6	28.0	80	4.5	2.9	70	3.55	2.3	130	0.78	0.5	95	0.58	0.4	100	0.57	0.4	120	0.48	0.3
M940505D	17	160.2	0.009817	0.5890	11.84	65	23.0	23.7	105	5	3.1	60	3.9	2.4	105	0.73	0.5	65	0.57	0.4		0		75	0.41	0.3
Averages					12.6	69	26.6	29.2	88	4.5	2.9	65	3.6	2.4	125	0.7	0.5	87	0.4	0.4	95	0.3	0.3	90	0.3	0.3
M940203E	-9	145.9	0.009405	0.5643	11.35	46	12.8	13.5	105	5.1	3.5	60	15.5	10.6	170	1.07	0.7	65	5.4	3.7	90	1.7	1.2	90	1.95	1.3
M940228E	-9	144.3	0.009410	0.5646	11.35	30	12.1	13.4	100	4.95	3.4	70	13	9.0	150	0.97	0.7	95	3.85	2.7	100	1.6	1.1	90	2.6	1.8
M940322E	7	130.1	0.009514	0.5708	11.48	50	11.4	12.3	120	4.45	3.4	60	11.1	8.5	150	0.97	0.7	100	6	4.6	100	2.28	1.8	90	5.3	4.1
M931215E	9	137.5	0.011030	0.6618	13.31	47	10.4	11.6	100	4.5	3.3	50	18	13.1	115	8.8	6.4	95	6	4.4	100	2.45	1.8	95	2.95	2.1
Averages					11.9	43	11.7	12.7	106	4.8	3.4	60	14.4	10.3	146	3.0	2.1	89	5.3	3.8	98	2 0	1.5	91	3.2	2.3
M940207F	-16	127.9	0.004100	0.2460	4.95	215	41.9	43.6	235	9.7	7.6	180	10.02	7.8	375	2.47	1.9	210	1.72	1.3	330	1.21	0.9	245	1.44	1.1
M940120F	-15	133.4	0.004254	0.2552	5.13	200	41.0	45.6	260	10.3	7.7	250	12.3	9.2	510	3.2	2.4	150	1.7	1.3	120	0.53	0.4	210	1.3	1.0
M940324F	3	143.6	0.002756	0.1654	3.33	320	39.2	40.8	315	13.85	9.7	270	16.2	11.3	575	5.7	4.0	320	2.88	2.0	295	2.88	1.9	330	2.97	2.1
M940503F	11	120.4	0.002248	0.1349	2.71	360	45.0	50.0	375	19	15.8	325	15.5	12.9	825	6.7	5.6	485	7	5.8	450	5.1	4.2	360	6.6	5.6
Averages					4.0	274	41.8	45.0	296	13.2	10.2	256	13.5	10.3	571	4.5	3.5	291	3.3	2.6	299	2.4	1.9	286	3.1	2.4
M940125G	-18	85.93	0.016540	0.9924	19.96	55	61.2	68.0	60	14.7	17.1	35	15.5	18.0	45	14.8	17.2	55	13.8	16.1	25	16.4	19.1	55	14.2	16.5
M931209G	0	156.9	0.029400	1.7640	35.47	68	64.0	72.7	65	15.25	9.7	70	15.3	9.8	65	15.25	9.7	61	15.2	9.7	52	15.5	9.9	73	14.8	9.4
M940428G	0	156.7	0.033330	1.9998	40.21	50	57.0	63.3	52	14.85	9.5	43	15.9	10.1	52	15.2	9.7	48	13.4	8.6	17	16.7	10.7	50	14.2	9.1
M940502G	8	144.8	0.030040	1.8024	36.24	65	62.8	68.3	65	15.1	10.4	43	15.5	10.7	50	15	10.4	59	14.5	10.0	38	16.2	11.2	61	14.7	10.2
M940512G	8	150.6	0.032150	1.9290	38.79	58	52.5	65.6	57	15.8	10.5	37	16.2	10.8	46	15.75	10.5	53.5	14.75	9.8	22	17.4	11.6	54	15	10.0
Averages					34.1	59	59.5	67.6	60	15.1	11.4	46	15.7	11.9	52	15.2	11.5	55	14.3	10.8	31	16.4	12.5	59	14.6	11.0

* SF6 decay in MBR - single exponential curve fit: C=Co exp(-I t)

** Timing and relative height of N2O peak in MBR (target zone behaviour)

*** Timing and relative heights of SF6 peaks in target zones.

These observations support those from the single tracer gas tests' results. The partially distributed exhaust system and the minimal ducted supply system seem to mechanically ensure that at least 10 L/s of ventilation air is supplied to the closed master bedroom. The local exhaust fan strategy without deliberate inlet vents does not seem capable of providing 10 L/s of supply air flow rate to the closed master bedroom and seems little better than accidental leakage in that regard. The local exhaust fan strategy with deliberate inlet vents still does not provide as much as 10 L/s of ventilation air on average to the closed master bedroom.

12.3 QUALITATIVE INTERPRETATION OF INTERIOR AIR FLOW PATTERNS

Also listed in Table 9, in its Target Zone section, are the times, and magnitudes of the concentration peaks in the target zones for each of the multiple tracer gas tests. Where table entries are missing or incomplete, the measured concentration profiles either did not exhibit the general shape of target zone behaviour or no detectable concentrations of SF_6 gas occurred in those rooms.

In general, the presence of SF_6 detected in areas other than the MBR indicates that there was air flow from the MBR into those areas. The presence of N_2O detected in the MBR indicates that there were air flows from other areas in the house into the MBR. The peak or maximum concentration of the other gas detected in a zone where it was not dosed, i.e., in target areas, would be related in some way to the flow rate from its source zone into that target zone.

As expected, the reference case of Configuration G, with the furnace fan running continuously, displayed the earliest and largest peaks in almost all the target zones, since it moves the largest amount of air within the house. Another expected result was that the other reference case, Configuration F, displayed the latest peaks which were also the second largest in all zones except the kitchen, where the SF_6 peak for

Configuration E was on average larger than the peak for Configuration F. With the smallest air change rate for the whole house, Configuration F presents the most time available for the two tracer gases to mix throughout all rooms in the house. Configuration E would have had the effect of supplying ventilation air directly to the MBR, possibly displacing the SF_6 into the hallway where some of it could be captured by air flowing to the kitchen for exhaust through the kitchen fan. Another possible explanation for the observed peak in the kitchen being larger for Configuration E than Configuration F is that the supply to the MBR could have created a modest pressurization there, and the exhaust fan in the kitchen should have caused a modest depressurization there creating a net pressure difference that could have driven air flow from the MBR through accidental internal flowpaths into the vertically adjacent kitchen.

The direct exhaust from the master bedroom by the partially distributed exhaust system (Configurations C and D) resulted in the smallest peaks of SF_6 in all the other zones. Those peaks were barely detectable except in the upper storey zones BR2 and 2B which are both adjacent to the MBR. That direct exhaust from the MBR also resulted in the N_2O peaks in the MBR being earlier and on average larger than those for the local exhaust system (Configurations A and B). The smaller N_2O peaks in the MBR for Configuration D than for Configuration C suggest that the central passive inlet vent was effectively providing a supply of outdoor air, and that some of that outdoor air was drawn into the MBR. These observations indicate that the direct mechanical exhaust from the MBR was quite effective at containing the SF_6 in the master bedroom by actually encouraging the flow of interior air into that zone, and that the central passive inlet vent was effective.

The direct supply to the master bedroom by the minimal ducted supply system (Configuration E) resulted in the smallest and earliest N_2O peaks in the master bedroom indicating that interior flows into the MBR were discouraged. It also resulted in SF_6 peaks in other zones (except in the other bedrooms on the second storey) being on average larger than for any of the exhaust-only system configurations. These observations indicate that the direct supply to the MBR was effective at preventing or minimizing the transport of air contaminants into the MBR by interior airflows from other regions of the house. The same action of Configuration E in the other bedrooms would explain why their SF_6 peak concentrations were not increased like other zones (the exception noted earlier).

The local exhaust strategy of Configurations A and B neither directly supplied nor exhausted air to or from the MBR. Consequently, the interior airflow patterns of these configurations to and from the MBR are less directly linked to the mechanical ventilation and may be more directly affected by the air flow patterns driven by air leakage which would, in effect, be exhausting air directly from the MBR to outside. This is indicated by the generally later and larger target gas peaks in all the rooms for these configurations (similar in trend to observations for Configuration F which is only air leakage). In the second storey rooms the target gas peaks are earlier and smaller for Configuration B than for Configuration A, probably due to the generally larger natural ventilation rates and overall air change rates for Configuration B. However, the target gas peaks are later and either smaller or undetectable in the ground floor rooms for Configuration B than for Configuration A. This is probably due to the larger overall air change rates and larger upward air flow rates caused by the dominance of stack effect on interior flow patterns with Configuration B's well distributed deliberate envelope leakage (passive inlet vents). Less tracer gas migrates downstairs for Configuration B than for Configuration A due to the stronger upward movement of air within the house for Configuration B, both less than for Configuration E, but more and later than for Configurations C and D.

In summary, the multiple tracer gas results provide the following qualitative information about the interior airflow patterns. Continuous operation of the furnace fan can create well-mixed conditions in the house, even with bedroom doors closed with undercuts sized according to the CSA F326 standard. In the absence of any mechanical ventilation, interior air flow patterns due to natural air leakage allow contaminants the time to spread throughout the house. The partially distributed exhaust system is effective at drawing into the closed master bedroom its ventilation airflow requirement, and the central passive inlet vent was effective at helping provide outdoor air to the master bedroom. The minimal ducted supply system is effective at meeting the ventilation requirements of the closed master bedroom and discourages interior air movement into it from other zones. Ventilation by local kitchen and bathroom fans was not effective at meeting the master bedroom's ventilation requirements, either with or without deliberate passive inlet vents. The passive vents helped but seemed to be inadequate, because their principal effect seemed to be to increase the natural air leakage flow patterns, including strong airflows upward inside the house and out through the upper storey rooms to outdoors, so the increase in total ventilation in the master bedroom due to the opened vents would be interior air, not fresh outdoor air.

13. CONCLUSIONS

The principal objective of this research was to identify which of the tested simplified ventilation systems showed promise for meeting the ventilation rate and air distribution requirements of the CAN/CSA-F326-M91 standard. The results from the analysis of the measured data can be summarized in the following conclusions.

1. The exhaust-only ventilation strategy that uses only typical exhaust fans and relies upon accidental leakage for its make-up air supply (Configuration A) does not provide adequate ventilation in the house. This approach provided neither sufficient air exchange in the house overall, nor adequate distribution of that ventilation air to critical areas such as closed bedrooms.
2. The exhaust-only ventilation strategy that uses typical exhaust fans together with deliberate passive inlet vents (Configuration B) distributed in the first and second storeys (which for the second storey can be described as a single central exhaust with distributed passive make-up air supply) does not provide acceptable ventilation in the house. It generally provides excess ventilation for the house overall, mostly overventilating the first floor rooms, but does not distribute it adequately. It provides too much ventilation air to main floor rooms and not enough ventilation in the closed bedrooms. The overventilation of the main floor would be wasteful of heating energy and could be expected to cause poor thermal comfort.
3. The exhaust-only ventilation strategy that uses a partially distributed exhaust system in the second storey (Configurations C and D) was effective at providing good distribution of ventilation air to the closed bedrooms. The ventilation air supply to first floor rooms met or exceeded the standard requirements. The air supplied to the bedrooms was largely indoor air in the absence of a deliberate passive inlet vent. When the centralized single inlet vent was open (Configuration D–a system which can be described as a distributed exhaust with centralized passive make-up air supply) it was effective at providing sufficient outdoor air to the critical closed bedrooms, and improved the air exchange rate for the house overall.
4. The minimal ducted supply system (Configuration E), operated as a balanced ventilation system with the exhaust provided by the kitchen and bathroom fans, was effective at meeting the standard requirements for the supply and distribution of ventilation air to all the rooms in the house.

5. When passive inlet vents are provided for the main living areas of the house, whether distributed or centralized, basement leakage became less important as a contribution to the total inflow of outdoor air. With deliberate vents opened, the ventilation rates due to air leakage into the basement typically decreased and very closely matched the standard requirements for those basement rooms.
6. As expected, air infiltration and exfiltration alone, with all doors, windows, vents and flues closed, does not provide adequate outdoor air supply to the house overall.
7. The tests of the forced-air heating system's air distribution, as a reference case, confirmed that continuous furnace fan operation does effectively mix the air well within the house. These results also confirmed that door undercuts sized according to the CSA F326 specifications are adequate to allow effective air distribution to all closed rooms.
8. Natural driving forces for air leakage, and their consequent interior air flow patterns, exert an influence on the air distribution in the house. This influence can be quite substantial during cold weather when stack effect is dominant, and especially so when deliberate vents are opened, increasing the effective leakage area of the building envelope.
9. For a ducted supply and local exhaust balanced approach to house ventilation, providing deliberate ducted supply of ventilation air to small rooms where exhaust fans are operated (such as bathrooms) seems to be a poor practice, and is probably wasteful of ventilation and heating/cooling energy.
10. The multiple tracer gas test results indicated that the single tracer gas method may underestimate the total air supply to individual rooms on the upper storey where much of their supply air is interior "stale" air from other (predominantly lower storey) rooms. However, the single tracer gas test measurement results provide a reasonably fair basis for comparing the relative performance of the various ventilation systems in terms of their effective supply of outdoor air to the various rooms in the house.

The ventilation systems that merit further research and development efforts, based on their successful air distribution performance, are the partially distributed exhaust system, especially with deliberate inlet venting, and the minimal ducted supply system. The approach using only typical local exhaust fans in the kitchen and bathrooms does not seem to provide adequate air distribution to all rooms in a multi-storey house. Recommendations are provided in the next section.

14. RECOMMENDATIONS

14.1 GENERAL RECOMMENDATIONS

1. Ventilation strategies using only local exhaust fans in the kitchen and bathrooms should not be relied upon to provide adequate air supply and distribution in reasonably airtight (typical modern) houses. Despite the forced mechanically-moved (exhausted) airflow, this ventilation strategy performed little better than natural air leakage at providing air exchange and distribution in the research house.
2. Vertically distributed passive venting, as a strategy, should not be relied upon to provide adequate distribution of outdoor air supply for an exhaust-only ventilation system comprised of local exhaust fans. Such vents do not offer suitable control over the amount or distribution of the make-up air supply, and are not always effective as inlet vents.
3. Simple ventilation strategies can provide adequate air supply and distribution in houses that do not have forced-air heating systems. Baseboard and other alternative heating systems can be compatible with modern ventilation requirements.

14.2 RECOMMENDATIONS FOR FURTHER RESEARCH

The ventilation systems tested in this project were constructed for research convenience, not as market-ready prototypes. The objective was to assess their ventilation air distribution performance. They were designed and installed without regard to their ultimate thermal comfort provisions, noise of operation, impact on energy consumption, or installation cost. Now that some system design approaches have been identified as successful for air distribution, the thermal comfort conditions provided by these designs must be examined, and market prototypes need to be developed. Energy usage impacts, noise, and costs of equipment, material and labour for the various acceptable systems will need to be examined and installation practices developed for market acceptance and the successful implementation of these systems in real homes.

Based on the findings of this research project, described in the conclusions stated previously, the following ventilation strategies present interesting possibilities and should be considered for further research.

1. The partially distributed exhaust system combined with the distributed second storey passive inlet vents. Configuration C results for the PDE system with no make-up air vents already provided adequate ventilation air supply to basement and main floor rooms, so the main floor inlet vents of Configuration B are not required. Individual inlet vents in each bedroom might improve the fresh air supply to the closed bedrooms. Without the main floor vents helping to lower the neutral pressure level, bedroom level vents may be more effective as make-up air inlets. High sidewall passive vents on the second storey are not likely to serve successfully as inlet vents. Improvements to the thermal comfort impacts of low sidewall passive inlet vents on the second storey will be necessary.
2. The minimal ducted supply system combined with the partially distributed exhaust system. This system is almost a completely designed/engineered dedicated ventilation system. It would deliberately distribute both the supply air delivery and the exhaust air pick-up in the bedrooms. This strategy could incorporate a heat recovery ventilator relatively easily.
3. The minimal ducted supply system reconfigured to exclude ducted supplies in the bathrooms, and later in the kitchen. The system would be rebalanced so additional supply air requirements for these excluded rooms would be distributed amongst the supply rates to the remaining "habitable" rooms. This would address the concerns raised by some individuals that the minimal ducted supply system design tested in this project does not reflect common existing design practices.

Further theoretical and experimental examination of the application of the single tracer gas decay technique to multizone situations could help improve our understanding of its results and its sources of uncertainty, and could lead to an improved field investigation tool.

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APPENDIX A
DETAILED DESCRIPTION OF THE VENTILATION SYSTEMS
- INSTALLATION AND CONSTRUCTION

INTRODUCTION

Five ventilation systems were tested in this research project. Four systems employed an exhaust-only strategy and the fifth employed a balanced supply-exhaust strategy. The first two exhaust-only systems used only local exhaust fans in the kitchen and the two bathrooms, with and without deliberate passive inlet vents to provide the make-up air supply. The other two exhaust-only systems supplemented the local exhaust fans with a partially distributed exhaust system which withdrew air from each bedroom on the second floor, with and without a deliberate passive inlet vent for the make-up air supply. The balanced system used the local exhaust fans for its exhaust side and a minimal ducted supply system to deliberately supply the ventilation air to each "habitable" room as defined in the CSA F326 standard [1].

GENERAL LAYOUT

All the mechanical ventilation strategies tested in this project involved the use of exhaust fans in the kitchen, the main floor powder room and the second floor bathroom. The exhaust of each of these fans was ducted to the outside through plywood panels inserted into the openings of the casement windows in the kitchen, the family room (the powder room has no window) and the second floor bathroom. Venting to the outside in this way enabled the outlet openings of the fans to be sealed conveniently by simply closing the casement windows on their tight-fitting gasket seals. It also avoided having to add more penetrations through the building's exterior envelope. The exhaust duct for each fan was instrumented to enable direct measurement of the exhaust flow rate.

The bathroom exhaust fan was connected to two exhaust ducts both leading outside. They were sized and ultimately balanced for the two design flowrates required of this fan, only one or the other exhaust duct was used for any one test.

The partially distributed exhaust (PDE) system for the second storey bedrooms was comprised of an exhaust fan located in the second storey storage room whose exhaust was ducted to the outside through a plywood panel inserted into the casement window of the smallest bedroom (BR3) and whose inlet was connected to a system of ducts with their pick-up ends located near the centre of the ceiling in each bedroom. The pick-up arrangement in the master bedroom (MBR) actually included two pick-up branches since the ventilation requirements for the MBR are double the requirements for the other bedrooms. Each pick-up branch of the PDE inlet duct system was instrumented to measure the flow rate directly exhausted from each room or zone. For convenient access, all the ductwork was located in the headroom just below the ceiling on the second storey.

The minimal ducted supply (MDS) system was actually split into two subsystems: one supplied ventilation air to the second floor rooms (MDS-2), and the other supplied ventilation air to rooms in the basement and on the first floor (MDS-1B). The fan for the MDS-2 subsystem was located in the second floor storage room and its inlet was ducted to the outside through a plywood panel inserted in the casement window of the middle bedroom (BR2). Its outlet was connected to a system of ducts which supplied ventilation air to openings in each bedroom and the second floor bathroom. The supply openings simulated high side wall delivery in each room. The MBR was supplied by two delivery ducts, to meet its double-size ventilation requirement. The inlet duct to the fan incorporated an electric preheater to temper the incoming air, and ensure a minimum supply air temperature of 15.5°C (60°F). Each delivery branch of the supply duct system was instrumented to enable direct measurement of the supply flow rate to each room or zone. The inlet and supply ducts were located in the headroom just below the ceiling on the second storey. The general components and layout of the MDS-1B subsystem were the same, including an electric preheater to temper the incoming air, and a fully instrumented delivery duct system to enable direct measurement of the supply flow rate to each delivery point. The basement room (BT) was supplied by two delivery ducts, to meet its double-size ventilation requirement. The fan, preheater and trunk ducts were located in the headroom just beneath the basement ceiling. The inlet to the MDS-1B fan was ducted to the outside through the basement dryer-type vent in the top of the foundation wall on the south side of the house.

The deliberate passive inlet venting for the local exhaust strategy involved distributed deliberate openings in rooms on the first and second floors. Vents were installed in plywood panels inserted in the casement window openings in the three bedrooms on the second floor and in the living room and the dining room on the first floor. This enabled the vents to be sealed conveniently by simply closing the casement windows and avoided having to add more penetrations through the building's exterior envelope. The deliberate venting for the PDE strategy involved one single centralized vent large enough to provide for the entry of the make-up air supply for the entire house. This vent required more permanent installation that involved making an extra penetration of the exterior building envelope.

For the local exhaust fan strategy, the kitchen and powder room fans were sized and their flow rates adjusted to provide a total flow to meet the total ventilation requirements for the basement and ground floor rooms, namely 40 L/s. The kitchen fan flow rate was set at 30 L/s and the powder room fan at 10 L/s. The second floor bathroom fan's flow rate was set through its larger exhaust duct to provide the total ventilation requirement for the second storey rooms, namely 25 L/s. The flow rates for the kitchen and powder room fans remained the same for all the mechanical ventilation system configurations tested in this project, in keeping with a zoned approach to the system designs. The total mechanical exhaust for the whole house was 65 L/s for the local exhaust strategy tests.

For the PDE strategy, the second floor bathroom fan's exhaust flow rate was set through its smaller exhaust duct to provide only 10 L/s, the minimum allowed by the CSA F326 standard. The exhaust flow rate in each pick-up branch of the PDE's duct system was set to 5 L/s, thereby withdrawing 5 L/s from each of the smaller bedrooms and a total of 10 L/s from the master bedroom. The PDE was therefore set to exhaust a total of 30 L/s from the second storey zone. The kitchen and powder room exhausts remained set to provide 30 L/s and 10 L/s respectively, so the whole house total mechanical exhaust for the PDE tests was 70 L/s.

For the MDS strategy, the exhaust flow rates from the kitchen, powder room and bathroom remained set at 30 L/s, 10 L/s and 25 L/s respectively, for a whole house total mechanical exhaust of 65 L/s. The supply fan and delivery ducts for the MDS-1B subsystem were set to provide 5 L/s through each delivery branch duct for a total mechanical supply to the combined basement and ground floor of 40 L/s. The supply fan and delivery ducts for the MDS-2 subsystem were also set to provide 5 L/s through each delivery branch duct for a total mechanical supply to the second floor zone of 25 L/s.

FANS

The kitchen fan was a commercially available, variable-speed kitchen range hood exhaust appliance with a maximum capacity rated at 200 cfm (95 L/s). In the absence of a cooktop, over which the standard specifies dimensions for the installation of the range hood device, the appliance was attached to the ceiling in the approximate centre of the kitchen. Its inlet opening was within the 300 mm of the ceiling in accord with the specified standard requirements. Its variable-speed control was used to adjust the fan's exhaust flow rate.

The powder room fan was a commercially available, single-speed bathroom ceiling exhaust appliance with a maximum capacity rated at 110 cfm (52 L/s). It was attached to the ceiling, rather than installed in the ceiling's joist space. The inlet grille of the appliance was partially obstructed using duct tape to adjust the fan's exhaust flow rate.

The second floor bathroom's fan was an identical commercially available, single-speed bathroom ceiling exhaust appliance with a maximum capacity rated at 110 cfm (52 L/s). It was attached to the ceiling, rather than installed in the ceiling's joist space. In addition to the two differently sized exhaust ducts mentioned above, its inlet grille was partially obstructed using duct tape to adjust the fan's exhaust flow rate to the two design settings.

The fan of the PDE system was another identical commercially available, single-speed bathroom ceiling exhaust appliance with a maximum capacity rated at 110 cfm (52 L/s). It case and its inlet and outlet ducts were carefully sealed to prevent air leakage and to ensure that the flow rates measured in each of its inlet branch ducts totalled to the actual flow rate of the fan exhausted to the outside. The flow rates were adjusted using dampers fixed to the inlet ends of the pick-up branch ducts in the three bedrooms.

The fan of the MDS-2 subsystem was another identical commercially available, single-speed bathroom ceiling exhaust appliance with a maximum capacity rated at 110 cfm (52 L/s). Its inlet grille was removed and its case and its inlet and outlet ducts were carefully sealed to prevent air leakage and to ensure that the flow rates measured in each of its supply branch ducts totalled to the actual inlet flow rate of the fan drawn in from outside. The flow rates in each of the supply branch ducts were adjusted using dampers fixed to the outlet ends of those branch ducts.

The fan of the MDS-1B subsystem was a Utility Blower, size 60H, manufactured by American Standard Products. The fan and its motor were installed in an airtight box connected to the inlet duct and its outlet supply duct system, which were carefully sealed to prevent air leakage and to ensure that the flow rates measured in each of its supply branch ducts totalled to the actual inlet flow rate of the fan drawn in from outside. Its installed flow rate capacity was measured to ensure that it could provide the required ventilation supply with a reserve capacity. Those measurements confirmed its suitability for this application. The flow rates in each of the supply branch ducts were adjusted using dampers fixed to the outlet ends of those branch ducts.

VENTS

An earlier research project in the research house [7] had indicated that a seasonal average representative pressure difference across the building envelope was 3.6 Pa. This pressure difference value was used to size the passive inlet vents in the bedrooms and the main floor rooms for the local exhaust strategy. Each vent was constructed of a sheet metal plate attached to a cut out in a plywood panel which was inserted in the casement window opening in each vented room. The vent opening was a precisely-cut round hole in that sheet metal plate, forming a sharp-edged orifice plate. The diameter of the hole was calculated using the orifice plate equation below, assuming a discharge coefficient, C_d, equal to 0.6, a pressure difference, ΔP, equal to 3.6 Pa, and air at standard conditions with mass density, ρ, equal to 1.285 kg/m^3.

$$Q = Y \cdot F \cdot C_d \cdot A \cdot [2 \cdot \Delta P / \rho_{air}]^{0.5} \qquad \text{(A-1)}$$

where Q is the volumetric flow rate through the orifice, [m^3/s],
Y is the compressibility factor, here assumed to be unity,
F is the velocity-of-approach correction factor, here unity,
C_d is the discharge coefficient, here assumed to be 0.6,
A is the area of the orifice opening, [m^2],
ΔP is the pressure difference across the orifice, [Pa], and
ρ_{air} is the mass density of the air flowing, [kg/m^3].

The vent in the master bedroom was sized to admit a flow rate of 10 L/s of air from outside. This required an opening with a diameter of 95 mm, which was rounded up to 4 in. (101.6 mm). The vents in each of the other two bedrooms were sized to admit a flow rate of 5 L/s of air from outside into each bedroom. This required that each vent opening have a diameter of 67 mm, which was rounded up to 3 in. (76.2 mm). The vents in the living room and the dining room were each sized to admit a flow of 20 L/s of air from outside, for a total combined flow of 40 L/s to meet the total ventilation requirement for the combined first floor and basement. The diameter of each vent opening was 134 mm which was rounded up to 5.5 in. (139.7 mm). All of these vents were also provided with a flexible magnetic seal plate, of the same material used to cover and seal the supply and return registers of the forced-air heating system after mixing was complete for the tracer gas tests. These additional seals were required especially for the BR2 and BR3 bedrooms, since their single casement window openings served the dual role as the MDS-2 inlet opening and the PDE outlet opening, respectively. The flexible seals were used when either of these windows were opened for the PDE or MDS tests.

The single centralized passive inlet vent for the PDE system was provided by a rectangular-sectioned duct leading from the stairwell (connecting the first and second storeys) to the front (north) face of the house above the main entrance door. For convenience, but also to simulate its typical location-in-practice in the floor-ceiling joist space separating the two storeys, this duct was laid on the floor of the master bedroom and it was well insulated with extruded polystyrene insulation board to prevent excessive heat loss in the master bedroom through which it passed. This vent was sized to admit a make-up air flow rate of 65 L/s, using a maximum limit of bulk flow velocity of 250 ft/min (1.27 m/s) as a design criterion (one quarter the threshold limit to avoid duct noise). The actual rectangular vent opening was 102 mm by 457 mm (4 in. by 18 in.). The sheet metal duct connecting the exterior and interior vent openings was 2.04 m (6 ft 8.5 in.) long with an oversized cross-section of 203 mm by 610 mm (8 in. by 24 in.). The interior opening of this inlet vent was also provided with a flexible magnetic seal plate, which was also usually sealed with duct tape for tests which did not include its use.

DOORWAYS

The doors for the dining room, kitchen and living/family room were removed for these tests, since they were otherwise in the way and doors to these rooms are typically open in most Canadian homes. The doors for the utility room, powder room, the second floor bathroom, all three bedrooms on the second floor, and at the top of the basement stairs were all closed for these tests. Rather than provide grilles in these doors to provide for the unobstructed flow of air, their undercuts (above painted wooden floors) were sized according to the provisions in the CSA F326 standard. Clause 8.3.7 of that standard specifies that the undercut be large enough to provide sufficient free area that the bulk flow velocity of the required ventilation be no greater than 2.5 m/s. For the nominal 30 in. wide doors (actual width of undercut opening was 30.25 in. or 768 mm) and the various design flow rates of these rooms and zones (between 5 L/s and 25 L/s) the undercut sizes ranged between less than 6 mm (1/4 in.) to 13 mm (1/2 in.). Typical construction often provides larger undercut dimensions than these minimum values. For standardization, all door undercuts were made 19 mm (3/4 in.) to ensure the free flow of ventilation air and to allow for any floor irregularities, and other defects typical of real construction.

DUCTS

The inlet ducts for the MDS subsystem's fans were assembled from 150 mm (6 in.) diameter galvanised sheet metal and housed the electric preheaters which tempered the incoming outdoor air. All the rest of the ducts for the MDS, PDE and local exhaust fans' systems were assembled from various diameter thin-wall PVC plastic pipe and fittings, of the standard type used for modern domestic waste plumbing systems. This plastic material was inexpensive, readily available, easy to work with using ordinary cutting tools, and permitted airtight assembly using its special solvent/glue. Since most building codes permit air duct systems that provide only ventilation and not space heating to be constructed of flammable materials, this material choice might be practical for installations in real houses.

The sizing of the various ducts were constrained by several sometimes conflicting design criteria. The first criterion was that the ducts be sized with little enough flow resistance to allow the various selected fans to drive their design flow rates. The second criterion was that the bulk flow velocities in the various ducts be large enough to permit dependable and accurate measurement of the flow rates using averaging tube techniques (which were the flow rate measurement option which offered the least additional flow resistances). The third constraint was that the duct sizes be selected from the standard sizes for commercially available pipe materials. This third constraint limited the duct sizes to nominal diameters of 2 in., 3 in., and 4 in. (51 mm, 76 mm, and 102 mm); no larger sizes were required.

The exhaust duct from the kitchen fan's outlet to its opening to outside through its window insert panel was constructed of 76 mm dia. pipe, and included two 90° elbow fittings. The exhaust duct from the powder room fan's outlet to its opening to outside was constructed of 76 mm dia. pipe (due to its length) and included four 90° elbow fittings. The two exhaust ducts for the second floor bathroom's double-ducted outlet were made from 51 mm and 76 mm dia. pipe for the 10 L/s and 25 L/s flow rates, respectively, connected with a Y fitting and a 45° elbow fitting. Each of these two ducts also included two 90° elbow fittings. The outlet ends of these two bathroom fan exhaust ducts were only taped to their respective openings in their outlet window panel, not glued in place with sealant as the other single-flow-rate exhaust fans' ducts. This allowed the outlet end of the unused duct (e.g., the 51 mm duct for a test calling for 25 L/s exhaust flow rate) to be removed from the panel and its outlet and the matching hole in the panel sealed with duct tape.

The individual pick-up branches of the PDE system were constructed of 51 mm dia. pipe. These branches were connected to the main trunk which was made of 102 mm dia. pipe by one 90° elbow fitting and three tee fittings. The exhaust duct from the PDE fan to its opening to outside was made of 102 mm dia. pipe and included two 90° elbow fittings.

The individual delivery branches of the MDS subsystems were assembled using 51 mm dia. pipe. These were connected to the mostly 102 mm dia. trunks using either 90° elbow fittings or combinations of Y and 45° elbow fittings. The outlet ends of all delivery branches were oriented to provide a horizontal throw along the ceiling in their respective rooms, except for the powder room, where the throw was oriented downward toward the floor to avoid direct short circuiting of the supply air into the inlet of the exhaust fan.

Baffle plates were attached to each PDE pick-up branch inlet and to each MDS supply branch outlet. These baffle plates were used to adjust the flow rate in each branch during the system balancing to set the design flow rates. Once the balancing was completed, the baffle plates were securely fixed in their balanced positions to maintain the design flow rates in each ventilation system component.

FLOW METERS

Averaging tubes were used to measure the flow rates in the various ventilation systems' components of interest. They were installed in the exhaust ducts of the three principal exhaust fans (kitchen, powder room and bathroom), in each pick-up branch of the PDE system and in each delivery branch of the MDS subsystems. Each installation located the averaging tube in as long a straight run of duct as possible, and as far downstream of an inlet fitting as could be without crowding the downstream fitting in order to reduce the flow disturbance at the measurement location. The general principles for designing averaging tubes may be found in the ASHRAE Handbook of Fundamentals [14]. The averaging tubes used in this project were made from 1/4 in. (6 mm) dia. rigid-wall copper tubing.

Each averaging tube, installed in its actual piece of straight duct, was calibrated against a laminar flow element in the laboratory before it and its duct section were installed in its appropriate ventilation system in the research house. The general form of the calibration relationships was the following.

$$Q = C \bullet (\Delta P)^n \qquad \text{(A-2)}$$

where Q is the volumetric flow rate, [L/s],
C is the flow coefficient, [L/sPa^n],
ΔP is the measured dynamic/static pressure difference, [Pa], and
n is the flow exponent.

The typical average values for the calibration flow coefficients and exponents for the averaging tubes installed in the 51 mm dia. ducts were 2.437 L/sPa^n and 0.5162. The typical average values for the calibration flow coefficients and exponents for the averaging tubes installed in the 76 mm dia. ducts were 5.434 L/sPa^n and 0.4990. The averaging tubes were connected to pressure transducers to measure the pressure differences. The transducers were connected to the flow/temperature/pressure computerized data acquisition system to record and display real-time measurements of the flow rates in each instrumented duct. This facility was used to advantage to balance each ventilation system after its installation, and to monitor the flow rates throughout each tracer gas test.

PREHEATERS

A Chromalox Model F16-4 Residential Fresh Air Heater was installed in the inlet duct of each MDS subsystem to temper the incoming air. These devices ensured a minimum supply air temperature of 15.5°C (60°F). Each preheater had its own dedicated electric circuit to provide its 240 VAC power supply.

APPENDIX B
TABLES OF THE COMPLETE SUMMARIES OF THE SINGLE TRACER GAS TESTS' RESULTS

On each of the following pages is a table of the summary of the results of the single tracer gas tests of one ventilation system configuration.

In each table, the top part lists the air change rates, in units of ac/h, measured by the single tracer gas technique in each sampled room in the research house. Summary statistics for the entire house and for each zone, including both all the sampled rooms' results as well as only the "habitable" rooms' results are also included. The bottom part of each table lists the ventilation ratesin each room , in units of L/s, calculated by multiplying the measured room air change rate by the room's interior volume. Summed ventilation rates for the whole house and for each storey zone, including both all the sampled rooms' results as well as only the "habitable" rooms' results are also included.

Table B-1
SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION A

		Zonal Average Air Change Rates					Measured Room Air Change Rates												
Test ID	OAT	Total	2ndFlr	1stFlr	Bsmnt	OAT	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]		[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]
0210A	-23.0	0.528	0.286	0.730	0.530	-23.0	0.136	0.530	0.530	0.755	0.745	0.728	0.738	0.750	0.662	0.127	0.143	0.466	0.559
0117A	-16.5	0.471	0.214	0.641	0.560	-16.5	0.116	0.515	0.605	0.661	0.656	0.638	0.619	0.631		0.170	0.118	0.453	
0104A	-9.0	0.491	0.223	0.745	0.393	-9.0	0.225	0.393	0.393	0.780	0.745	0.726	0.747	0.725		0.097	0.118	0.453	
0113A	-8.4	0.431	0.213	0.573	0.513	-8.4	0.124	0.451	0.575	0.582	0.545	0.577	0.590	0.573		0.146	0.130	0.452	
1125A	-7.0	0.348	0.205	0.547	0.134	-7.0	0.134	0.134	0.134	0.536	0.511	0.477	0.487	0.725		0.147	0.120	0.418	
1222A	-5.4	0.421	0.227	0.557	0.467	-5.4	0.160	0.470	0.464	0.579	0.575	0.553	0.568	0.511		0.166	0.206	0.377	
1118A	2.0	0.414	0.239	0.553	0.418	2.0	0.194	0.439	0.398	0.574	0.501	0.564	0.571	0.557		0.150	0.167	0.444	
0328A	3.3	0.404	0.281	0.516	0.375	3.3	0.197	0.377	0.373	0.579	0.543	0.490	0.500	0.518	0.468	0.168	0.179	0.430	0.432
0413A	4.8	0.453	0.299	0.548	0.550	4.8	0.194	0.505	0.595	0.582	0.534	0.520	0.557	0.597	0.499	0.251	0.171	0.440	0.441
0601A	9.7	0.449	0.321	0.561	0.435	9.7	0.233	0.419	0.451	0.596	0.573	0.549	0.559	0.553	0.534	0.199	0.195	0.482	0.496
0425A	10.7	0.461	0.306	0.570	0.522	10.7	0.194	0.494	0.550	0.608	0.598	0.547	0.556	0.563	0.550	0.282	0.173	0.440	0.444
0525A	17.1	0.408	0.278	0.518	0.404	17.1	0.197	0.411	0.397	0.557	0.537	0.514	0.528	0.486	0.484	0.219	0.187	0.386	0.400
Averages:		0.440	0.258	0.588	0.442	-1.8	0.175	0.428	0.455	0.616	0.589	0.574	0.585	0.599	0.533	0.177	0.159	0.437	0.462
Min:		0.348	0.205	0.516	0.134		0.116	0.134	0.134	0.536	0.501	0.477	0.487	0.486	0.468	0.097	0.118	0.377	0.400
Max:		0.528	0.321	0.745	0.560		0.233	0.530	0.605	0.780	0.745	0.728	0.747	0.750	0.662	0.282	0.206	0.482	0.559

		Zonal Summed Ventilation Flow Rates							Measured Room Ventilation Flow Rates											
Test ID	OAT	Total	Total*	2ndFlr	2ndFlr*	1stFlr	1stFlr*	Bsmnt	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]
0210A	-23.0	67.48	57.59	10.67	6.86	33.41	27.33	23.39	2.74	15.58	7.82	6.63	6.50	6.83	6.48	0.89	6.08	1.04	0.89	2.19	3.81
0117A	-16.5	54.34	54.34	6.59	6.59	23.70	23.70	24.05	2.32	15.13	8.92	5.81	5.73	5.99	5.43	0.75		1.40	0.74	2.13	
0104A	-9.0	53.11	53.11	8.19	8.19	27.58	27.58	17.34	4.52	11.55	5.79	6.86	6.50	6.81	6.55	0.86		0.79	0.74	2.13	
0113A	-8.4	49.49	49.49	6.63	6.63	21.14	21.14	21.71	2.50	13.23	8.48	5.12	4.76	5.41	5.17	0.68		1.19	0.81	2.13	
1125A	-7.0	31.29	31.29	6.61	6.61	18.77	18.77	5.91	2.69	3.93	1.97	4.71	4.46	4.47	4.27	0.86		1.21	0.75	1.97	
1222A	-5.4	49.18	49.18	7.64	7.64	20.89	20.89	20.65	3.21	13.81	6.84	5.09	5.02	5.18	4.99	0.61		1.36	1.29	1.77	
1118A	2.0	47.40	47.40	8.27	8.27	20.37	20.37	18.75	3.91	12.88	5.87	5.04	4.37	5.29	5.00	0.66		1.23	1.05	2.09	
0328A	3.3	51.72	44.48	11.42	8.48	23.72	19.43	16.58	3.95	11.08	5.50	5.09	4.74	4.60	4.39	0.61	4.29	1.38	1.12	2.02	2.95
0413A	4.8	60.57	52.98	12.11	9.10	24.85	20.26	23.61	3.90	14.84	8.78	5.12	4.67	4.88	4.89	0.71	4.58	2.06	1.07	2.07	3.00
0601A	9.7	58.01	49.72	13.18	9.80	25.85	20.95	18.97	4.68	12.32	6.66	5.23	5.01	5.15	4.91	0.66	4.91	1.63	1.22	2.27	3.38
0425A	10.7	61.29	53.21	12.38	9.36	26.29	21.24	22.62	3.89	14.51	8.11	5.34	5.22	5.13	4.88	0.67	5.06	2.31	1.08	2.07	3.03
0525A	17.1	53.47	46.30	11.48	8.75	24.07	19.62	17.92	3.97	12.07	5.85	4.89	4.69	4.82	4.64	0.58	4.45	1.80	1.17	1.82	2.73
Averages:		53.11	49.09	9.60	8.02	24.22	21.77	19.29	3.52	12.58	6.72	5.41	5.14	5.38	5.13	0.71	4.90	1.45	0.99	2.06	3.15
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		0.82	0.76	0.38	0.32	0.97	0.87	1.29	0.35	1.26	1.34	1.08	1.03	1.08	1.03	0.14		0.29	0.20	0.41	
Min/Req't:		0.48	0.48	0.10	0.10	0.29	0.29	0.09	0.23	0.39	0.39	0.94	0.87	0.89	0.85	0.12		0.16	0.15	0.35	
Max/Req't:		1.04	0.89	0.20	0.15	0.51	0.42	0.37	0.47	1.56	1.78	1.37	1.30	1.37	1.31	0.18		0.46	0.26	0.45	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.

Table B-2
SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION B

Test ID	OAT	Zonal Average Air Change Rates				OAT	Measured Room Air Change Rates												
		Total	2ndFlr	1stFlr	Bsmnt		MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]
0208B	-24.4	1.098	0.685	1.645	0.487	-24.4	0.309	0.502	0.471	2.001	1.828	1.482	1.580	1.538	1.442	0.472	0.526	0.983	1.133
0117B	-13.3	0.965	0.675	1.399	0.460	-13.3	0.411	0.474	0.446	1.607	1.449	1.356	1.328	1.255		0.470	0.917	0.904	
0105B	-13.3	1.314	0.866	2.045	0.384	-13.3	0.939	0.436	0.332	1.862	1.796	2.456	2.303	1.806		0.675	0.699	1.150	
1130B	-3.2	0.844	0.629	1.247	0.270	-3.2	0.697	0.314	0.227	1.132	1.068	1.422	1.439	1.173		0.463	0.514	0.841	
1123B	0.7	0.597	0.420	0.847	0.325	0.7	0.236	0.329	0.321	1.168	0.833	0.762	0.743	0.730		0.244	0.593	0.607	
0217B	1.6	0.771	0.417	1.211	0.333	1.6	0.188	0.350	0.316	1.454	1.263	1.142	1.150	1.184	1.076	0.159	0.192	0.668	0.878
1206B	3.3	0.740	0.463	1.136	0.301	3.3	0.206	0.302	0.299	1.343	1.222	1.011	1.033	1.072		0.232	0.634	0.781	
0413B	4.0	0.622	0.506	0.818	0.326	4.0	0.343	0.327	0.324	1.031	0.923	0.742	0.732	0.775	0.705	0.326	0.622	0.595	0.641
0414B	9.9	0.681	0.705	0.789	0.298	9.9	0.388	0.284	0.313	1.081	0.836	0.724	0.727	0.702	0.664	1.075	0.631	0.685	0.747
0418B	11.2	0.638	0.497	0.887	0.242	11.2	0.250	0.245	0.240	1.160	0.973	0.808	0.841	0.809	0.728	0.519	0.547	0.538	0.631
Averages:		0.827	0.586	1.202	0.343	-2.4	0.397	0.356	0.329	1.384	1.219	1.190	1.188	1.104	0.923	0.464	0.587	0.775	0.806
Min:		0.597	0.417	0.789	0.242		0.188	0.245	0.227	1.031	0.833	0.724	0.727	0.702	0.664	0.159	0.192	0.538	0.631
Max:		1.314	0.866	2.045	0.487		0.939	0.502	0.471	2.001	1.828	2.456	2.303	1.806	1.442	1.075	0.917	1.150	1.133

Test ID	OAT	Zonal Summed Ventilation Flow Rates							Measured Room Ventilation Flow Rates												
		Total	Total*	2ndFlr	2ndFlr*	1stFlr	1stFlr*	Bsmnt	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]
0208B	-24.4	123.81	102.84	25.74	18.01	76.38	63.13	21.69	6.22	14.75	6.95	17.59	15.96	13.90	13.86	1.82	13.24	3.87	3.29	4.63	7.73
0117B	-13.3	95.24	95.24	22.10	22.10	52.62	52.62	20.51	8.25	13.93	6.58	14.12	12.65	12.72	11.65	1.49		3.85	5.73	4.25	
0105B	-13.3	129.34	129.34	34.21	34.21	77.44	77.44	17.69	18.88	12.80	4.90	16.37	15.68	23.04	20.21	2.14		5.54	4.37	5.41	
1130B	-3.2	84.17	84.17	24.98	24.98	46.64	46.64	12.55	14.02	9.21	3.34	9.95	9.33	13.34	12.63	1.39		3.80	3.21	3.96	
1123B	0.7	59.78	59.78	13.31	13.31	32.06	32.06	14.41	4.74	9.67	4.73	10.26	7.27	7.15	6.51	0.87		2.01	3.71	2.86	
0217B	1.6	86.25	70.38	15.42	9.43	55.88	46.00	14.94	3.78	10.28	4.66	12.78	11.02	10.71	10.08	1.40	9.88	1.30	1.20	3.15	5.98
1206B	3.3	69.25	69.25	13.68	13.68	42.29	42.29	13.29	4.14	8.88	4.41	11.80	10.67	9.49	9.06	1.27		1.91	3.97	3.67	
0413B	4	72.93	62.08	20.64	16.27	37.90	31.42	14.39	6.90	9.61	4.78	9.06	8.06	6.96	6.42	0.92	6.48	2.68	3.89	2.80	4.37
0414B	9.9	78.73	67.53	28.88	23.79	36.90	30.80	12.95	7.79	8.33	4.62	9.50	7.30	6.79	6.38	0.83	6.10	8.82	3.95	3.22	5.09
0418B	11.2	71.58	60.58	19.56	15.25	41.29	34.60	10.73	5.04	7.19	3.54	10.20	8.50	7.57	7.37	0.96	6.69	4.26	3.42	2.53	4.30
Averages:		87.11	80.12	21.85	19.10	49.94	45.70	15.32	7.98	10.46	4.85	12.16	10.64	11.17	10.42	1.31	8.48	3.80	3.67	3.65	5.50
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		1.34	1.23	0.87	0.76	2.00	1.83	1.02	0.80	1.05	0.97	2.43	2.13	2.23	2.08	0.26		0.76	0.73	0.73	
Min/Req't:		0.92	0.92	0.53	0.38	1.28	1.23	0.72	0.38	0.72	0.67	1.81	1.45	1.36	1.28	0.17		0.26	0.24	0.51	
Max/Req't:		1.99	1.99	1.37	1.37	3.10	3.10	1.45	1.89	1.47	1.39	3.52	3.19	4.61	4.04	0.43		1.76	1.15	1.08	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.

Table B-3

SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION C

Test ID	OAT	Zonal Average Air Change Rates				OAT	Measured Room Air Change Rates												
		Total	2ndFlr	1stFlr	Bsmnt		MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]
0106C	-19.3	0.585	0.358	0.769	0.580	-19.3	0.283	0.567	0.593	0.812	0.770	0.742	0.763	0.757		0.300	0.328	0.521	
1124C	-10.1	0.543	0.362	0.738	0.416	-10.1	0.328	0.421	0.411	0.777	0.672	0.750	0.742	0.752		0.318	0.299	0.504	
0111C	-9.4	0.542	0.298	0.698	0.639	-9.4	0.248	0.555	0.723	0.719	0.715	0.670	0.653	0.733		0.260	0.267	0.418	
0124C	-8.8	0.596	0.406	0.791	0.485	-8.8	0.302	0.489	0.482	0.859	0.843	0.762	0.707	0.809	0.768	0.293	0.312	0.500	0.626
1201C	-1.2	0.530	0.318	0.645	0.668	-1.2	0.242	0.624	0.713	0.653	0.647	0.616	0.634	0.676		0.306	0.292	0.430	
0323C	4.4	0.531	0.418	0.622	0.542	4.4	0.307	0.523	0.560	0.672	0.635	0.620	0.617	0.583	0.605	0.336	0.368	0.496	0.584
0307C	5.4	0.530	0.395	0.637	0.545	5.4	0.286	0.497	0.593	0.694	0.657	0.605	0.651	0.639	0.578	0.341	0.346	0.456	0.546
0414C	8.2	0.498	0.404	0.598	0.432	8.2	0.289	0.403	0.462	0.623	0.624	0.572	0.616	0.602	0.554	0.352	0.359	0.482	0.541
0425C	10.7	0.480	0.389	0.564	0.453	10.7	0.300	0.417	0.488	0.610	0.568	0.550	0.571	0.562	0.522	0.346	0.326	0.446	0.529
0517C	11.6	0.514	0.453	0.621	0.346	11.6	0.366	0.356	0.336	0.654	0.624	0.619	0.640	0.623	0.567	0.327	0.399	0.547	0.624
0603C	19.0	0.520	0.454	0.599	0.450	19.0	0.342	0.426	0.475	0.624	0.617	0.597	0.592	0.581	0.583	0.377	0.408	0.542	0.600
0427C	19.3	0.587	0.497	0.707	0.450	19.3	0.322	0.394	0.506	0.718	0.704	0.725	0.702	0.708	0.681	0.423	0.476	0.595	0.670
Averages:		0.538	0.396	0.666	0.501	2.5	0.301	0.473	0.528	0.701	0.673	0.652	0.657	0.669	0.607	0.331	0.348	0.495	0.590
Min:		0.480	0.298	0.564	0.346		0.242	0.356	0.336	0.610	0.568	0.550	0.571	0.562	0.522	0.260	0.267	0.418	0.529
Max:		0.596	0.497	0.791	0.668		0.366	0.624	0.723	0.859	0.843	0.762	0.763	0.809	0.768	0.423	0.476	0.595	0.670

Test ID	OAT	Zonal Summed Ventilation Flow Rates							Measured Room Ventilation Flow Rates												
		Total	Total*	2ndFlr	2ndFlr*	1stFlr	1stFlr*	Bsmnt	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]
0106C	-19.3	66.47	66.47	12.65	12.65	28.41	28.41	25.41	5.69	16.66	8.75	7.13	6.72	6.96	6.69	0.90		2.46	2.05	2.45	
1124C	-10.1	59	59	13.44	13.44	27.13	27.13	18.43	6.60	12.36	6.07	6.83	5.86	7.04	6.51	0.89		2.61	1.87	2.37	
0111C	-9.4	63.14	63.14	10.75	10.75	25.44	25.44	26.95	4.98	16.30	10.65	6.32	6.24	6.29	5.73	0.87		2.14	1.67	1.97	
0124C	-8.8	74.77	63.45	17.04	12.77	36.27	29.22	21.46	6.06	14.36	7.10	7.55	7.36	7.15	6.20	0.96	7.05	2.40	1.95	2.35	4.27
1201C	-1.2	63.58	63.58	11.23	11.23	23.53	23.53	28.82	4.87	18.31	10.51	5.74	5.65	5.78	5.56	0.80		2.51	1.83	2.02	
0323C	4.4	70.11	60.57	17.55	13.56	28.93	23.37	23.64	6.17	15.37	8.26	5.90	5.55	5.82	5.41	0.69	5.56	2.75	2.30	2.34	3.98
0307C	5.4	69.21	60.18	16.58	12.86	29.28	23.97	23.35	5.75	14.60	8.75	6.10	5.73	5.67	5.71	0.76	5.31	2.80	2.17	2.15	3.72
0414C	8.2	63.02	54.24	16.89	13.2	27.48	22.4	18.64	5.80	11.83	6.81	5.47	5.45	5.36	5.40	0.71	5.09	2.89	2.24	2.27	3.69
0425C	10.7	62.01	53.61	16.62	13.01	25.95	21.15	19.45	6.03	12.26	7.19	5.36	4.96	5.16	5.01	0.67	4.79	2.84	2.04	2.10	3.61
0517C	11.6	63.35	53.88	19.37	15.12	28.57	23.36	15.4	7.37	10.45	4.95	5.75	5.45	5.81	5.61	0.74	5.21	2.68	2.49	2.58	4.26
0603C	19	66.38	56.93	19.16	15.07	27.71	22.35	19.5	6.88	12.50	7.00	5.49	5.39	5.60	5.20	0.69	5.36	3.09	2.55	2.55	4.09
0427C	19.3	71.84	61.01	20.3	15.74	32.52	26.26	19.02	6.48	11.56	7.46	6.31	6.15	6.80	6.16	0.84	6.26	3.47	2.98	2.80	4.57
Averages:		66.07	59.67	15.97	13.28	28.43	24.72	21.67	6.06	13.88	7.79	6.16	5.88	6.12	5.77	0.79	5.58	2.72	2.18	2.33	4.02
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		1.02	0.92	0.64	0.53	1.14	0.99	1.44	0.61	1.39	1.56	1.23	1.18	1.22	1.15	0.16		0.54	0.44	0.47	
Min/Req't:		0.91	0.82	0.43	0.43	0.94	0.85	1.03	0.49	1.05	0.99	1.07	0.99	1.03	1.00	0.13		0.43	0.33	0.39	
Max/Req't:		1.15	1.02	0.81	0.63	1.45	1.17	1.92	0.74	1.83	2.13	1.51	1.47	1.43	1.34	0.19		0.69	0.60	0.56	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.

Table B-4
SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION D

Test ID	OAT [C]	Total [ac/h]	2ndFlr [ac/h]	1stFlr [ac/h]	Bsmnt [ac/h]	OAT [C]	MB [ac/h]	BT [ac/h]	UT [ac/h]	DR [ac/h]	KT [ac/h]	LR [ac/h]	FR [ac/h]	PR [ac/h]	H1 [ac/h]	B2 [ac/h]	B3 [ac/h]	2B [ac/h]	H2 [ac/h]
		Zonal Average Air Change Rates					Measured Room Air Change Rates												
0106D	-23.4	0.719	0.473	1.023	0.451	-23.4	0.369	0.461	0.442	1.035	1.006	1.028	1.036	1.010		0.393	0.469	0.659	
0208D	-19.7	0.836	0.606	1.143	0.488	-19.7	0.401	0.495	0.482	1.174	1.151	1.139	1.137	1.105	1.153	0.424	0.527	0.741	0.940
0112D	-15.0	0.736	0.485	1.070	0.405	-15.0	0.379	0.423	0.387	1.093	1.048	1.101	1.057	1.050		0.382	0.490	0.688	
0222D	-11.4	1.318	0.899	1.941	0.498	-11.4	0.617	0.547	0.450	1.970	1.925	2.099	2.038	1.872	1.740	0.780	0.990	1.188	0.922
0309D	-6.6	0.657	0.508	0.879	0.361	-6.6	0.356	0.363	0.358	0.905	0.893	0.864	0.868	0.845	0.901	0.354	0.482	0.631	0.716
0307D	0.6	0.590	0.499	0.758	0.315	0.6	0.358	0.316	0.314	0.837	0.803	0.672	0.723	0.757	0.755	0.363	0.453	0.604	0.717
1220D	4.5	0.578	0.458	0.782	0.307	4.5	0.344	0.305	0.310	0.874	0.822	0.685	0.677	0.853		0.399	0.460	0.627	
1202D	4.6	0.529	0.424	0.699	0.315	4.6	0.317	0.302	0.327	0.754	0.729	0.674	0.673	0.664		0.378	0.416	0.587	
0426D	6.4	0.595	0.577	0.724	0.257	6.4	0.375	0.270	0.245	0.965	0.913	0.518	0.475	0.754	0.717	0.413	0.532	0.726	0.839
0526D	8.4	0.609	0.610	0.724	0.263	8.4	0.420	0.281	0.245	0.878	0.932	0.502	0.516	0.777	0.736	0.451	0.581	0.799	0.801
0419D	12.2	0.610	0.633	0.706	0.263	12.2	0.392	0.278	0.248	0.871	0.841	0.651	0.658	0.575	0.640	0.396	0.539	0.743	1.097
0412D	14.9	0.605	0.606	0.722	0.251	14.9	0.349	0.240	0.263	0.964	0.922	0.534	0.522	0.725	0.665	0.412	0.543	0.781	0.945
Averages:		0.699	0.565	0.931	0.348	-2.0	0.390	0.357	0.339	1.027	0.999	0.872	0.865	0.916	0.913	0.429	0.540	0.731	0.872
Min:		0.529	0.424	0.699	0.251		0.317	0.240	0.245	0.754	0.729	0.502	0.475	0.575	0.640	0.354	0.416	0.587	0.716
Max:		1.318	0.899	1.941	0.498		0.617	0.547	0.482	1.970	1.925	2.099	2.038	1.872	1.740	0.780	0.990	1.188	1.097

Test ID	OAT [C]	Total [L/s]	Total* [L/s]	2ndFlr [L/s]	2ndFlr* [L/s]	1stFlr [L/s]	1stFlr* [L/s]	Bsmnt [L/s]	MB [L/s]	BT [L/s]	UT [L/s]	DR [L/s]	KT [L/s]	LR [L/s]	FR [L/s]	PR [L/s]	H1 [L/s]	B2 [L/s]	B3 [L/s]	2B [L/s]	H2 [L/s]
		Zonal Summed Ventilation Flow Rates							Measured Room Ventilation Flow Rates												
0106D	-23.4	74.55	74.55	16.69	16.69	37.81	37.81	20.05	7.43	13.53	6.51	9.10	8.79	9.65	9.09	1.20		3.22	2.93	3.10	
0208D	-19.7	99.30	82.30	24.74	18.32	52.93	42.34	21.64	8.07	14.53	7.11	10.32	10.05	10.69	9.97	1.31	10.59	3.48	3.29	3.48	6.41
0112D	-15.0	74.78	74.78	17.07	17.07	39.59	39.59	18.12	7.63	12.41	5.71	9.60	9.15	10.32	9.27	1.25		3.13	3.07	3.24	
0222D	-11.4	149.45	127.19	36.88	30.59	89.89	73.91	22.68	12.41	16.05	6.63	17.32	16.81	19.69	17.88	2.22	15.98	6.40	6.19	5.59	6.29
0309D	-6.6	77.63	64.47	20.94	16.06	40.75	32.48	15.94	7.17	10.66	5.28	7.96	7.80	8.10	7.62	1.00	8.27	2.91	3.01	2.97	4.88
0307D	0.6	69.50	57.67	20.75	15.86	34.85	27.91	13.90	7.20	9.28	4.62	7.36	7.01	6.30	6.34	0.90	6.94	2.98	2.83	2.84	4.89
1220D	4.5	57.77	57.77	16.02	16.02	28.22	28.22	13.52	6.92	8.95	4.57	7.68	7.17	6.42	5.94	1.01		3.28	2.87	2.95	
1202D	4.6	54.54	54.54	14.83	14.83	26.01	26.01	13.70	6.37	8.87	4.82	6.63	6.36	6.32	5.91	0.79		3.10	2.60	2.76	
0426D	6.4	67.88	55.57	23.39	17.67	32.95	26.36	11.53	7.54	7.92	3.62	8.48	7.97	4.86	4.17	0.89	6.59	3.39	3.33	3.42	5.72
0526D	8.4	69.66	57.43	25.00	19.54	32.78	26.02	11.87	8.44	8.25	3.62	7.72	8.14	4.71	4.63	0.92	6.76	3.70	3.63	3.76	5.46
0419D	12.2	70.73	57.38	25.47	17.99	33.44	27.56	11.83	7.87	8.17	3.66	7.66	7.34	6.11	5.77	0.88	5.88	3.25	3.37	3.50	7.48
0412D	14.9	67.93	55.38	23.92	17.48	33.08	26.97	10.93	7.03	7.05	3.88	8.47	8.05	5.01	4.58	0.86	6.11	3.38	3.40	3.68	6.44
Averages:		77.81	68.25	22.14	18.18	40.19	34.60	15.48	7.84	10.47	5.00	9.02	8.72	8.18	7.59	1.09	8.39	3.52	3.38	3.44	5.95
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		1.20	1.05	0.89	0.73	1.61	1.38	1.03	0.78	1.05	1.00	1.80	1.74	1.64	1.52	0.22		0.70	0.68	0.69	
Min/Req't:		0.84	0.84	0.59	0.59	1.04	1.04	0.73	0.64	0.70	0.72	1.33	1.27	0.94	0.83	0.14		0.58	0.52	0.55	
Max/Req't:		2.30	1.96	1.48	1.22	3.60	2.96	1.51	1.24	1.61	1.42	3.46	3.36	3.94	3.58	0.44		1.28	1.24	1.12	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.

Table B-5
SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION E

Test ID	OAT	Zonal Average Air Change Rates Total	2ndFlr	1stFlr	Bsmnt	OAT	Measured Room Air Change Rates MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]
0110E	-14.0	0.617	0.587	0.640	0.621	-14.0	0.498	0.618	0.624	0.602	0.604	0.613	0.627	0.752		0.555	0.682	0.613	
0202E	-8.9	0.659	0.630	0.671	0.697	-8.9	0.519	0.627	0.768	0.624	0.617	0.681	0.702	0.771	0.631	0.648	0.781	0.620	0.583
0124E	-6.9	0.588	0.561	0.620	0.564	-6.9	0.471	0.553	0.575	0.584	0.588	0.596	0.605	0.722	0.624	0.537	0.663	0.567	0.563
1201E	-0.1	0.558	0.551	0.582	0.512	-0.1	0.472	0.538	0.487	0.542	0.537	0.560	0.547	0.722		0.539	0.646	0.547	
1221E	2.5	0.571	0.571	0.613	0.466	2.5	0.513	0.467	0.464	0.580	0.569	0.564	0.577	0.777		0.537	0.664	0.571	
0418E	5.1	0.545	0.562	0.546	0.502	5.1	0.497	0.485	0.519	0.547	0.530	0.536	0.545	0.606	0.513	0.540	0.692	0.541	0.539
0412E	8.1	0.526	0.535	0.534	0.482	8.1	0.472	0.473	0.492	0.518	0.514	0.503	0.500	0.673	0.494	0.526	0.640	0.518	0.516
0323E	10.1	0.506	0.530	0.495	0.476	10.1	0.468	0.456	0.496	0.479	0.480	0.495	0.499	0.540	0.478	0.526	0.668	0.492	0.498
0509E	11.1	0.511	0.541	0.507	0.447	11.1	0.479	0.459	0.435	0.513	0.510	0.497	0.495	0.540	0.488	0.528	0.666	0.518	0.513
0511E	11.9	0.632	0.678	0.631	0.524	11.9	0.545	0.504	0.544	0.601	0.615	0.599	0.555	0.838	0.576	0.755	0.866	0.612	0.613
Averages:		0.571	0.575	0.584	0.529	1.9	0.493	0.518	0.541	0.559	0.556	0.564	0.565	0.694	0.543	0.569	0.697	0.560	0.546
Min:		0.506	0.530	0.495	0.447		0.468	0.456	0.435	0.479	0.480	0.495	0.495	0.540	0.478	0.526	0.640	0.492	0.498
Max:		0.659	0.678	0.671	0.697		0.545	0.627	0.768	0.624	0.617	0.681	0.702	0.838	0.631	0.755	0.866	0.620	0.613

Test ID	OAT	Zonal Summed Ventilation Flow Rates Total	Total*	2ndFlr	2ndFlr*	1stFlr	1stFlr*	Bsmnt	MB	Measured Room Ventilation Flow Rates BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]
0110E	-14.0	71.77	71.77	21.71	21.71	22.71	22.71	27.35	10.01	18.16	9.20	5.29	5.27	5.75	5.50	0.89		4.55	4.27	2.88	
0202E	-8.9	87.40	77.64	27.54	23.57	30.12	24.33	29.74	10.44	18.41	11.32	5.48	5.38	6.39	6.16	0.91	5.79	5.32	4.88	2.92	3.97
0124E	-6.9	77.02	67.44	24.55	20.70	27.75	22.02	24.72	9.48	16.24	8.48	5.13	5.14	5.59	5.30	0.86	5.73	4.41	4.15	2.67	3.84
1201E	-0.1	63.87	63.87	20.53	20.53	20.37	20.37	22.98	9.49	15.80	7.18	4.76	4.69	5.26	4.80	0.86		4.42	4.04	2.57	
1221E	2.5	63.47	63.47	21.56	21.56	21.34	21.34	20.58	10.31	13.73	6.85	5.10	4.97	5.29	5.06	0.92		4.41	4.15	2.69	
0418E	5.1	71.55	63.17	24.98	21.30	24.68	19.97	21.90	10.00	14.24	7.66	4.81	4.63	5.03	4.78	0.72	4.71	4.43	4.33	2.54	3.67
0412E	8.1	68.39	60.33	23.77	20.25	23.48	18.93	21.14	9.49	13.88	7.26	4.55	4.49	4.72	4.38	0.80	4.54	4.32	4.01	2.44	3.52
0323E	10.1	66.79	59.00	23.62	20.22	22.45	18.07	20.71	9.41	13.40	7.31	4.21	4.19	4.64	4.38	0.64	4.39	4.32	4.18	2.31	3.40
0509E	11.1	67.04	59.05	24.06	20.56	23.09	18.61	19.88	9.63	13.47	6.42	4.51	4.45	4.66	4.35	0.64	4.48	4.33	4.17	2.44	3.60
0511E	11.9	79.86	70.39	29.63	25.45	27.42	22.12	22.82	10.95	14.80	8.02	5.28	5.37	5.62	4.86	0.99	5.29	6.20	5.42	2.88	4.18
Averages:		71.72	65.61	24.19	21.59	24.34	20.85	23.18	9.92	15.21	7.97	4.91	4.86	5.29	4.96	0.82	4.99	4.67	4.36	2.63	3.73
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		1.10	1.01	0.97	0.86	0.97	0.83	1.55	0.99	1.52	1.59	0.98	0.97	1.06	0.99	0.16		0.93	0.87	0.53	
Min/Req't:		0.98	0.91	0.82	0.81	0.81	0.72	1.33	0.94	1.34	1.28	0.84	0.84	0.93	0.87	0.13		0.86	0.80	0.46	
Max/Req't:		1.34	1.19	1.19	1.02	1.20	0.97	1.98	1.09	1.84	2.26	1.10	1.08	1.28	1.23	0.20		1.24	1.08	0.58	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.

Table B-6
SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION F

		Zonal Average Air Change Rates					Measured Room Air Change Rates												
Test ID	OAT	Total	2ndFlr	1stFlr	Bsmnt	OAT	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]
0209F	-16.4	0.325	0.154	0.440	0.409	-16.4	0.101	0.440	0.378	0.443	0.437	0.443	0.432	0.442	0.441	0.106	0.066	0.103	0.392
0118F	-13.5	0.180	0.049	0.244	0.282	-13.5	0.045	0.276	0.288	0.204	0.194	0.233	0.226	0.364		0.041	0.040	0.071	
0111F	-12.6	0.185	0.081	0.243	0.304	-12.6	0.054	0.303	0.305	0.228	0.223	0.239	0.233	0.291		0.052	0.037	0.074	
0222F	-8.1	0.244	0.123	0.340	0.259	-8.1	0.067	0.282	0.237	0.334	0.344	0.335	0.338	0.364	0.327	0.078	0.078	0.114	0.277
1129F	-1.0	0.102	0.035	0.138	0.180	-1.0	0.017	0.185	0.176	0.130	0.130	0.128	0.127	0.172		0.011	0.015	0.028	
1207F	2.0	0.127	0.062	0.165	0.192	2.0	0.026	0.201	0.183	0.174	0.167	0.153	0.154	0.178		0.026	0.048	0.085	
0411F	5.5	0.159	0.097	0.210	0.157	5.5	0.061	0.170	0.144	0.220	0.219	0.208	0.203	0.196	0.212	0.043	0.057	0.121	0.206
1117F	8.4	0.085	0.029	0.112	0.159	8.4	0.012	0.164	0.155	0.113	0.110	0.112	0.108	0.117		0.011	0.014	0.021	
0518F	12.2	0.201	0.122	0.277	0.168	12.2	0.122	0.179	0.158	0.286	0.283	0.279	0.278	0.259	0.276	0.079	0.046	0.087	0.276
0509F	13.2	0.107	0.066	0.125	0.157	13.2	0.023	0.157	0.157	0.118	0.120	0.117	0.120	0.156	0.121	0.019	0.060	0.115	0.112
0511F	14.6	0.144	0.087	0.186	0.160	14.6	0.034	0.138	0.182	0.126	0.125	0.152	0.176	0.387	0.147	0.068	0.103	0.109	0.124
Averages:		0.169	0.082	0.225	0.221	0.4	0.051	0.227	0.215	0.216	0.214	0.218	0.218	0.266	0.254	0.049	0.051	0.084	0.231
Min:		0.085	0.029	0.112	0.157		0.012	0.138	0.144	0.113	0.110	0.112	0.108	0.117	0.121	0.011	0.014	0.021	0.112
Max:		0.325	0.154	0.440	0.409		0.122	0.440	0.378	0.443	0.437	0.443	0.432	0.442	0.441	0.106	0.103	0.121	0.392

		Zonal Summed Ventilation Flow Rates							Measured Room Ventilation Flow Rates												
Test ID	OAT	Total	Total*	2ndFlr	2ndFlr*	1stFlr	1stFlr*	Bsmnt	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]
0209F	-16.4	45.21	38.48	6.48	3.81	20.23	16.18	18.50	2.04	12.93	5.57	3.89	3.82	4.15	3.79	0.52	4.05	0.87	0.41	0.48	2.67
0118F	-13.5	22.26	22.26	1.83	1.83	8.08	8.08	12.35	0.91	8.10	4.25	1.79	1.69	2.19	1.98	0.43		0.33	0.25	0.34	
0111F	-12.6	25.65	25.65	3.67	3.67	8.58	8.58	13.40	1.09	8.90	4.50	2.00	1.95	2.24	2.05	0.34		0.43	0.23	0.35	
0222F	-8.1	32.16	27.26	4.90	3.01	15.48	12.48	11.77	1.35	8.28	3.49	2.94	3.00	3.14	2.96	0.43	3.00	0.64	0.49	0.54	1.89
1129F	-1.0	14.35	14.35	1.52	1.52	4.80	4.80	8.02	0.34	5.43	2.60	1.14	1.13	1.21	1.12	0.20		0.09	0.10	0.13	
1207F	2.0	17.09	17.09	2.51	2.51	5.98	5.98	8.60	0.53	5.90	2.70	1.53	1.46	1.43	1.35	0.21		0.21	0.30	0.40	
0411F	5.5	20.78	17.43	3.90	2.50	9.77	7.82	7.11	1.22	4.99	2.13	1.93	1.91	1.95	1.78	0.23	1.95	0.35	0.36	0.57	1.40
1117F	8.4	12.45	12.45	1.26	1.26	4.09	4.09	7.09	0.25	4.80	2.29	0.99	0.96	1.05	0.95	0.14		0.09	0.08	0.10	
0518F	12.2	26.13	21.72	5.68	3.80	12.88	10.35	7.57	2.45	5.24	2.32	2.51	2.47	2.62	2.44	0.31	2.53	0.65	0.29	0.41	1.88
0509F	13.2	14.75	12.87	2.29	1.53	5.54	4.42	6.92	0.46	4.61	2.31	1.04	1.05	1.10	1.05	0.18	1.11	0.16	0.37	0.54	0.76
0511F	14.6	16.97	14.77	3.24	2.39	6.98	5.63	6.75	0.68	4.06	2.69	1.11	1.09	1.43	1.55	0.46	1.35	0.56	0.64	0.51	0.85
Averages:		22.53	20.39	3.39	2.53	9.31	8.04	9.83	1.03	6.66	3.17	1.90	1.87	2.05	1.91	0.32	2.33	0.40	0.32	0.40	1.58
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		0.35	0.31	0.14	0.10	0.37	0.32	0.66	0.10	0.67	0.63	0.38	0.37	0.41	0.38	0.06		0.08	0.06	0.08	
Min/Req't:		0.19	0.19	0.05	0.05	0.16	0.16	0.45	0.03	0.41	0.43	0.20	0.19	0.21	0.19	0.03		0.02	0.02	0.02	
Max/Req't:		0.70	0.59	0.26	0.15	0.81	0.65	1.23	0.24	1.29	1.11	0.78	0.76	0.83	0.76	0.10		0.17	0.13	0.11	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.

Table B-7
SUMMARY OF SINGLE TRACER GAS TEST RESULTS FOR CONFIGURATION G

		Zonal Average Air Change Rates					Measured Room Air Change Rates												
Test ID	OAT	Total	2ndFlr	1stFlr	Bsmnt	OAT	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[C]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]	[ac/h]
0209G	-18.6	0.232	0.233	0.230	0.233	-18.6	0.235	0.230	0.235	0.221	0.230	0.234	0.233	0.229	0.236	0.230	0.232	0.232	0.234
0110G	-14.6	0.207	0.204	0.205	0.219	-14.6	0.201	0.201	0.238	0.204	0.205	0.207	0.195	0.212		0.200	0.207	0.207	
0112G	-10.8	0.207	0.203	0.204	0.221	-10.8	0.206	0.216	0.226	0.204	0.207	0.201	0.202	0.205		0.203	0.202	0.201	
0309G	-1.3	0.161	0.161	0.157	0.174	-1.3	0.157	0.163	0.185	0.161	0.155	0.156	0.156	0.163	0.150	0.166	0.161	0.166	0.157
1206G	2.0	0.136	0.131	0.132	0.158	2.0	0.130	0.131	0.184	0.134	0.132	0.129	0.131	0.132		0.130	0.133	0.133	
1118G	4.6	0.125	0.125	0.125	0.126	4.6	0.127	0.126	0.125	0.126	0.129	0.122	0.124	0.124		0.121	0.126	0.124	
0411G	8.3	0.138	0.138	0.133	0.155	8.3	0.131	0.144	0.165	0.131	0.132	0.137	0.131	0.138	0.130	0.136	0.142	0.147	0.135
0427G	9.8	0.092	0.093	0.094	0.083	9.8	0.094	0.083	0.083	0.095	0.091	0.094	0.096	0.091	0.096	0.093	0.092	0.091	0.094
0510G	10.6	0.126	0.126	0.126	0.124	10.6	0.126	0.127	0.121	0.124	0.128	0.128	0.126	0.125	0.126	0.125	0.126	0.128	0.126
0419G	14.4	0.182	0.181	0.182	0.183	14.4	0.180	0.179	0.187	0.183	0.179	0.185	0.184	0.177	0.185	0.182	0.180	0.180	0.183
Averages:		0.161	0.159	0.159	0.167	0.4	0.159	0.160	0.175	0.158	0.159	0.159	0.158	0.160	0.154	0.159	0.160	0.161	0.155
Min:		0.092	0.093	0.094	0.083		0.094	0.083	0.083	0.095	0.091	0.094	0.096	0.091	0.096	0.093	0.092	0.091	0.094
Max:		0.232	0.233	0.230	0.233		0.235	0.230	0.238	0.221	0.230	0.234	0.233	0.229	0.236	0.230	0.232	0.232	0.234

		Zonal Summed Ventilation Flow Rates							Measured Room Ventilation Flow Rates												
Test ID	OAT	Total	Total*	2ndFlr	2ndFlr*	1stFlr	1stFlr*	Bsmnt	MB	BT	UT	DR	KT	LR	FR	PR	H1	B2	B3	2B	H2
	[C]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]	[L/s]
0209G	-18.6	31.61	27.84	10.75	9.16	10.63	8.45	10.23	4.72	6.76	3.47	1.94	2.01	2.20	2.04	0.27	2.17	1.89	1.45	1.09	1.59
0110G	-14.6	24.85	24.85	7.95	7.95	7.48	7.48	9.41	4.04	5.91	3.50	1.79	1.79	1.94	1.71	0.25		1.64	1.29	0.97	
0112G	-10.8	25.19	25.19	8.02	8.02	7.51	7.51	9.66	4.15	6.33	3.33	1.79	1.81	1.89	1.78	0.24		1.67	1.26	0.95	
0309G	-1.3	22.06	19.61	7.37	6.29	7.17	5.80	7.52	3.15	4.79	2.73	1.42	1.35	1.47	1.37	0.19	1.37	1.36	1.01	0.78	1.07
1206G	2.0	16.53	16.53	5.13	5.13	4.84	4.84	6.56	2.61	3.84	2.72	1.18	1.15	1.21	1.15	0.16		1.07	0.83	0.63	
1118G	4.6	15.07	15.07	4.92	4.92	4.61	4.61	5.54	2.55	3.70	1.84	1.10	1.13	1.14	1.08	0.15		1.00	0.79	0.58	
0411G	8.3	19.01	16.89	6.24	5.32	6.10	4.90	6.66	2.63	4.22	2.44	1.15	1.15	1.29	1.15	0.16	1.20	1.11	0.89	0.69	0.92
0427G	9.8	12.33	10.80	4.31	3.67	4.35	3.47	3.67	1.90	2.44	1.22	0.83	0.80	0.88	0.85	0.11	0.88	0.77	0.68	0.43	0.64
0510G	10.6	17.12	15.11	5.79	4.94	5.82	4.67	5.51	2.53	3.73	1.78	1.09	1.11	1.21	1.11	0.16	1.15	1.03	0.79	0.59	0.86
0419G	14.4	24.77	21.82	8.34	7.09	8.43	6.73	8.01	3.62	5.26	2.75	1.61	1.56	1.73	1.61	0.21	1.70	1.49	1.12	0.85	1.25
Averages:		20.85	19.37	6.88	6.25	6.69	5.85	7.28	3.19	4.70	2.58	1.39	1.39	1.50	1.38	0.19	1.41	1.30	1.00	0.76	1.06
Requirement:		65.00	65.00	25.00	25.00	25.00	25.00	15.00	10.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	
Avg/Req't:		0.32	0.30	0.28	0.25	0.27	0.23	0.49	0.32	0.47	0.52	0.28	0.28	0.30	0.28	0.04		0.26	0.20	0.15	
Min/Req't:		0.19	0.17	0.17	0.15	0.17	0.14	0.24	0.19	0.24	0.24	0.17	0.16	0.18	0.17	0.02		0.15	0.12	0.09	
Max/Req't:		0.49	0.43	0.43	0.37	0.43	0.34	0.68	0.47	0.68	0.70	0.39	0.40	0.44	0.41	0.05		0.38	0.29	0.22	

* Total* [L/s] excludes H1 and H2. 2ndFlr* [L/s] excludes H2. 1stFlr* [L/s] excludes H1.