VENTILATION CONTROL IN MEDIUM AIR TIGHTNESS HOUSES

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This housing research project had three major objectives. The first objective was to determine information on air pollutant source strengths in 20 houses of medium (between 2 and 7 air changes per hour at 50 pascals) air tightness; a second objective was to determine the appropriateness of the proposed changes to the 1995 Building Code related to ventilation and house depressurization; a third objective was to field test in four houses an exhaust-only ventilation system that is controlled based on the outdoor air temperature, and to perform computer modelling on this ventilation scheme.

Pollutant source measurements in the 20 Saskatoon houses included formaldehyde, 26 volatile organic chemicals, relative humidity, and carbon dioxide. In addition, average air change rates were measured over a seven day period using the perfluorocarbon tracer technique.

The formaldehyde readings in the houses averaged 0.034 ppm, and 19 out of the 20 houses measured below the Health Canada guideline of 0.1 ppm. In addition, 19 out of the 20 houses were able to meet the 0.05 ppm Health Canada target for new houses.

The sum of the twenty-six VOCs sampled in the houses averaged 127 micrograms/m^3. D-limonene was the chemical that registered highest in 13 out of the 20 houses. No standards exist for VOCs in houses, although a tentative European standard of 300 $\mu g/m^3$ for Total VOCs has been suggested. The Total VOCs (TVOCs) normally would exceed the sum of the twenty-six VOCs that were measured in this study. In the proposed European standard, no one chemical should represent more than 30 $\mu g/m^3$. Thirteen of the 20 houses had individual VOCs that exceeded 30 $\mu g/m^3$.

Relative humidity measurements in the houses averaged 35%, with values varying between a low of 18% and a high of 64%. If only those measurements that were taken in winter are counted, the maximum relative humidity was 47%. Seven of the 15 houses with winter relative humidity measurements were found to be below the value of 30% relative humidity recommended by Health Canada Guidelines.

Carbon dioxide values, based on two spot measurements in each of the 20 houses, averaged 708 ppm, with the highest value equal to 1127 ppm. These measurements were all made in the living room of the houses during the daytime. All of the houses used forced warm air heating systems fuelled by natural gas. The ASHRAE 62-89 standard recommends a maximum value of 1000 ppm; the Health Canada guideline allows a maximum value of 3500 ppm.

Air change rates measured in 19 of the 20 houses varied from a low of 0.08 air changes per hour to a high of 0.43 ac/h. The average air change rate was 0.20 ac/h. The average air tightness of the 20 houses was 2.61 ac/h at 50 Pa.

Eighteen of the 20 houses tested were able to meet the CGSB backdrafting standard of 5 pascals for intermittent operation of fans. The two houses unable to meet the standard had range hood fans with flows of 110 and 120 L/s.

On 17 of the 20 houses tested, the chimneys were able to establish flow when an exhaust flow of 90 L/s was placed on the houses using a blower door fan. The value of 90 L/s was the threshold value originally proposed for the 1995 National Building Code. Below 90 L/s of ventilation flow, an exhaust only system could be used. Above 90 L/s, a supply fan would be required to provide pressure balance. In subsequent revisions to the NBC, the value was lowered to 75 L/s.

The average total exhaust flow due to bathroom exhaust fans, range fans, clothes dryers and other exhaust fans in the houses was equal to 66.6 L/s, with the clothes dryers having an average flow of 39.4 L/s. The highest measured flow from a single fan amounted to 120 L/s from a range fan.

The Outdoor Temperature Controlled Ventilation (OTCV) systems were installed and monitored in 4 houses. The monitoring period extended for a 12 week period from April through June, 1994. Air flows between 28 and 34 L/s were used for the exhaust fans. The outdoor temperature threshold above which the exhaust fan would operate for the four houses ranged between 6.0°C and 8.5°C. Compared to natural ventilation, the OTCV strategy was found to reduce indoor carbon dioxide levels in the houses by an average of 239 ppm in the four houses over the monitoring period. Using computer simulation with the HOT-2000 program, the increase in annual space heating energy associated with OTCV was estimated to range from 1.1 to 2.6% for the four houses tested.

Based on these measured results, the OTCV systems shows considerable promise in improving indoor air quality in houses in the medium air tightness range with only small incremental increases in annual space heating requirements.

RÉSUMÉ

Ce projet de recherche dans le domaine du logement visait trois principaux objectifs. D'abord, il fallait recueillir des données sur les concentrations des sources de pollution de l'air dans 20 maisons moyennement étanches à l'air (c'est-à-dire présentant un taux de renouvellement d'air se situant entre 2 et 7 r.a./h à 50 pascals). Ensuite, on devait déterminer la pertinence des changements proposés au Code national du bâtiment de 1995 concernant la ventilation et la dépressurisation des maisons. Enfin, il s'agissait de mettre à l'essai, dans quatre maisons, un système de ventilation à extraction d'air seulement régulée en fonction de la température de l'air extérieur et procéder à une modélisation informatique de ce mode de ventilation.

Les mesures des sources de polluants prises dans les 20 maisons de Saskatoon ont porté sur le formaldéhyde, 26 composés organiques volatils, l'humidité relative et le dioxyde de carbone. De plus, les taux de renouvellement d'air moyens ont été mesurés sur une période de sept jours au moyen de la technique du perfluocarbone traceur.

Les lectures du formaldéhyde dans les maisons ont atteint en moyenne 0,034 ppm, et 19 des 20 maisons affichaient une concentration inférieure à la directive de Santé Canada établie à 0,1 ppm. En outre, 19 maisons sur 20 ont pu atteindre le niveau cible de 0,05 ppm de Santé Canada relatif aux maisons neuves.

Ensemble, les 26 COV prélevés dans les maisons présentaient une concentration moyenne de 127 microgrammes/m³. Le D-limonène est la substance chimique qui a enregistré la valeur la plus élevée dans 13 des 20 maisons. Aucune norme ne régit les COV dans les habitations, bien qu'en Europe on ait déjà proposé une norme de 300 µg/m³ pour les émissions totales de COV. Normalement, les émissions totales de COV (COVT) devraient excéder la somme des 26 COV mesurés lors de cette étude. Dans la norme européenne proposée, aucune substance chimique ne devrait avoir à elle seule une concentration supérieure à 30 µg/m³. Or, 13 des 20 maisons affichaient des concentrations excédant 30 µg/m³ pour des COV pris seuls.

L'humidité relative mesurée dans les maisons a atteint en moyenne 35 %, les valeurs variant d'un minimum de 18 % à un maximum de 64 %. Si l'on ne prend en considération que les mesures prises en hiver, l'humidité relative maximale atteint 47 %. Sept maisons, sur les 15 dont les valeurs d'humidité relative ont été mesurées en hiver, ont obtenu un pourcentage d'humidité relative inférieur aux 30 % recommandés par Santé Canada.

Les valeurs du dioxyde de carbone, fondées sur deux mesures ponctuelles réalisées dans chacune des 20 maisons, ont atteint en moyenne 708 ppm, la plus haute étant 1 127 ppm. Ces mesures ont toutes été prises dans le séjour des maisons durant le jour. Toutes les maisons étaient dotées d'une installation de chauffage à air chaud pulsé alimentée au gaz naturel. La norme ASHRAE 62-89 recommande une valeur maximale de 1 000 ppm, alors que la directive de Santé Canada tolère une valeur maximale de 3 500 ppm.

Les taux de renouvellement d'air mesurés dans 19 des 20 maisons variaient d'un taux plancher de 0,08 r.a./h à un plafond de 0,43 r.a./h, le taux moyen étant 0,20 r.a./h. L'étanchéité à l'air moyenne des 20 maisons était de 2,61 r.a./h à 50 Pa.

Dix-huit des 20 maisons mises à l'essai ont pu satisfaire à la norme de refoulement de l'ONGC, relativement au fonctionnement intermittent des ventilateurs, établie à 5 pascals. Les deux maisons où la norme n'était pas observée étaient pourvues d'une hotte de cuisinière offrant un débit de 110 L/s et de 120 L/s respectivement.

Dans 17 des 20 maisons étudiées, les cheminées étaient en mesure d'établir le tirage lorsqu'un débit d'extraction de 90 L/s était imposé aux maisons au moyen d'un ventilateur à débit contrôlé. La valeur de 90 L/s constitue la valeur seuil initialement proposée pour le Code national du bâtiment de 1995. À un débit de ventilation inférieur à 90 L/s, il serait possible d'utiliser une installation à extraction d'air seulement. Par contre, à un débit de ventilation supérieur à 90 L/s, il faudrait avoir recours à un ventilateur de soufflage pour équilibrer la pression. Toutefois,lors de révisions subséquentes du CNB, cette valeur a été abaissée à 75 L/s.

Le débit d'extraction total moyen engendré par les ventilateurs de salle de bains, les hottes de cuisinière, les sécheuses et autres ventilateurs d'extraction utilisés dans les maisons a atteint 66,6 L/s, les sécheuses affichant un débit moyen de 39,4 L/s. Le débit le plus élevé mesuré pour un seul ventilateur a été de 120 L/s; il s'agissait d'une hotte de cuisinière.

Des systèmes à ventilation régulée en fonction de la température extérieure ont été installés et contrôlés dans 4 maisons. La période de contrôle s'est étalée sur 12 semaines, soit du mois d'avril au mois de juin 1994. Des débits d'air variant de 28 à 34 L/s ont été utilisés pour les ventilateurs d'extraction. Le seuil de température extérieure mettant en marche le ventilateur d'extraction des quatre maisons oscillait entre 6,0 °C et 8,5 °C. Comparativement à la ventilation naturelle, la stratégie faisant appel aux systèmes à ventilation régulée en fonction de la température extérieure a été en mesure de réduire les concentrations intérieures de dioxyde de carbone dans les quatre maisons, selon une valeur moyenne de 239 ppm durant la période de contrôle. Grâce au logiciel de simulation HOT-2000, on a pu estimer l'augmentation annuelle de la consommation énergétique requise pour le chauffage des locaux dotés d'un système à ventilation régulée en fonction de la température extérieure à une valeur variant entre 1,1 % et 2,6 % pour les quatre maisons d'essai.

Ces résultats laissent entrevoir un avenir prometteur pour les systèmes à ventilation régulée en fonction de la température extérieure dans l'amélioration de la qualité de l'air des habitations moyennement étanches à l'air au prix d'une augmentation minime de la consommation énergétique requise pour le chauffage des locaux.

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1.0 INTRODUCTION

This project involved a study of ventilation control on 20 houses with medium air tightness. For the purposes of this project, a house with medium air tightness was defined as one having air tightness levels between approximately 2 and 7 air changes per hour at 50 pascals (Pa) when tested using the CGSB Standard CAN/CGSB-149.10-M86. The R-2000 standard for houses is 1.5 air changes/hour at 50 Pa. Parameters tested included ventilation, indoor air quality, backdrafting potential, and related parameters.

The proposed 1995 National Building Code has the following sentences in 9.32.3.7. Protection Against Depressurization:

1. Except as provided in Sentence (8), in a dwelling unit which is located in an area where soil gas is deemed to be a problem or which contains a fuel fired appliance which is required to be vented and is vented through a chimney, any exhausting device, or group of devices operated by a single control, with a net exhaust capacity >90 L/s shall be provided with make-up air.

2. Where make-up air is required to reduce the net exhaust capacity of an air exhausting device to comply with Sentence (1), make-up air shall be provided by a supply fan rated to deliver make-up air at a rate equal to not less than the amount by which the net exhaust rate of the device exceeds 90 L/s and not more than that amount plus 90 L/s.

3. The supply fan required by Sentence (2) shall be wired so that it is activated whenever the device which is required by Sentence (1) to be supplied with make-up air is activated.

After this project began, the draft code was changed to lower the flow from 90 L/s to 75 L/s.

Most Canadian homes will have a code requirement for less than 75 litres per second (L/s) of mechanical ventilation air and yet they will still be prone to depressurization by the exhaust air system. The exhaust air system could backdraft combustion equipment such as furnaces and water heaters. A key piece of information to be gained in this project was how much depressurization will be caused by exhaust-only ventilation systems in medium air tightness houses and to what extent this depressurization will cause combustion equipment such as furnaces and water heaters to backdraft and degrade the air quality in the houses.

A summary of research worked carried out on the topic of combustion venting failures is contained in a 1987 report (Scanada Sheltair Consortium, 1987).

In this project, information on the physical characteristics of 20 houses with medium air tightness levels was also gathered to provide inputs to the HOT 2000 computer program (Version 6.02).

A review of several recent residential ventilation studies conducted in Canada was carried out as part of this project.

In four of the 20 houses, a study was conducted on the operation of an outdoor temperature controlled ventilation (OTCV) system. The systems were installed and commissioned in four houses, and the operation of the systems monitored for 12 weeks from April to June of 1994. In the OTCV mode the mechanical ventilation system would run only when the outdoor temperature was above a certain threshold. The intent of this ventilation scheme was to provide supplementary ventilation to the houses during periods when the natural ventilation provided by inside-outside temperature differences was reduced.

2.0 OBJECTIVES

One objective of this project was to present information on the variation and frequency of air pollutant source strengths in 20 houses.

A second objective was to determine the appropriateness of the proposed changes to the 1995 Building Code related to ventilation and house depressurization.

A third objective was to field test an exhaust-only ventilation system that is controlled based on the outdoor air temperature, and to perform computer modelling on the ventilation control scheme.

3.0 METHODOLOGY

3.1 Evaluation of 20 houses for ventilation, indoor air quality and related parameters.

Twenty houses with forced warm air heating systems and expected air tightness levels between approximately 2 and 7 air changes per hour (ac/h) at 50 pascals had the following information gathered: (The twenty houses were chosen to ensure that at least seven of the houses were in the range of 2 to 3 ac/h at 50 Pa.)

i. Mechanical ventilation system performance: air flows were measured using a pressure-balanced flow grid on all fans providing either supply or exhaust ventilation. These fans included bathroom fans, kitchen fans, central vacuum cleaners, clothes dryers and central exhaust fans.

ii. Air tightness testing using both the CGSB 149 protocol and a single pressure point test. A calibrated Minneapolis Blower Door™ was used.

iii. HOT 2000 computer analysis of each house using the version 6.02.

iv. Measurement of the neutral pressure plane height in four of the houses. This measurement was performed to accurately predict the amount of depressurization required to backdraft the chimney. A digital micromanometer was used to measure the indoor-outdoor pressure difference at four different heights in the houses. A software program was used to check the validity of the slope of the pressure difference versus height best fit line, based on the temperatures inside and outside, and the atmospheric pressure. This test was done on the four houses which have the OTCV systems and datalogging equipment.

v. Measurement of the amount of whole house exhaust flow and the pressure difference required to cause the combustion equipment to backdraft. The Minneapolis Blower Door™ was be used to create the negative pressure.

There are three types of backdrafting that can occur. One type occurs when the combustion appliances are not firing. In this condition, the chimney can be backdrafted with only a few pascals of negative pressure, and the only products of combustion that enter the house are those from one or more pilot lights, in the case of natural gas or propane fired equipment. The second condition occurs when the chimney is already in a reverse flow mode and the appliances are started and attempt to establish flow up the chimney. The latter condition is generally more serious, in that large amounts of combustion products can spill into the house. Because of the seriousness of this condition, testing for this condition was performed on the full complement of 20 houses so as to develop a larger data base of information on this topic. The information will be of use in determining if the levels of allowable exhaust-only ventilation flow proposed for the 1995 Code in Sentence 9.32.3.7 (1) (Protection Against Depressurization) are appropriate.

The third condition occurs when the appliances are firing normally with flow up the chimney. If a strong negative pressure is created in the house, the chimney will backdraft.

vi. Pollutant source strength measurements.

Pollutant source strength were performed by simultaneous pollutant concentration and air change rate measurement. The following pollutants were measured:

a. Formaldehyde using a passive sampler (AQRI) with a seven day exposure time.

b. Volatile organic chemicals (3M passive sampler) with a seven day exposure time. The sampler was analyzed using a gas chromatograph/mass spectrometer by Bovar-Concord Environmental. This was the technique used in the recent study of 44 houses in Ontario and Saskatchewan (Dumont, 1992). A listing of 26 compounds measured was provided by the analysis company along with the concentrations measured. The 26 compounds were recommended by a Health Canada staff person (Otson, 1990).

c. Indoor temperature and relative humidity. A clock driven hygrothermograph was used to determine both indoor temperature and relative humidity over the one week interval that the indoor air quality measurements were taken. The hygrothermograph uses a hair-element device for relative humidity measurement. The relative humidity sensing elements were calibrated against a wet and dry bulb psychrometer at two humidity levels--approximately 50% rh and 20% rh. The accuracy of the hygrothermograph was about $\pm$ 5% in absolute terms.

d. Carbon dioxide. Spot readings were taken twice by using air sample balloons and a Beckman Non-Dispersive Infrared $C0_2$ analyser, once at the start of the one-week interval, and once at the end. The analyzer was calibrated using a calibration gas with a known concentration of CO_2, and a gas scrubber to provide a zero reading calibration. A survey of sensor companies was done to determine if a seven day passive CO_2 sensor was available, but none was found.

e. Air change rates were measured using the perfluorocarbon tracer (PFT) technique and equipment supplied by Brookhaven Laboratories, New York (seven day test period). For the 20 houses measured, the average air change rate was 0.20 ac/h.

f. Carbon monoxide. Gastec tube readings were performed as an extra in the contract in 15 of the 20 houses. The readings were taken adjacent to the furnaces. None of the houses had natural gas stoves, which are a potential source of carbon monoxide. Only one house had a CO reading (7 ppm) that was detectible using the GASTEC tubes.

Pollutant measurements were compared with those found in existing literature.

3.2 *Outdoor Temperature Controlled Ventilation*

i. A consolidation of research findings from previous trials by Sibbitt, Dumont, Lemire and Lind was performed. The ventilation system design and control strategy for the OTCV was established based on previous field trials, CSA F326, and residential indoor air quality guidelines. An important additional consideration was to avoid chimney backdrafting when the major exhaust air sources in the houses such as clothes dryers, kitchen, bathroom and other exhaust fans were in operation.

ii. A total of four houses were selected from the group of 20 houses for trials of the OTCV and for monitoring. An individual system was designed for each of the four houses. A key parameter was the outside temperature above which the ventilation system would run continuously. Three of the houses used forced warm air heating; the fourth house was modified to simulate the use of baseboard heating. On the fourth house, a dedicated ventilation system for the master bedroom was developed using a low noise, low electrical power fan to provide ventilation air to the room when the door to the bedroom was closed. To minimize permanent alteration to the house during the testing, the fan was mounted on a temporary door which replaced the existing door to the bedroom for the test period. The fan would operate only when the door was closed. A nitrous oxide tracer gas measurement was used on a one-time basis to measure the air change in the bedroom with the door closed and the fan running, and also when the door was closed and the fan was not running.

The dataloggers were installed in two of the houses in December 1993 with the final two installations performed in February of 1994. Telaire™ continuous reading $C0_2$ monitors were calibrated in the laboratory using a two point calibration prior to the field installation. The accuracy of the Telaire Units is estimated at about ± 100 ppm.

3.3 *Consolidation of Research Findings from recent residential ventilation research studies in Canada.*

Four recent studies supported by Canada Mortgage and Housing dealing with various aspects of residential ventilation were analyzed.

Ventilation in houses with forced air heating systems

The first was a study (Dumont, 1992) of ventilation in 4 houses built between 1983 and 1986 with mechanical ventilation systems which were expected to meet the CSA F326 Mechanical Ventilation Requirements.

The air tightness of these four detached houses varied from 0.68 ac/h at 50 pascals to 2.2 ac/h at 50 Pa. Two of the houses had central exhaust systems; two had balanced flow air to air heat exchangers. All four of the houses used forced air heating systems.

The ventilation systems were tested for air flow, individual room flows, duct leakage, electrical energy consumption of the fans and house depressurization levels.

The main findings of the study were as follows:

1. Quantities of ventilation air measured at the fans and HRVs were sufficient to provide at least 0.3 ac/h in three of the four houses. However, distribution of the air was less than ideal because of leakage problems in the ducts.

2. Significant air leakage was found in the warm air heating system ducts, particularly on the return air side. As a consequence, distribution of the ventilation air throughout the houses was less than ideal. In one house only 9% of the return air passed through the return air grilles; the remainder of the air entered through duct leakage. Air leakage in the return air systems varied from 27% to 91% in the four houses. Ventilation air distribution in the basements was likely poor, as most of the supply air from the warm air system was provided at the ceiling and returned to the warm air system via leakage into the return air ducts at the ceiling level. Stratification of cool air on the floor in the basement of one house was a problem, likely caused by poor room air distribution. The cold air returns at the floor level in the basement were ineffective because of duct leakage. As no detailed tracer gas measurements were made in the basement rooms, a calculation of ventilation effectiveness was not performed.

3. Significant air leakage was found on those ventilation systems using galvanized ductwork without sealing measures. On one system using galvanized ductwork only 56% of the air exhausted from the fan passed through the exhaust air grilles; the remainder entered through duct leakage. Dramatically lower air leakage rates were found with systems that used flexible ductwork. The disadvantage of flexible ductwork is the greater pressure drop for the same duct diameter and length. However, in systems with a substantial number of elbows, the flexible ductwork may have advantages because of the lower leakage rate and ease of installation.

4. Noise levels from fans can be a problem. Rigid mounting techniques along with inflexible connections to rigid ductwork are likely to cause problems, particularly at the low frequencies. Only two of the four houses could meet the ASHRAE Recommended Noise Criterion of NC 30 or less.

5. Dust and dirt accumulation on continuously running fans is likely to be a problem both in terms of reducing air flow and in increasing noise levels from fans. All of the fans used in the study were forward curved centrifugal fans. On one of the fans that had run continuously for about seven years without a filter, there was an accumulation of about 6 mm of dirt on the fan rotor. Because of dirt buildup the fan flow had reduced from 63 to 39 L/s. Filtration systems and methods of easy access to the fans for cleaning should be incorporated.

6. Electrical energy consumption of the fans in the warm air heating system and in the ventilation fans was substantial. The electrical power consumption of the warm air furnace fans varied from 247 to 556 watts on high speed; on low speed the power consumption of the two furnace fans incorporating two-speed motors was 185 and 187 watts. The efficiency of one of the fan-motor combinations was measured; the value calculated was 12.5%.

7. The electrical power consumption of the ventilation fans varied from 66 watts to 138 watts on high speed. Although efficiency of the fans was not presented, the efficiency of the ventilation fans would likely be as low or lower than the 12.5% measured with the furnace fan.

Performance of Ventilation Systems in Electric Baseboard Heated Houses

This study (Lind, 1993) focussed on ventilation systems and control strategies in several electric baseboard heated houses in a maritime climate of Nova Scotia.

Ventilation systems were installed in five houses without forced air heating systems or combustion appliances. The objectives were to test the systems for air flows, electrical consumption and noise generation, to demonstrate the applicability and acceptability of different control strategies, and to measure the distribution of ventilation air in houses with a partially ducted, exhaust-only ventilation strategy.

The ventilation systems were two central exhaust-only, two balanced heat recovery ventilators and one central exhaust and central supply with tempering by recirculated air. The operating air flow rates were set to approximately one-half of the CSA F326 capacity requirements by means of various control strategies. Three control strategies were investigated: time-of-day controls, dehumidistat controls, and control based on outside temperature (fan set to run only when the outside temperature was above a -5°C setpoint).

The houses had air tightness levels between 3.4 and 4.1 ac/h at 50 Pa, roughly similar to that of recent standard Nova Scotia construction. The ductwork was galvanized with joints taped with duct tape, but with the duct seams not taped.

The ductwork was installed to HRAI recommendations.

Some of the findings from the study were as follows:

1. Time-of-day control received favourable occupant reaction. This control operated morning and evening for a total of eight hours per day at three times the design flow. (The design flow was set at about one-half of the CSA F326 flow capacity rates.) The other two control mechanisms received less favourable reaction. The outdoor temperature based control system flow rate was set at only one-third the flow rate of the time-of-day control. With this low flow rate, the flows seemed too low for the occupants. The judgment of the authors was that the dehumidistat control was not adequate: "Consideration should also be given to the suggestion that the dehumidistat is so problematical in the moist climates of Atlantic Canada and the Pacific Coast that it should no longer be named in the NBC as part of a residential ventilation system."

2. Two bedrooms with closed doors and no fan assisted air supply or exhaust flows experienced air changes of only 0.96 L/s when tested using a tracer gas. The CSA F326 recommended capacity flows are 10 L/s for a master bedroom and 5 L/s for all other bedrooms.

3. The systems generally operated within ASHRAE noise guidelines of NC 30, with problems arising from fan noise in two houses exceeding this limit. In one house the fan housing was in contact with the framing of the house. It was recommended that, as is currently done with HRV units, the fans be vibrationally isolated and the manufacturer be encouraged to provide specific recommendations for vibrationally isolating the fans. The author also recommended that fans not be located near sleeping and other noise-sensitive areas of the house.

4. Ventilation rates lower than the CSA F326 recommended capacity do seem to be adequate for most purposes in the houses tested. However, no measurements of indoor air pollutants were performed in the houses.

Low-Cost Ventilation Systems without heat recovery

This report (Sibbitt and Hamlin, 1991) investigated eight low capital cost residential ventilation systems not incorporating heat recovery. Systems for electric baseboard heated houses and for forced warm-air heated houses were installed, commissioned and tested for air flow and air change rates. In addition, simulations were used to evaluate several different ventilation system configurations, with various occupancies and building leakage characteristics.

Conclusions from the study included the following:

1. Generally, upgraded bathroom exhaust fans and kitchen range hoods that exhaust directly to outdoors are an effective way of providing the required exhaust capacity. Upgrading is required to avoid noise and durability problems.

2. For houses without a fresh air distribution system the addition of a limited distribution system, employing small diameter ducts, or small fan units, appear to be viable options for ventilation air supply to rooms. Direct supply distribution does not appear to be necessary for rooms that are open to one another when one of them is exhausted.

3. Second floor passive inlets for ventilation air through outside walls may stagnate under some normal operating conditions due to stack effect and wind, and therefore do not constitute a reliable ventilation system option.

4. In houses with forced air distribution systems, the addition of a central fan-powered outside air supply system is a relatively simple undertaking. Recirculation rates as low as 0.5 ac/h appear to be adequate for good outside air supply distribution.

5. A novel air exhaust system incorporating a combined function exhaust-air-fan/draft-inducing combustion gas exhaust fan on the furnace appears to be a promising option for houses with one or more natural draft heating appliances. Appropriate regulatory approvals must still be obtained before this approach may be used outside of the lab.

6. Examination of continuous CO_2 measurements in two mechanically ventilated houses suggested that the outside air supply rates specified by the CSA F326 Ventilation Standard provide good control of this contaminant.

The study adds weight to the evidence that houses will suffer poor air quality in rooms that have closed doors and do not have provisions for either the supply or exhaust of air from these rooms. The study also found that houses with continuously running warm air distribution systems generally have a spatially uniform rate of air change; i.e., the house can be treated as one zone. Duct leakage was mentioned as a problem in achieving F326 required air flows in one of the houses with a ducted ventilation air supply system.

Noise Level Measurements in Residential Ventilation

A study (Lemire, 1993) was completed on the subject of noise from residential ventilation fans used on heat recovery ventilators. A comparison was made between noise levels measured in a laboratory setting and in the field. The noise study was done on two heat recovery ventilators using the sections of the CSA-C260 Standard relating to noise measurements.

One of the main findings was that the test procedure contained in the CSA-C260 standard is not always appropriate given that much of the sound radiated from the fan equipment is emitted not from the fan apparatus or heat recovery ventilator itself but from the grilles on the ducts. The testing also found that the sound power radiated from the fans was strongly dependent on the configuration of the ductwork and the isolation of the ductwork from the fan. A modified test procedure developed by Quirt of the Institute for Research in Construction at the National Research Council was used. The method was found to give good agreement between the laboratory and the field measurements.

3.4 Development of an outdoor temperature controlled ventilation system for 4 houses.

A total of four houses were selected from the group of 20 houses for study of the outdoor temperature controlled ventilation (OTCV) system. The basic idea of OTCV is to provide mechanical ventilation only during times of the year when the outdoor temperature is above a certain value.

For illustration purposes, the estimated air change for a naturally ventilated house located in Saskatoon is presented in figure 1, as calculated by the HOT 2000 computer program. Windows and doors are assumed to be closed throughout the 12 months. As can be seen, the natural air change rate varies from month to month, with greater values in the colder months. By adding a mechanical ventilation system which operates only above a certain outdoor temperature threshold, the ventilation rate in the warmer months can be increased. Two important parameters to select for OTCV on a particular house are the rate of ventilation in litres/second from the mechanical fan and the outdoor temperature above which the fan will operate.

In figure 2, a plot of monthly average temperatures for Saskatoon is presented. As can be seen, the months of the year with average temperatures above 0°C are April through October. For these months, the air change rate of the house will be down substantially when naturally ventilated. Thus it would seem reasonable to set the OTCV threshold temperature somewhere in the range around 0-10°C for Saskatoon climate conditions.
The rate of ventilation to be chosen for a house with OTCV can be chosen from a number of perspectives. One of the simplest criteria is to use the capacity rates in the CSA F326 Standard. For a typical house 3 bedroom house with an unfinished basement the recommended rate is about 70 L/s, or about 0.5 air changes per hour in a 100 m^2 bungalow with a 100 m^2 basement area. As mentioned in the study by Lind (Lind, 1993), however, such a flow rate will often result in complaints about high energy consumption and dryness in typical occupancy houses unless a humidifier is used. Because each of

the four houses in this study had atmospheric vented combustion appliances and clothes dryers vented to the outside, there was a concern that use of the CSA F326 recommended rates would cause chimney backdrafting when the clothes dryers were operating. For these two reasons, the flow rates were set at approximately one-half the CSA F326 recommended rates. Each of the fans was a single speed unit. For speed control a variable voltage transformer was used with each of the fans. (The fans were all permanent split capacitor forward-curved centrifugal units.) The mechanical ventilation air change rates chosen for the OTCV were as follows:

House Code	OTCV fan flow L/s	Equivalent ac/h based on total interior volume of house	Ratio of OTCV flow to CSA F326 recommended flow
P94-1	28	0.21	0.35
P94-3	37	0.29	0.53
P94-5	34	0.25	0.43
P94-13	34	0.23	0.49

Table 1. Mechanical Ventilation Rates Chosen for OTCV

Because the basement ceilings of the four houses were finished, it would have been very difficult to place ductwork to each bathroom and kitchen. For the 12 week test period, a simplified system was used. The OTCV fan was connected in the basement to the return air system of the warm air furnace. Flexible ducts of 150 mm diameter were connected from the return air system to the exhaust fan, and the exhaust fan was connected by a flexible duct to the outdoors. A temporary piece of plywood was installed in the basement window opening, and the duct passed to the outside through the plywood. The outdoor temperature sensor for the OTCV was a filled-bulb sensor which was placed above ground level outdoors in a radiant shield to minimize solar radiation effects. A sketch of a typical system is presented in figure 3.

The temperature settings used for the OTCV threshold were as follows for each of the houses:

HOUSE	°C
P94-1	6.5
P94-3	8.5
P94-5	6.8
P94-13	6.0

Table 2. Temperature Settings for OTCV Controllers

There was a dead band of about 1°C in the temperature controller that was used (Penn Model A19ABC-24C). The fans used on three of the houses were recently-introduced centrifugal fans made by the Panasonic Company. The fans were chosen based on the manufacturer's claims of low noise and low electrical energy consumption. For the FV-20VQ units, the manufacturer's literature states a free air delivery of 104 L/s, a flow of 73 L/s at a static pressure of 50 Pa, a power consumption of 33 watts, and a noise level of 1.5 sones. The cost of each fan was $245 U.S. On the fourth house, a smaller centrifugal fan made by the Penn Ventilator Company was used. This fan has a free air delivery flow of 62 L/s, a power consumption of 30 watts, and a low noise level comparable to the Panasonic fans.

On house number P94-1, the master bedroom was altered to simulate the use of baseboard heating. The floor register for the warm air heating system was blocked and an electric baseboard heater was placed in the room. A temporary dedicated air exchange system for the bedroom was developed by placing a small (rotor diameter of 114 mm), low noise (1800 rpm), low flow (26 L/s) fan (Dayton Axial Flow Fan No. 4C548) in the top of a temporary door to the room. The fan would operate only when the door was closed. Measurements were made of the air exchange rates in the room using a nitrous oxide tracer gas system in the decay mode with two different room conditions: one, with the door closed and the fan off, and two, with the door closed and the fan running. The sound level of the fan was measured using a dBA meter (Bruel and Kjaer Type 2215).

The four houses were run in three modes of ventilation:

a. Natural ventilation, i.e. no mechanical ventilation (normal operating mode of the house.)

b. Continuous mechanical ventilation using the centrifugal exhaust fans as shown in figure 3.

c. Outdoor temperature controlled ventilation.

The houses were monitored for a minimum of 12 weeks, or four weeks in each of the three modes. Each mode was run for one week at a time. The first cycle began on April 7, 1994, and the testing ran until June 30, 1994. A summary of the testing done on the four houses is shown in Table 3.

WEEK 1								
HOUSE	MODE	MEASUREMENTS						
	NATURAL VENTILATION	PFT 7d	HCOH 7d	Rn 7d	VOC 1d	CO_2 CONT	ENERGY CONT	RH CONT
P94-1	✓	✓	✓	✓	✓	✓	✓	✓
P94-3	✓	✓	✓	✓	✓	✓	✓	✓
P94-5	✓	✓	✓		✓	✓	✓	✓
P94-13	✓	✓	✓		✓	✓	✓	✓

WEEK 2					
HOUSE	MODE	MEASUREMENTS			
	CONTINUOUS VENTILATION	Rn 7d	CO_2 CONT	ENERGY CONT	RH CONT
P94-1	✓	✓	✓	✓	✓
P94-3	✓	✓	✓	✓	✓
P94-5	✓		✓	✓	✓
P94-13	✓		✓	✓	✓

WEEK 3					
HOUSE	MEASUREMENTS				
	OTCV	Rn 7d	CO_2 CONT	ENERGY CONT	RH CONT
P94-1	✓	✓	✓	✓	✓
P94-3	✓	✓	✓	✓	✓
P94-5	✓		✓	✓	✓
P94-13	✓		✓	✓	✓

1 d = one day average
7 d = seven day average
CONT = continuous data logging

Table 3. Tests performed in four houses with OTCV system.
(The cycle of the tests in weeks one, two and three would be repeated a total of four times over a 12 week period. In cycles 2, 3 and 4, the PFT, HCOH and VOCs were not repeated for cost reasons.)

The following parameters were monitored in the houses with OTCV systems. Except where noted, the parameters were logged using a Sciemetric data logger attached to an IBM compatible personal computer:

i. Energy consumption.

A relay was added to the space heating thermostat for the house in order to measure the on-time of the furnace. The natural gas consumption rate of the furnace was calibrated using the natural gas meter for the house and the amount of time taken to consume 4 ft^3 of natural gas. Manual readings were also taken each week of the utility-supplied natural gas and electricity meters.

ii. Ventilation rate.

Because of the high cost of the PFT tests ($290 per test), the ventilation rate was only measured one time in each of the four houses in the natural ventilation mode.

iii. Indoor air quality.

a. Relative humidity and indoor temperature.

A Vaisala RH Sensor (Model No. HMD 20U) and a type T thermocouple were used to measure indoor conditions. The RH sensor and the thermocouple were placed adjacent to the carbon dioxide monitor in the living room of the house. The RH sensor was calibrated using a saturated salt solution apparatus.

b. Carbon dioxide

A Telaire unit (Catalog No. 1050) with continuous readout was used. The voltage output was monitored by the data logger. The unit was calibrated with calibration gases.

c. Radon daughters

Thomson and Nielsen Radon Sniffers were placed in houses P94-1 and P94-3. These units have a liquid crystal display, and were read manually once per week. Calibration checks were performed and new filters installed every week.

iv. Outdoor air temperature and relative humidity.

Outdoor air temperatures were measured at each house using a type T thermocouples with a radiation shield. On one house a Vaisala sensor (Model No. HMD 20U) was used to measure exterior relative humidity.

v. On-time of the ventilation system.

A relay connected to the fan provided a contact closure that served as an on-time signal to the data logger.

vi. Sound levels

Sound level measurements were conducted at a distance of 1 meter from the fans. On one of the houses a detailed sound pressure level measurement was made over the frequency bands from 63 to 8,000 hz.

vii. A questionnaire with four questions related to the occupants' perception of the OTCV system was administered in each of the four houses.

An agreement was made to remediate where feasible any of the houses where health limit guidelines were exceeded. However, none of the residences exceeded the Health Canada Residential Indoor Air Quality Guidelines (Health Canada, 1989)

3.5 Computer Simulation

The AQ1 (Indoor Air Quality Analysis in Detached Residences) and HOT 2000 computer programs were to be calibrated to approximate the performance of the four houses with OTCVs.

A special version of the HOT 2000 program (Version 6.03) was used to estimate the effect of using the OTCV system. The computer program allows one to select the outdoor temperature threshold and the flow rate of the OTCV system. The effect on air change rates and annual space heating consumption in the four OTCV houses were modelled using version 6.03. Version 7 of HOT 2000, now on the market also incorporates the OTCV capability.

4.0 RESULTS

4.1 *Evaluation of 20 houses for ventilation, indoor air quality, air tightness and backdrafting. The results of this testing are presented in Table 3.*

a. Age of houses, and space heating type (Table 3a).

The year of construction of the houses dated from 1921 to 1990. The average year of construction was 1970. All the houses were located in Saskatoon and were heated with natural gas forced air heating systems. All the houses had chimneys connected to the natural gas furnaces and/or water heaters. Two of the houses (P94-7 and P94-18) used induced draft or pulse combustion furnaces. These two houses, however, used natural draft gas water heaters.

House Code	Year Built	Volume (m3)	Number of Occupants	House Type	Furnace Type (Natural Gas)
P94-1	1957	485	4	Bungalow	Standard with pilot
P94-2	1983	537	4	4 Level split	Standard with spark ignition
P94-3	1965	467	3	Bungalow	Standard with pilot
P94-4	1980	842	6	Bungalow	Standard with pilot
P94-5	1986	491	4	Bungalow	Standard with pilot
P94-6	1964	440	2	Bungalow	Standard with pilot
P94-7	1990	528	2	4 Level split	Induced draft and glow ignition
P94-8	1959	445	3	Bungalow	Standard with pilot
P94-9	1980	626	4	Raised bungalow	Standard with pilot
P94-10	1968	424	2	Bungalow	Standard with pilot
P94-11	1982	558	5	4 Level split	Standard with pilot
P94-12	1977	574	4	Bungalow	Standard with pilot
P94-13	1957	539	1	4 Level split	Standard with pilot
P94-14	1978	614	4	2 Storey	Standard with pilot
P94-15	1972	386	4	Bungalow	Standard with pilot
P94-16	1990	718	2	2 Storey	Standard with pilot
P94-17	1957	456	3	Raised bungalow	Standard with pilot
P94-18	1957	461	2	Bungalow	Sealed combustion
P94-19	1921	468	1	2 Storey	Standard with pilot
P94-20	1978	645	3	2 Storey	Standard with pilot
Average=	1970	535	3.2		
Maximum=	1990	842	6		
Minimum=	1921	386	1		
S.D.=	16	111	1.3		

Table 3a. House Characteristics

b. Air tightness of houses (Table 3b).

The air tightness of the houses averaged 2.61 air changes/hour at 50 Pa. The houses in the sample were tighter than expected. None of the houses were R-2000 certified, and yet 3 out of the 20 houses had air tightness readings less than the R-2000 standard of 1.5 ac/h at 50 Pa.

House Code	Air-tightness Test (ac/h @50 Pa)	Normalized Leakage Area (cm2/m2)	Chimney Height (m)	Top of Chimney-Height Above Grade (m)	Wind Speed (km/h)	Indoor Temp. (Deg.C)	Outdoor Temp. (Deg.C)	Station Pressure (kPa)
P94-1	2.59	1.377	5.60	5.66	7	20.0	-2.5	96.4
P94-2	2.65	1.072	6.40	6.29	4	22.0	-29.0	95.5
P94-3	2.74	1.137	5.40	5.40	21	21.0	-2.0	96.3
P94-4	1.26	0.549	5.82	6.13	15	20.0	-6.0	94.3
P94-5	1.65	0.721	5.49	5.58	9	19.0	-10.0	95.7
P94-6	3.80	1.501	5.47	5.32	11	20.0	-10.0	96.6
P94-7	1.75	0.704	6.33	6.69	7	19.0	-7.0	96.3
P94-8	3.53	1.491	5.90	6.13	0	20.5	-28.4	94.8
P94-9	2.23	0.950	6.25	7.06	28	15.0	-24.0	95.3
P94-10	3.04	1.214	5.34	5.27	6	18.9	-21.0	95.7
P94-11	3.34	1.411	6.12	5.64	15	17.0	-10.0	94.8
P94-12	2.19	0.948	5.93	5.68	5	19.5	-32.5	94.9
P94-13	3.29	1.220	5.22	5.38	26	18.0	-21.2	97.2
P94-14	1.41	0.737	7.64	7.47	17	21.0	-16.0	95.6
P94-15	4.08	1.713	5.12	5.08	6	20.0	-4.0	96.0
P94-16	1.81	0.845	7.77	7.89	15	22.5	18.0	94.6
P94-17	2.77	1.231	5.45	5.05	22	22.0	12.2	95.9
P94-18	1.40	0.496	5.07	5.51	10	23.0	5.0	96.0
P94-19	3.25	0.921	7.45	8.18	4	22.0	-1.0	96.6
P94-20	3.47	1.671	7.92	8.10	7	20.0	6.0	95.3
Average=	2.61	1.095	6.08	6.18	11.8	20.0	-9.2	95.7
Maximum	4.08	1.713	7.92	8.18	28.0	23.0	18.0	97.2
Minimum=	1.26	0.496	5.07	5.05	0.0	15.0	-32.5	94.3
S.D.=	0.86	0.361	0.92	1.03	7.8	1.9	13.9	0.8

Table 3b. House air tightness values

c. Exhaust air devices in the houses (Table 3c).

The average of the sum of the exhaust air device flows in each of the 20 houses was 66.6 L/s, with values ranging from a low of 32 L/s to a high of 165 L/s. The clothes dryer flows were generally the highest, with an average measured flow of 39.4 L/s. The bathroom exhaust fans had an average of 11.0 L/s . Only two of the 20 houses had a kitchen range hood which exhausted to outdoors. The remaining houses had either no range hood or recirculating range hoods.

House Code	EXHAUST AIR DEVICES (Flows in L/s) Bathroom Exhaust Fans 1	2	3	Total Bathroom Fans	Kitchen Range Hood	Clothes Dryer	Other Fans	Total Fans
P94-1	--	--	--		Recirc.	34.9	--	34.9
P94-2	--	--	--		Connected to central exhaust	33.7	1.2	34.9
P94-3	14.0	15.0	--	29.0	--	39.7	--	68.7
P94-4	16.5	16.5	--	33.0	--	43.2	43.0	119.2
P94-5	8.4	4.2	--	12.6	--	29.2	--	41.8
P94-6	19.0	25.5	--	44.5	--	Vents into house	--	44.5
P94-7	9.8	18.6	--	28.4	--	27.2	--	55.6
P94-8	13.0	--	--	13.0	--	40.1	--	53.1
P94-9	15.2	13.7	5.1	34.0	Recirc.	51.3	--	85.3
P94-10	--	--	--		Recirc.	33.0	--	33.0
P94-11	14.0	14.3	14.0	42.3	Recirc.	Vents into house	--	42.3
P94-12	8.4	11.1	--	19.5	--	34.9	--	54.4
P94-13	--	--	--		--	63.2	--	63.2
P94-14	14.3	13.3	--	27.6	Recirc.	32.6	--	60.2
P94-15	0.0	--	--	0.0	120	44.6	--	164.6
P94-16	50.3	--	--	50.3	--	36.3	--	86.6
P94-17	13.0	--	--	13.0	--	44.4	--	57.4
P94-18	--	--	--		110	32.0	--	142.3
P94-19	--	--	--		--	51.2	--	51.2
P94-20	--	--	--		--	38.2	--	38.2
Average=	11.5	10.2	9.6	26.7	115	39.4	22.1	66.6
Maximum	50.3	25.5	14.0	50.3	120	63.2	43.0	164.6
Minimum	0.0	4.2	5.1	0.0	110	27.2	1.2	33.0
S.D.=	13.2	5.5	6.3	14.6	6.9	8.8	29.6	36.5

Table 3c. Exhaust air devices

d. HOT 2000 takeoff using Version 6.02 of the program.

Physical measurements were taken of the houses, and the information entered into Version 6.02 of the program. The air tightness of the house, along with the number of occupants were also entered. The printouts of the HOT 2000 runs are presented in Appendix 1. A computer disk with the HOT 2000 runs is also available. A summary of the volumes, house types, design heat loss and projected annual space heating of the houses is presented in Table 4.

House Code	House Volume (m3)	House Type	Annual Space Heating (GJ)	Design Heat Loss at -35 deg. C (kW)
P94-1	485.2	Bungalow	160.2	12.8
P94-2	537.0	Split level	80.3	9.4
P94-3	467.4	Bungalow	202.9	13.6
P94-4	842.0	Bungalow	226.0	13.3
P94-5	490.7	Bungalow	120.6	7.5
P94-6	439.6	Bungalow	182.4	12.1
P94-7	527.6	Split level	122.1	15.7
P94-8	444.6	Bungalow	197.2	13.3
P94-9	626.1	Bi-level	213.1	16.3
P94-10	423.6	Bungalow	136.3	10.7
P94-11	557.6	Split level	161.6	11.6
P94-12	573.5	Bungalow	158.1	11.2
P94-13	539.0	Split level	237.6	17.1
P94-14	614.0	Two storey	121.8	10.4
P94-15	385.6	Bungalow	188.9	12.7
P94-16	718.3	Two storey	238.1	17.2
P94-17	456.1	Bi-level	289.1	16.2
P94-18	460.7	Bungalow	96.7	10.1
P94-19	467.5	Two storey	201.5	15.7
P94-20	645.2	Two storey	266.1	18.7
Average=	535.1		180.0	13.3

Table 4. Summary of HOT 2000 Computer Runs

A plot of the average annual air change per hour for each house (as calculated by HOT 2000 program) as a function of the air tightness of the houses is presented in figure 4. There is a fair amount of scatter in the data in the lower ranges. The major reason for this is that Version 6.02 of the HOT 2000 program assigns a fixed value for the air flow up the atmospheric-vented furnace chimney, if a chimney is specified as part of the heating system. On two of the tighter houses there are no atmospheric-vented chimneys. Version 7.0 of the program will use a more detailed model of the house-furnace combination that varies the chimney air flow depending on the air tightness of the house.

The authors (Dumont and Snodgrass, 1990) have measured air flows up the chimney on an atmospheric-vented natural gas furnace with a pilot light. Air flows of about 20 L/s up the chimney were measured with the furnace gas burners off, and about 28 L/s were measured with the furnace burners on. The furnace was a 32.2 kW input unit connected to a 127 mm diameter B vent chimney in a single storey house. At the time of measurement, the outdoor temperature was -12°C.

e. Measurement of the neutral pressure plane of the four houses with OTCV systems.

Plots of the indoor-outdoor pressure differences in the houses are presented in figures 5 to 8. The height at which a zero pressure difference occurs is the neutral pressure plane. The outdoor ground level is used as the reference height.

A summary of the neutral pressure level measured in the four houses is presented in Table 5.

House Code	Neutral Pressure Level (m)	Height of top floor ceiling above grade (m)	Ratio of NPL to top floor ceiling height
P94-1	3.94	3.26	1.21
P94-3	3.69	3.19	1.16
P94-5	3.38	3.19	1.06
P94-13	3.78	4.20	0.90

Table 5. Location of Neutral Pressure Levels

In three of the four houses, the neutral pressure level was located above the top floor ceiling. Thus the entire occupied part of these houses was at a negative pressure relative to outdoors. The relatively tight building envelopes along with atmospheric vented chimneys tend to result in high neutral pressure levels.

f. Backdrafting experiment.

Four tests were performed on the 20 houses. The test results are presented in Table 6.

1. *CGSB Test*

The first test was a test to the CGSB 51.71-M Protocol: "A method to determine the potential for pressure-induced spillage from vented, fuel-fired space heating appliances, water heaters and fireplaces. Sixth Draft February, 1994."

Because the authors of this report were not aware of this protocol at the time of the test measurements, a mathematical procedure was used in conjunction with the measured exhaust fan flows and the air tightness of the house in the unsealed condition to estimate the pressure difference caused by the exhaust fans. An airtightness test for the house can be expressed by the following equation:

$$Q = C\,\Delta P^{\,n} \qquad (1)$$

where Q = air flow (L/s)
C = flow coefficient ($L/s \cdot Pa^n$)
ΔP = pressure difference (Pa)
n = flow exponent

Solving the above equation for ΔP

$$\Delta P \;=\; 10 \uparrow (\log\,(Q/C)/n) \qquad (2)$$

The CGSB protocol requires the following fans to be turned on:

1. All exhaust fans and soil gas system fans intended for continuous use.
2. Continuous air supply system (e.g. a furnace blower designed to operate on low speed, with a fresh air inlet duct connected to the return air plenum).
3. The clothes dryer if it exhausts outdoors.
4. The kitchen exhaust fan if it exhausts outdoors.
5. All other exhaust devices rated at more than 75 L/s.

If an open fireplace (one that does not have glass, steel or ceramic doors that can be closed during fireplace operation) is present, the fireplace shall be operated.

The depressurization limits for combustion appliances with draft hoods or relief openings is 5 pascals for both the continuous pressure limit (dealing with fans 1 and 2 in the CGSB protocol) and the intermittent pressure limit (dealing with fans 1 through 5 and open fireplaces).

The appropriate exhaust fan flows and the air tightness characteristics of the 20 houses were input to equation 2 to calculate the depressurization that would occur. This depressurization value was then compared with the limit of 5 pascals in the CGSB standard. In table 6, the pressure changes caused by fans are calculated in the second column. Two houses, P94-95 and P94-18, failed the 5 pascal test. Both houses had relatively large kitchen range hood fans exhausting to the outdoors with flows of 120 and 110 L/s respectively. As house P94-18 was considerably tighter than house P94-15, the pressure change caused by the exhaust fans was -32.6 pascals.

House Code	Pressure change caused by CGSB Test (Pa)	Pass or Fail CGSB Test	Pressure change required to backdraft cold chimney (Pa)	Pressure change required to backdraft hot chimney (Pa)	Airtightness Test (C) (L/s-Pa^n)	Airtightness Test Exponent (n)
P94-1	-1.5	Pass	-6.6	-20.2	25.9	0.719
P94-2	-1.0	Pass	-10.9	-25.7	34.7	0.653
P94-3	-2.5	Pass	-6.3	-17.0	18.9	0.798
P94-4	-1.6	Pass	-6.9	-15.9	31.9	0.627
P94-5	-1.5	Pass	-5.0	-25.0	21.8	0.717
P94-6	0.0	Pass	-7.3	-14.4	32.2	0.713
P94-7	-1.6	Pass	-5.7	-17.0	19.3	0.738
P94-8	-1.4	Pass	-8.9	-22.9	31.8	0.685
P94-9	-2.5	Pass	-8.8	-27.3	26.3	0.741
P94-10	-1.0	Pass	-7.0	-20.6	33.0	0.653
P94-11	0.0	Pass	-7.5	-23.9	25.0	0.798
P94-12	-1.1	Pass	-10.7	-27.0	32.9	0.669
P94-13	-2.8	Pass	-8.8	-18.4	27.8	0.793
P94-14	-1.8	Pass	-11.0	-30.2	22.5	0.663
P94-15	-10.4	* Fail	-4.6	-18.1	32.7	0.691
P94-16	-2.0	Pass	-3.0	-29.8	21.8	0.737
P94-17	-1.3	Pass	-5.5	-18.4	36.9	0.620
P94-18	-32.6	* Fail	-4.9	-14.8	10.5	0.749
P94-19	-2.2	Pass	-7.2	-25.1	27.8	0.761
P94-20	-0.8	Pass	-5.4	-22.0	45.8	0.693
Average=	-3.48		-7.10	-21.69	28.0	0.71
Maximum	0.00		-3.00	-14.40	45.8	0.80
Minimum=	-32.62		-11.00	-30.20	10.5	0.62
S.D.=	7.00		2.15	4.79	7.6	0.05

Table 6. CGSB and other Backdrafting Tests

2. Backdraft test with burners off

The amount of negative pressure required to backdraft the chimney when the gas burners on the furnace (or water heaters, for houses P94-7 and P94-18) were not on was recorded. The negative pressure increase needed to backdraft the chimneys averaged 7.1 Pa.

3. Backdraft test with gas burners on

The amount of exhaust air flow and the negative pressure required to backdraft the chimney when the gas burners on the furnace (or water heater, for houses P94-7 and P94-18) were on was recorded. For this condition the negative pressure increase needed to backdraft the chimneys averaged to 21.7 Pa.

4. Test with 90 L/s of exhaust flow

An exhaust flow of 90 L/s was impressed on each of the houses. The gas burners on the furnace (or the water heater, for houses P94-7 and P94-18) were turned on, and a visual check was made to see if the chimney flow would establish itself properly. The results were that 17 out of the 20 houses were able to establish flow eventually. However, various time delays were present with a number of the 17 houses.

g. Pollutant source strength measurements.

In Table 7, the pollutant levels measured in the 20 houses are presented.

House Code	HCHO (ppm)	VOC Sum (ug/m3)	Highest Individual VOC (name, conc.) (ug/m3)	Average Outdoor Temp. During Test Period (deg C)	Indoor conditions RH Aver. (%)	RH Max. (%)	RH Min. (%)	Temp. Aver. (C)	Temp. Max. (C)	Temp. Min. (C)	Carbon Dioxide (start) (ppm)	Carbon Dioxide (finish) (ppm)	Air Exchange PFT (ac/h)	Carbon Monoxide in Furnace Room (ppm)
P94-1	0.022	155.8	d-limonene, 88.6	7.8	37	40	31	24	27	23	608	875	0.08	<5
P94-2	0.018	112.8	d-limonene, 63.8	-11.7	31	35	28	20	23	16	583	581	0.08	
P94-3	0.020	146.7	d-limonene, 60.7	-20.3	32	35	29	19	21	18	747	700	0.12	
P94-4	0.041	104.9	d-limonene, 31.2	-3.0	28	31	27	25	28	16	1060	828	0.09	<5
P94-5	0.036	151.4	d-limonene, 47.8	-12.0	38	43	36	18	23	16	853	521	0.11	7
P94-6	<0.01	61.9	d-limonene, 24.4	-14.3	23	28	21	21	24	18	561	493	0.25	
P94-7	0.025	100.2	Pinene, 52.4	-15.1	22	25	18	17	23	14	493	415	0.28	<5
P94-8	0.032	56.9	Toluene, 12.7	-25.4	38	47	31	19	22	17	552	441	0.43	
P94-9	0.029	199.1	n-hexane, 59.4	-28.3	25	30	20	18	22	12	594	570	0.28	<5
P94-10	0.015	57.2	d-limonene, 13.5	-28.1	27	29	25	17	19	15	870	654	0.31	<5
P94-11	0.039	64.1	d-limonene, 17.4	-20.3	18	28	12	17	26	10	586	677	0.34	<5
P94-12	0.045	188.1	d-limonene, 70.1	-17.4	32	38	29	22	26	19	960	596	0.25	<5
P94-13	0.030	53.3	Dichloromethane, 15.3	-17.9	19	22	17	19	21	16	660	515	0.17	<5
P94-14	0.039	209.1	Toluene, 52.9	-18.9	27	31	25	21	23	17	610	678	0.21	<5
P94-15	0.032	165.4	d-limonene, 92.4	-1.3	42	45	38	20	26	16	790	755	0.13	<5
P94-16	0.120	314.5	a-pinene, 107.8	15.0	48	53	42	23	27	19	1000	862		<5
P94-17	0.015	29.4	d-limonene, 6.0	12.9	42	48	39	23	26	20	720	806	0.16	<5
P94-18	0.039	128.8	d-limonene, 52.5	5.5	58	63	49	21	23	19	994	1127	0.09	<5
P94-19	0.028	135.4	n-decane, 27.1	5.5	43	45	38	23	25	21	1022	555	0.22	<5
P94-20	0.047	108.4	d-limonene, 37.7	4.2	64	75	59	20	22	18	735	670	0.18	<5
Average=	0.034	127.2			35	39	31	20	24	17	749.9	666.0	0.20	
Maximum	0.120	314.5			64	75	59	25	28	23	1060	1127	0.43	
Minimum=	<0.01	29.4			18	22	12	17	19	10	493	415	0.08	
S.D.=	0.023	66.7			12	13	11	2	2	3	177.8	169.0	0.10	

Table 7. Formaldehyde, VOC, Relative Humidity, Carbon Dioxide, Air Change and Carbon Monoxide Readings

i. Formaldehyde levels

The average value for the houses was 0.034 ppm, with the highest reading equal to 0.12 ppm. The Health Canada Guideline is 0.10 ppm, with the target guideline for new houses equal to 0.05 ppm. Nineteen of the 20 houses were able to meet the 0.05 ppm guideline.

ii. Volatile organic compounds.

A list of the quantitative value of each of the 26 compounds measured in each house is provided in Appendix 2. A listing of the sum of the 26 compounds in each of the houses is presented in Table 8.

Limonene was the compound with the highest concentration in 13 of the 20 houses. Toluene was the chemical with the highest value in 2 of the 20 houses.

The average of the sum of the 26 compounds for the 20 houses was equal to 127 micrograms per cubic metre ($\mu g/m^3$). This number may be compared with the value found in a study (Dumont, 1992) of 44 houses in Saskatoon and Tillsonburg, Ontario. For these houses, the sum of the 26 compounds was equal to 245 $\mu g/m^3$ measured using an identical protocol done by the same analysis company. For that study, the average for the Total Volatile Organic Compounds (TVOC) was equal to 554 $\mu g/m^3$.

A likely reason that lower VOC readings were found in the present study of 20 houses was that most of the homes in this study were older.

The reason that the sum of the 26 compounds does not equal the TVOC value is two-fold. In most houses there are additional chemical compounds present in the air which contribute to the TVOC value. In addition the TVOC value is calculated using an averaged response from the chromatograms using the response of toluene as the reference response.

There is no Canadian residential guideline for Volatile Organic Compounds.

In Europe, there is a proposed standard (Health Canada, 1993) for TVOC of 300 $\mu g/m^3$ for office environments. In that standard, no single VOC should exceed 30 $\mu g/m^3$. Thirteen of the 20 houses surveyed had at least one VOC with a value exceeding 30 $\mu g/m^3$.

iii. Relative humidity.

The average value for the relative humidity in the 20 houses using hygrothermographs was equal to 35%, with 8 of the twenty houses below 30%.

The average outdoor temperature during the times that the relative humidity measurements were taken are presented in Table 7.

The Health Canada Residential Guideline recommends values of 30% to 55% relative humidity in winter unless constrained by window condensation. In the summer period, the acceptable range is from 30% to 80%.

iv. Carbon dioxide

The average of the two readings of carbon dioxide in each house was equal to 750 ppm for the first measurement, and 666 ppm for the second measurement, with the maximum reading in one house equal to 1127 ppm. Normal outdoor readings are about 350 ppm.

The Health Canada Residential Guideline recommends values less than 3500 ppm. All of the houses had values less than this number.

The ASHRAE Standard 62-1989 (ASHRAE, 1989) recommends levels less than 1000 ppm, with the footnote that this level is not considered a health risk, but is a surrogate for human comfort (odor). Four of the twenty houses had readings above 1000 ppm. However, it is unlikely that the testing protocol used for CO_2 (mid-day, mid-house) would yield the highest CO_2 concentrations that could be found in these houses.

h. Air change rates

The air change readings for 19 of the 20 houses averaged 0.20 ac/h, with a maximum of 0.43 ac/h and a minimum of 0.08 ac/h. The analysis for the PFTs took approximately nine months to be done.

i. Carbon monoxide

Carbon monoxide readings were taken in 15 of the 20 houses. In one of the 15 houses, the CO level measured in the furnace room was 7 ppm. The Canadian ASTER guidelines are 11 ppm for an eight hour exposure and 25 ppm for one hour exposure. The homeowner was advised of the high reading and corrective action initiated.

4.2 Outdoor Temperature Controlled Ventilation

House with baseboard heating

In house P94-1, the use of baseboard heating was simulated in the master bedroom by blocking the warm air register and installing an electric baseboard heater. To provide ventilation air from the rest of the house, an axial fan was placed in the door for the room. The centre of the fan was located 100 mm below the top of the door, and the fan flow was into the bedroom.

The results of the testing of the ventilation in the room were as follows:

1. Room air change rate with door closed.

The room was first tested for air exchange with the door and windows closed and the fan covered temporarily with tape. Nitrous oxide was used as a tracer gas. The door was closed and the room filled with tracer gas. The tracer gas was mixed, and the decay of the gas monitored on a Miran 1B analyzer. The air change rate was essentially zero. (In 50 minutes the nitrous oxide level fell from 488 to 486 ppm.) At the time of the measurements, the outside air temperature was 20°C and the temperature in the bedroom was 22°C.

2. The husband and wife then slept in the room with the door closed. The carbon dioxide level in the room was measured with a Telaire unit. In figure 9, a plot of the carbon dioxide level in the room is presented. The couple went to bed at 22:30 hours and closed the door. As can be seen, the carbon dioxide level in the room increased rapidly, reaching a value of 2500 ppm at 24:30 hours. At that time the room was getting so "stuffy" and "uncomfortable" that the occupants could no longer tolerate having the door closed. The door was then opened and the occupants were able to sleep. In figure 10 a plot of the carbon dioxide level in the family room on the same floor is presented along with carbon dioxide level in the master bedroom.

3. Room air change with the door closed and the air exchange fan operating.

The door mounted fan was placed in operation with the door closed. The tracer gas was mixed and the decay of the gas monitored. For this condition, the air change rate was equal to 1.2 ac/h. The room volume was 31.1 m^3. Thus the fan driven flow was equal to 10.4 L/s. The axial flow fan has a nominal flow capacity of 25.9 L/s, but the flow output was reduced for noise reasons to the 10.4 L/s value. The fan was mounted in a hollow core door, and vibration from the fan at high speed was disturbing to the occupants of the room. At high speed the noise level measured at a 1 metre distance from the fan was 37 dBA. At a reduced flow rate of 10.4 L/s the noise output fell to 26 dBA. The background noise in the bedroom with the fan off was 21 dBA.

The house was operated with the bedroom fan running for 11 days. A plot of the CO_2 levels in both the master bedroom and the family room is presented in figure 11. Also shown are the inside and outside temperatures over the test period. As can be seen, the CO_2 levels in the master bedroom are higher than those in the family room. However, they did not reach the level of 2500 ppm found with the fan not running.

On day 197 the bedroom door was left open and the axial flow fan turned off. Natural convection air change through the open door greatly reduced the difference in CO_2 levels between the bedroom and the family room. This effect can be seen in figure 11.

Based on the measured increase in CO_2 levels, when the door fan was in operation, it would have been desirable to have a greater air exchange rate between the master bedroom and the rest of the house. A level of about 10 L/s per occupant or 20 L/s for the room (a figure similar to the 10 L/s of outside air per person suggested in the ASHRAE 62-89 standard for a number of occupancies) would have helped reduce the CO_2 levels in the bedroom relative to the family room.

Space heating energy consumption

The four houses were run using three different modes of ventilation: natural ventilation, OTCV ventilation and continuous ventilation. The systems were in place for a total of 12 weeks in each house in the months of April, May and June 1994.

The expected relationship between type of ventilation and space heating energy consumption was not found in this experiment. Normally one would expect that the space heating energy consumption would increase during the period that the ventilation system was operating. However, the outdoor temperature was not similar during the different weeks when the ventilation systems were operating. The space heating consumption of the furnaces in the houses is not directly proportional to the temperature difference between inside and outside. Internal heat gains from appliances, lights, and occupants, and solar gains from windows serve to reduce the need for space heating from the furnace in warmer weather.

As the weather became warmer in the months of May and June, the weekly space heating energy consumption was zero or near zero in most of the houses.

A greater number of weekly tests would be needed to better test the effect of the ventilation system on the space heating energy consumption.

Indoor air quality

i. Relative Humidity and Temperature

A plot of the outdoor temperature and relative humidity over the 12 week period is presented in figure 12.

Plots of the indoor relative humidity and indoor temperature for each of the 4 houses over the 12 week period are presented in figures 13 to 16. As can be seen from the figures, the indoor relative humidity started to trend upward in the houses at about day 140. Outdoor peak relative humidities (figure 12) began to rise a few days earlier.

ii. Carbon dioxide levels

Plots of the carbon dioxide levels in the houses over the 12 week monitoring period are presented in figures 17 to 20. Also shown on the figures are the percentage on-time values of the OTCV fan. Periods with continuous zero fan on-time correspond to the natural ventilation test modes. The first week of testing, beginning on day 97, began with natural ventilation. The second week in the cycle represented OTCV, and the third week represented continuous ventilation. The data was recorded hourly; hence some values for the fan on-time register as less than 100%, as the fan in the OTCV mode may have been on for less than a full hour. On House P94-5, an electrical noise problem in the house, perhaps related to a grounding problem with a number of circuits, caused some electrical interference with the fan on-time signal, as can be seen from figure 19.

For the three modes of ventilation, the average CO_2 levels are presented in Table 9.

	P94-1	P94-3	P94-5	P94-13
Natural Ventilation	1056	812	736	621
OTCV	734	609	485	443
Continuous Ventilation	705	644	484	476
Number of occupants Adults Children	 4 0	 3 0	 2 2	 1 0

Table 9. Average Carbon Dioxide Levels in Houses with Three Modes of Ventilation (ppm)

As can be seen, the carbon dioxide levels were highest during the periods of natural ventilation and lower during the periods of OTCV and continuous ventilation. A probable reason that the continuous ventilation did not always produce lower carbon dioxide readings than the OTCV ventilation in the four houses is as follows:

The tests on the four houses were carried out in relatively mild weather (April to June); as a consequence, the OTCV mode often resulted in similar fan run times as the continuous ventilation mode. Variations in the number of hours of occupancy during the various testing periods for the different modes of ventilation could then have accounted for the relatively small increases in CO_2 levels during the continuous ventilation mode as compared with the OTCV mode. In houses P94-3 and P94-13, the OTCV mode resulted in a slight decrease in CO_2 levels compared to the continuous ventilation mode.

Source strength for carbon dioxide will vary with the number of occupants. As can be seen from Table 9, the house (P94-1) with the greatest number of adults had the highest CO_2 levels under all 3 modes of ventilation. The house with the lowest number of adults (P94-13) had the lowest CO_2 levels under all three modes of ventilation. The effect of visitors on CO_2 levels can also be pronounced. As shown in figure 20, the CO_2 levels for house P94-13 were relatively high between days 97 and 100. During this time, visitors were in the house for the Easter holiday period.

iv. Radon levels

On two of the houses the radon daughters were measured on a weekly average basis. The results are presented in Table 10.

The following formula (Thomson and Neilsen, 1988) was used to convert the working level measurements of Radon daughters to an equilibrium equivalent concentration of Radon.

$$1 \text{ Bq/m}^3 = 2.7 \times 10^{-4} \text{ working levels}$$

As can be seen from the table, the radon levels were lowest for the case of continuous ventilation, and highest for the case of natural ventilation in both houses. Both of the houses had radon readings that were well below the Canadian standard of 800 Bq/m^3 for existing houses, and also well below the U.S. EPA standard of 148 Bq/m^3.

Week number	Ventilation mode	P94-1	P94-3
		Radon level (Bq/m^3)	Radon level (Bq/m^3)
1	Natural	10.3	---
2	Continuous	8.0	17.6
3	OTCV	9.2	28.3
4	Natural	14.1	32.6
5	Continuous	5.7	27.5
6	OTCV	4.1	25.1
7	Natural	4.7	28.0
8	Continuous	3.3	24.1
9	OTCV	4.1	25.7
10	Natural	3.8	25.3
11	Continuous	4.4	26.1
12	OTCV	3.7	22.4
Averages: Natural Continuous OTCV		 8.2 5.3 5.3	 28.6 23.8 25.4

Table 10. Average Radon Levels in Houses Using Three Modes of Ventilation

v. Sound level measurements

The spatial averages of three sound level measurements taken at a 1 metre radial distance from OTCV the ventilation fans in the four houses were as follows:

House Code	Fan Type	Sound Levels	
		Fan On dBA	Fan Off dBA
P94-1	Penn	30.5	28.9
P94-3	Panasonic	29.8	28.5
P94-5	Panasonic	30.0	28.7
P94-13	Panasonic	30.9	28.8

Table 11. Sound Level Measurements

The increase in sound levels in the room with the fans operating was very small. Normally an increase of three decibels is required before the change in sound level is noticeable.

The computer driven data loggers were located in the same room as the fans. The noise from the hard disk drives on the computers exceeded the noise from the fans in each of the four houses. At the time of the above sound level measurements, the computers were turned off.

With the fans set to maximum speed, the sound levels for the four fans varied between 41.2 and 42.7 dBA.

In house P94-1, a detailed frequency response of the sound pressure levels measured at a distance of 1 metre from the fan is presented in figure 18. Also shown on the graph is the noise level in the room with the fan off, and the ASHRAE Noise Criterion of NC 30. As can be seen, the fan noise was well below the ASHRAE NC 30 criterion.

d. Occupant questionnaire

The following four questions were asked of the occupants in the four houses with the OTCV systems.

1. Was the noise from the OTCV fan detectable?

2. Did you find the fan operation acceptable?

3. Did you notice any difference in the air quality during the various times during the 12 week testing?

4. Would you say your house normally has acceptable air quality without a continuously running fan?

The answers to these questions are presented in Table 12.

Question number	P94-1	P94-3	P94-5	P94-13
1	No	No	No	No
2	Yes	Yes	Yes	Yes
3	Yes	No	No	Not noticeable
4	Better with furnace fan on continuously	Yes	Yes (furnace fan on low speed continuously)	Yes

Table 12. Responses to questions regarding OTCV operation

4.3 Computer Simulation Results

Computer runs with HOT 2000 Version 6.03 were performed using the physical data, occupancy numbers, and measured electrical energy consumption for lights and appliances used on the four outdoor temperature controlled ventilation (OTCV) houses.

Two runs were done for each house. The first run was done with the house in the natural ventilation mode. The second run was done with the house in the OTCV mode. The outdoor temperature thresholds and fan flow rates used on the actual houses were input to the computer program.

In figures 22 through 25, the runs for houses P94-1, P94-3, P94-5, and P94-13 are presented.

As can be seen, the OTCV mode causes the houses to maintain a higher air change rate over the warmer months.

The relative energy consumption for space heating associated with the two modes of operation is presented in Table 13. The space heating consumption numbers were generated by the HOT 2000 program.

House Code	Ratio of space heating consumption values
P94-1	1.010
P94-3	1.016
P94-5	1.026
P94-13	1.011

Table 13. Relative energy consumption for space heating
(Ratio of annual space heating in OTCV mode to annual space heating in natural ventilation mode)

The increase in space heating consumption is relatively small for the four houses, varying from 1.1% to 2.6%.

Computer Simulation of Indoor Air Pollutant Levels

Measurements were taken of sufficient parameters to calculate the generation rate of several pollutants (carbon dioxide, formaldehyde, and the sum of 26 volatile organic chemicals)in the four houses with outdoor temperature controlled ventilation. For a one week period, measurements were made of the air change rate, and the concentration of these pollutants in the houses when the houses were operated in the natural ventilation mode. For these 4 houses, the concentrations of the pollutants were below generally recognized standards for carbon dioxide (1000 ppm) and formaldehyde (0.1 ppm). There is no generally accepted standard for the 26 VOCs.

Assuming steady state, well-mixed conditions throughout the houses, the following mass balance equation can be derived to calculate the net pollutant generation rate of an indoor air pollutant:

$$N = (C_i - C_o)^* Q \quad (1)$$

where N = net pollution generation rate (mg/h)

C_i = concentration of pollutant inside the house (mg/m^3)

C_o = concentration of pollutant outdoors (mg/m^3)

Q = volume air exchange (m^3/h)

For the four houses, the net pollution generation rates (for the one-week monitoring period in which the pollution concentrations and the air change rate were measured) are presented in Table 14.

The pollutant generation rates were calculated using the above equation. Because the air change rates were measured to only two significant figures, the pollutant generation rates are similarly presented to two significant figures.

Table 14. Air exchange rate and pollution generation rate

Pollutant Generation Rate (mg/h)				
House Code	**Air exchange rate (ac/h)**	**CO_2**	**HCHO**	**VOC sum**
P94-1	0.08	27,000	1.1	6.0
P94-3	0.12	38,000	1.4	8.2
P94-5	0.11	33,000	2.4	8.2
P94-13	0.17	25,000	2.2	3.2

Note: Outdoor CO_2 level is assumed to equal 350 ppm
Outdoor HCHO level is assumed to equal 0 ppm
Outdoor VOC sum is assumed to equal 0 μg/m^3

As can be seen from the table, the pollutant generation rate for carbon dioxide greatly exceeds the values for formaldehyde and for VOCs. The variation in the pollutant generation rates between the houses is not very great, with the ratio of the highest to the lowest values less than 2.6 for all three pollutants.

In order to use a computer model to estimate the annual variations in indoor air pollutant levels caused by the three types of pollutants, the following assumptions were made:

1. The pollutant generation rates shown in Table 14 were fixed throughout the year.

2. The pollutant is well mixed throughout each house. Each house has a forced air heating system, and the air is normally well mixed when the furnace fan is operating.

3. No significant absorption effects were present.

4. The house was assumed to have the windows and doors closed throughout both the heating season and the summer months.

5. The concentration of formaldehyde and VOCs outdoors is negligible, and the concentration of carbon dioxide is 350 ppm.

The following equation can be used to calculate the concentration of indoor air pollutants:

$$C_i = C_o + N/Q \qquad (2)$$

If the outdoor concentration (C_o) of the pollutant is assumed to be zero (as was assumed for formaldehyde and VOCs), the indoor concentration (C_i) is inversely proportional to the air change rate (Q) for a given pollutant generation rate.

The computer model AQ1 (Palmiter, 1992) is an indoor air quality model for a one-zone building written in Turbo Pascal. The program uses the AIM-2 infiltration model to calculate natural infiltration (Walker and Wilson, 1990). When mechanical ventilation is used, the air change rate is a function of the natural and mechanical ventilation rates. No absorption or desorption effects for air pollutants are included in the model. The indoor concentration of a pollutant is calculated using equation 2. above. The pollutant generation rate (N) may be expressed either as a constant value or as a rate which decays exponentially with time, but the pollutant generation rate is not allowed to be a function of temperature or humidity.

The HOT-2000 program Version 7.0 also uses the AIM-2 infiltration model based on a single zone. The program is thus similar to the AQ1 program.

As both the AQ1 and HOT-2000 models are single zone in nature, they are unable to model the pollutant concentrations in parts of houses such as bedrooms with baseboard heaters and no air circulation from the bedrooms to the rest of the house.

Because of the identical algorithms used in the two programs to calculate air exchange rates, computer modelling of pollutant concentrations was performed using the air exchange rates calculated by the HOT-2000 program. The air exchange rates were then used along with the pollutant generation rates in Table 14 to calculate the indoor air concentrations on a month-by-month basis using equation 2.

The air change rates were calculated using the physical data from the four houses. Air change rates were calculated using both the natural ventilation mode and the OTCV mode for the following six cities: Vancouver, Summerland, Toronto, Montreal, Swift Current and Winnipeg. The personal computer used for the analysis was a Dell Pentium 90 Mhz model. Execution time for each run was 0.11 seconds.

The heating degree-day values for the six cities are as follows:

Annual heating degree-days (°C-d)	
Vancouver	2924
Summerland	3502
Toronto	3646
Montreal	4538
Swift Current	5427
Winnipeg	5871

The results of the monthly air change rates for house P94-1 are presented in figure 26 for the natural ventilation mode for the locations of Vancouver and Winnipeg. Vancouver is the warmest city and Winnipeg is the coldest in the sample of six houses. (For clarity, the results for the other 4 cities are not shown in the figure 26.)

In figure 27, the monthly air change rates are presented for house P94-1 when operated in the OTCV mode. As can be seen from figure 26, in the natural ventilation mode, the house located in Vancouver has substantially smaller monthly average air change rates throughout all but the summer months. In the OTCV mode, however, the air change rates are much closer between the two cities.

In figure 28, the carbon dioxide levels for House P94-1 when operated in the natural ventilation mode are plotted on a monthly basis for the locations of Vancouver and Winnipeg. Because outdoor levels are approximately 350 ppm, the percentage variation in the carbon dioxide levels on a monthly basis is not as great as the variation in the natural ventilation rates shown in figure 26.

In figure 29, the carbon dioxide levels for House P94-1 when operated in the OTCV mode are plotted. The carbon dioxide levels are relatively constant on a monthly basis, as would be expected, given that the air change rates as shown in figure 27 are also relatively constant on a monthly basis.

A similar analysis was performed for the sum of the 26 VOCs that were measured.

In figure 30, the maximum monthly VOC sum values are presented for House P94-1 when located in Vancouver and Winnipeg assuming natural ventilation.

In figure 31, the maximum monthly VOC sum values are presented for House P94-1 assuming OTCV ventilation.

Because of the assumption that outdoor VOC levels were negligible, the percentage variation in the VOC levels shown in figure 30 is substantially greater than the percentage variation in CO_2 levels shown in figure 28. As was the case with the CO_2 levels, the OTCV ventilation mode results in lower VOC values compared with the natural ventilation mode.

In all, a total of 48 HOT-2000 computer runs were performed. The four houses were analyzed for the two ventilation modes--natural and OTCV--in six different locations.

Because of the great volume of data generated by the computer runs, it was decided to focus on the minimum and maximum monthly average ventilation rates. These two values are of importance in determining the maximum and minimum indoor air pollutant values.

In figure 32, the minimum and maximum monthly average ventilation rates for house P94-1 when located in the six cities are presented for the natural ventilation mode. In figure 33, the corresponding values are presented for the OTCV ventilation mode. It can be observed that the minimum ventilation rates for the OTCV mode are at least double those found with the natural ventilation mode. The variation between maximum and minimum ventilation rates is also much smaller for the OTCV mode.

The airtightness values for the four houses were measured as follows:

House Code	ac/h @ 50 Pa
P94-1	2.59
P94-3	2.74
P94-5	1.65
P94-13	3.29

In figure 34, the minimum monthly average air change values are presented for House P94-3 in the natural ventilation mode. In figure 35, similar plots are presented for the same house in the OTCV mode.

Similar groups of plots are presented for houses P94-5 and P94-13 in figures 36, 37, 38 and 39.

With all four houses, the OTCV mode of ventilation provided higher ventilation rates than did the natural ventilation mode. In addition, the minimum ventilation rates provided in the OTCV mode were roughly double those provided by the natural ventilation mode.

As expected, higher natural air exchange rates were generally found in the colder areas. The air exchange rates calculated for Swift Current were often higher than for Winnipeg, even though Winnipeg has higher annual heating degree-days. Swift Current is located in one of the windiest parts of Southern Canada, and the relatively high air exchange rates relative to Winnipeg are caused by the higher wind speeds.

5.0 DISCUSSION AND CONCLUSIONS

1. Pollutant Source Strength

Four types of pollutants were measured:

1. Formaldehyde

Formaldehyde concentrations in the twenty houses were all below the 0.05 ppm target for new houses, with one exception. House P94-16 had a reading of 0.12 ppm. The average year of construction of the 20 houses tested was 1970. The one house with the reading of 0.12 ppm was constructed in 1990.

2. Volatile Organic Compounds

In each of the 20 houses, twenty-six VOCs were measured. The most common chemical found was d-limonene. Thirteen of the 20 houses had d-limonene as the most abundant VOC measured. The sum of the 26 VOCs averaged 127 $\mu g/m^3$ for the 20 houses. For comparison, a similar survey of 44 houses in Saskatoon and Tillsonburg, Ontario found an average value of 245 $\mu g/m^3$. A likely reason that lower VOC readings were found in the present study was that most of the homes in this study were older. There is as yet no standard in Canada for VOCs. A proposed European standard would limit the total VOC levels to 300 $\mu g/m^3$, with no single VOC to exceed 30 $\mu g/m^3$. In the present study, thirteen of the 20 houses had at least one VOC with a value exceeding 30 $\mu g/m^3$.

3. Relative Humidity

Humidity levels in the 15 houses that were measured in winter conditions were found to average 29.2%, with 8 of the 15 houses below 30% . The Health Canada Guidelines recommend values between 30% and 55% in winter unless constrained by window condensation problems.

4. Carbon Dioxide

The average of the carbon dioxide readings for the 20 houses was 750 ppm for the first reading, and 666 ppm for the second reading. The maximum reading in one house was equal to 1127 ppm.

Although Health Canada recommends values less than 3500 ppm, a more commonly cited standard is 1000 ppm in the ASHRAE Standard 62-1989. Four of the 20 houses had readings above 1000 ppm.

2. Comparison of House Air Quality Values with Values from Houses Measured in Trois-Rivières, Quebec

A 1994 report (Stricker Associates et al, 1994) presents ventilation and air quality measurements for a group of 30 electric-baseboard-heated houses in Trois-Rivières, Quebec. The 30 house sample was chosen to represent air tightness levels with a distribution similar to the population of houses in Quebec. The average air tightness level of the houses was 4.77 ac/h at 50 pascals. Measurements of air quality in the houses included respirable suspended particulates, VOCs, formaldehyde, radon, and carbon dioxide. The measurements were made for one week during the period from December to March.

The average levels of the pollutants measured are presented in Table 15 along with values measured for the sample of 20 houses in Saskatoon.

Table 15. Comparison of Trois-Rivières and Saskatoon House Samples

	Trois-Rivières	**Saskatoon**	**Ratio**
House volume (m^3)	449	535	0.84
Air tightness (ac/h @ 50 Pa)	4.77	2.61	1.83
Air change (PFT) (ac/h under natural conditions)	0.23	0.20	1.15

	Trois-Rivières	Saskatoon	Ratio
Equivalent volume flow of air change (L/s)	27.6	28.7	0.96
Formaldehyde (ppm)	0.048	0.034	1.4
Carbon dioxide (ppm)	929	708	1.3

The average air change rates of the two groups of houses were relatively similar, with values of 0.23 and 0.20 ac/h respectively, even though the Saskatoon houses were considerably tighter. The Saskatoon houses all had atmospheric vented chimneys. It is likely that the presence of these chimneys, which are effectively holes in the building envelope at some distance from the neutral pressure plane, caused some of the proportionately higher air change rates. Other factors such as wind speeds, house exposure, height of the house, and temperature difference between inside and outside are also determinants of the air change rate of the houses. The Saskatoon houses had a volume average about 19% greater than the Trois-Rivières houses. As a consequence, the equivalent volume flows of air for the two houses were close, at 27.6 and 28.7 L/s respectively.

The average formaldehyde levels for the two groups of houses were both less than 0.05 ppm, the Health Canada target guideline for residential formaldehyde; the Trois-Rivières houses had levels that were about 1.4 times the values found in the Saskatoon houses. Formaldehyde is found in a variety of building products including pressed wood products, and is also a byproduct of tobacco smoking. Thirteen of the 30 houses in the Trois-Rivières sample had smokers present; only two of the 20 houses in the Saskatoon sample had smokers.

The carbon dioxide levels measured in the Trois-Rivières houses were about 1.3 times the level found in the Saskatoon houses. The carbon dioxide levels in the Trois-Rivières houses were measured continuously over the one week interval; in the Saskatoon houses, two spot readings during the daytime were measured. Normally the carbon dioxide levels in houses are greater during the evening hours when the occupancy is greater.

3. Air Change Rates

The air change rates measured over a one week interval in the houses averaged 0.20 ac/h, with values varying from a low of 0.08 ac/h to a high of 0.43 ac/h. During this period, no continuous fans were operating in the houses. The average volumetric air change value was 28.7 L/s for the 20 houses.

The ASHRAE 62-89 Standard recommends an outside air ventilation rate of not less than 7.5 L/s per person for residential facilities, and also not less than 0.35 ac/h. Using the 0.35 ac/h standard, only one of the 19 houses would have met this value.

At an average volumetric air change rate of 28.7 L/s, a 7.5 L/s per person flow rate would indicate sufficient air change for about 4 persons, using the ASHRAE guideline. The average occupancy in the 20 houses was 3.2 persons.

4. Backdrafting

Eighteen of the 20 houses tested were able to meet the CGSB Backdrafting standard of 5 pascals for intermittent operation of fans. The two houses that were not able to meet the standard had range hoods with flows of 110 and 120 L/s.

Seventeen of the 20 houses were able to establish chimney flow from gas burning furnaces or water heaters when an exhaust flow of 90 L/s was placed on the houses.

When the atmospheric vented gas furnaces or water heaters were not firing, an average pressure difference of 7.1 Pa was required to backdraft the chimneys. When the gas furnaces or water heaters were firing, an average pressure difference of 21.7 Pa was required to backdraft the chimneys.

5. OTCV Systems

The OTCV mode of ventilation provided lowered carbon dioxide readings relative to the natural ventilation mode in all of the four houses in which it was implemented. In the two houses with continuous radon measurements, the radon levels were also reduced when the OTCV systems were operating.

The controllers and fans used on the OTCV systems performed satisfactorily over the 12 week period during which the testing was done. The Panasonic fans used had a measured power consumption of 33 watts. Noise levels from the fans were very acceptable to the occupants. A low noise level is a very important feature to include with such a system, as the fan will cycle on and off based on the outside temperature. In existing houses with forced air systems, the return air plenum on the furnace appears to be a satisfactory duct to which the exhaust fan can be connected.

The fan flows chosen for the OTCV systems on the four houses were in the range of 0.35 to 0.53 of the values recommended in the CSA F326 standard, corresponding to whole house air change values in the range of 0.21 to 0.29 ac/h (fan flows in the range of 28 to 37 L/s). The temperature settings for the OTCV threshold were in the range of 6.0 to 8.5°C. Based on the computer modelling, this temperature band appears to be in an appropriate range for Saskatoon conditions.

Based on the relatively short monitoring period used in the April, May, and June of 1994, it was not possible to document the space heating consumption of the house in the OTCV mode as compared with the natural ventilation mode. However, the computer model indicates that the OTCV systems installed in the Saskatoon houses would have annual space heating consumption increases varying from 1.1% to 2.6% more compared with the natural ventilation mode.

6. Computer Modelling of OTCV Systems in different climate zones

The four OTCV houses that were physically tested in Saskatoon were computer modelled using the locations of Vancouver, Summerland, Toronto, Montreal, Swift Current, and Winnipeg.

The computer models indicated that the OTCV systems were able to function satisfactorily in all six of these climatic areas, even when using the flow rates and temperature thresholds selected for Saskatoon. The OTCV systems consistently demonstrated more even air change rates on a month-by-month basis that the naturally ventilated houses.

Overall, the OTCV system shows considerable promise for houses in the medium air tightness range. The system is simple in concept and relatively inexpensive to implement in both new and existing houses. A greater number of houses should undergo field trials to further test the concept. Future trials should extend over longer time intervals, and track indoor pollutants (VOCs, CO_2, HCHO) to better document the improved air quality possible from such a system.

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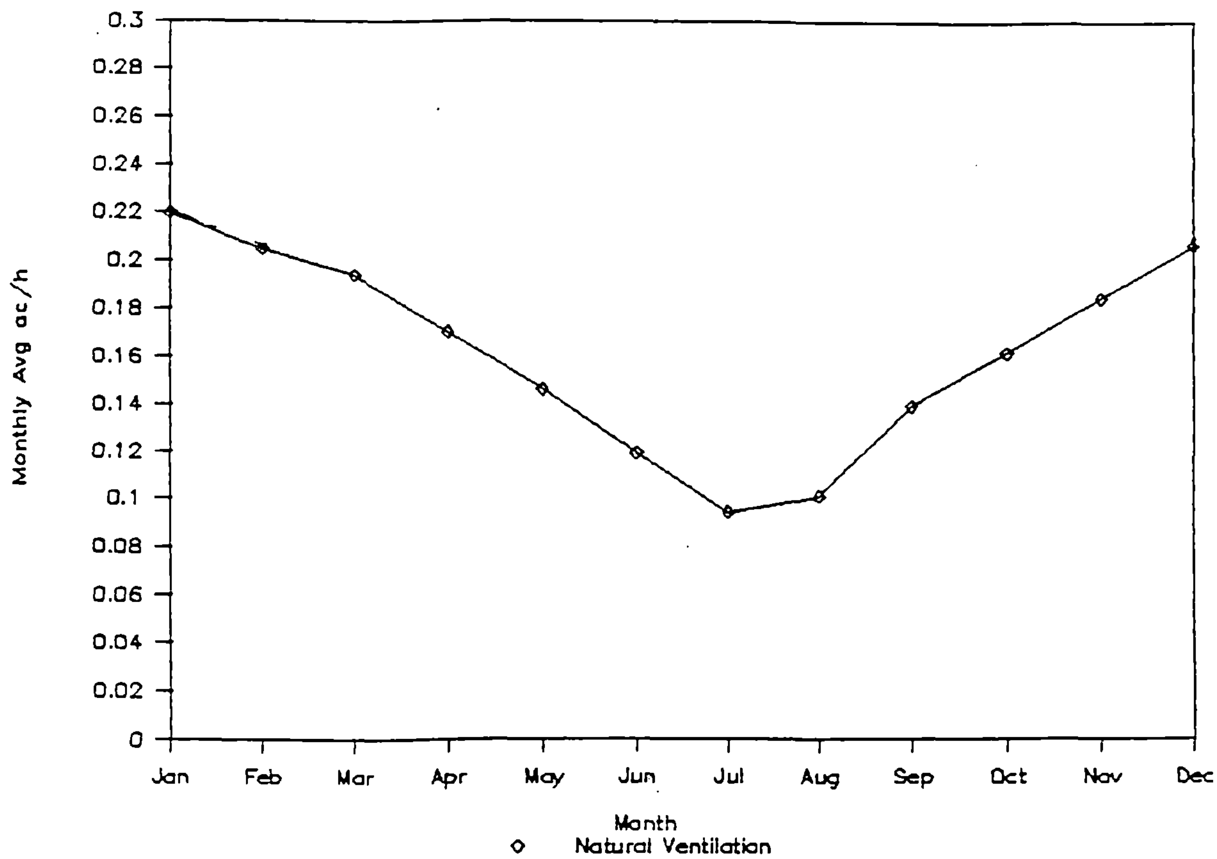


Figure 1. Monthly average air change rates in a naturally ventilated house.

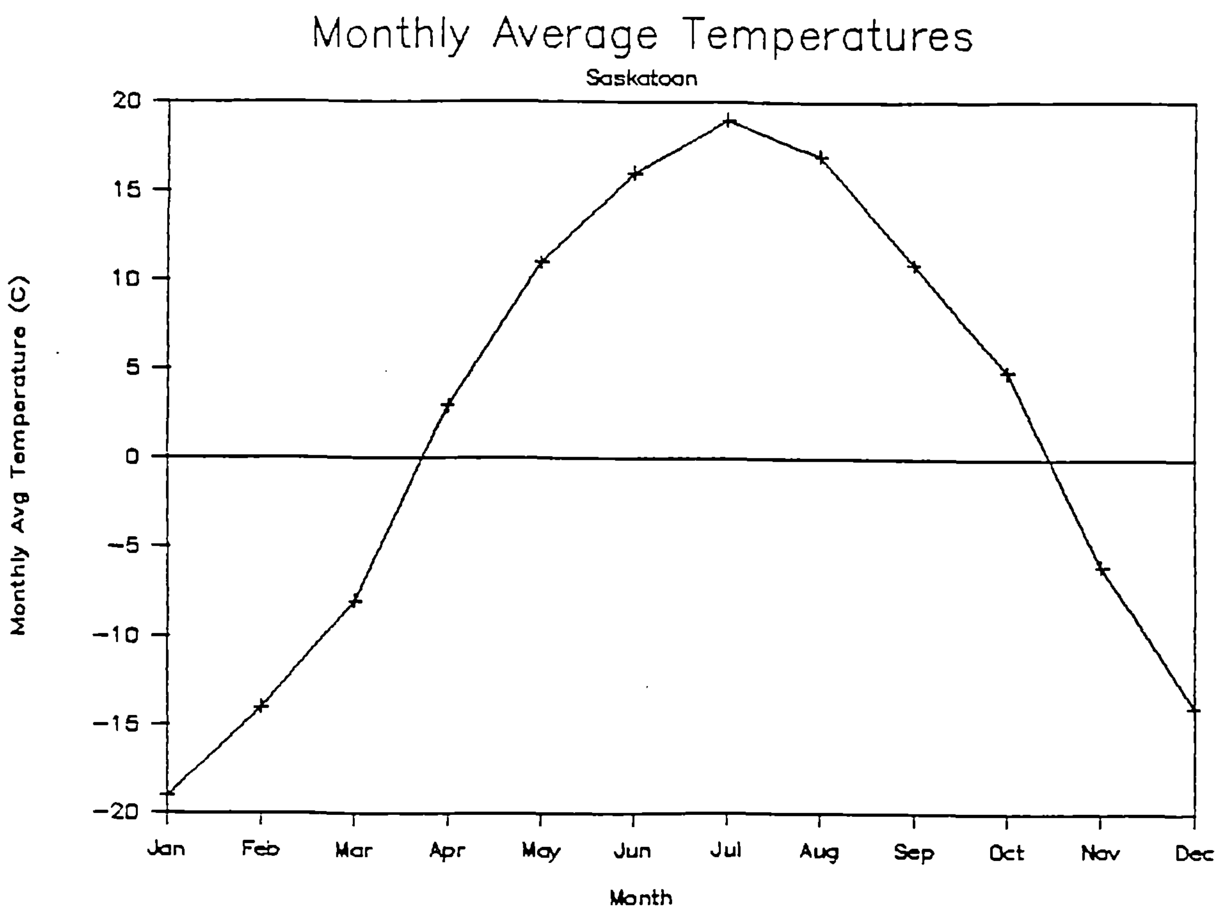


Figure 2. Monthly average outdoor air temperatures in Saskatoon.

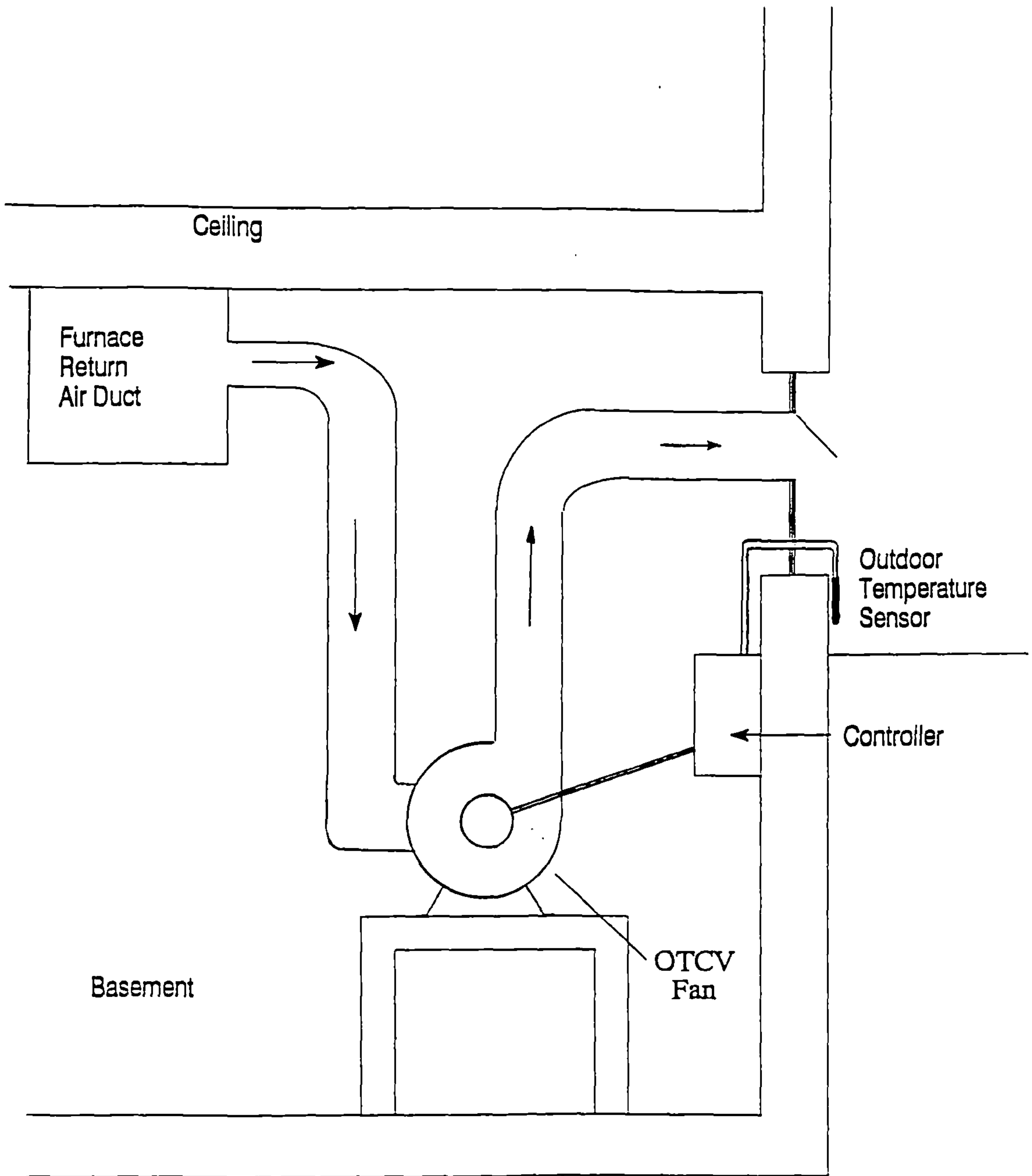


Figure 3. Exhaust fan and controller arrangement for outdoor temperature controlled ventilation system.

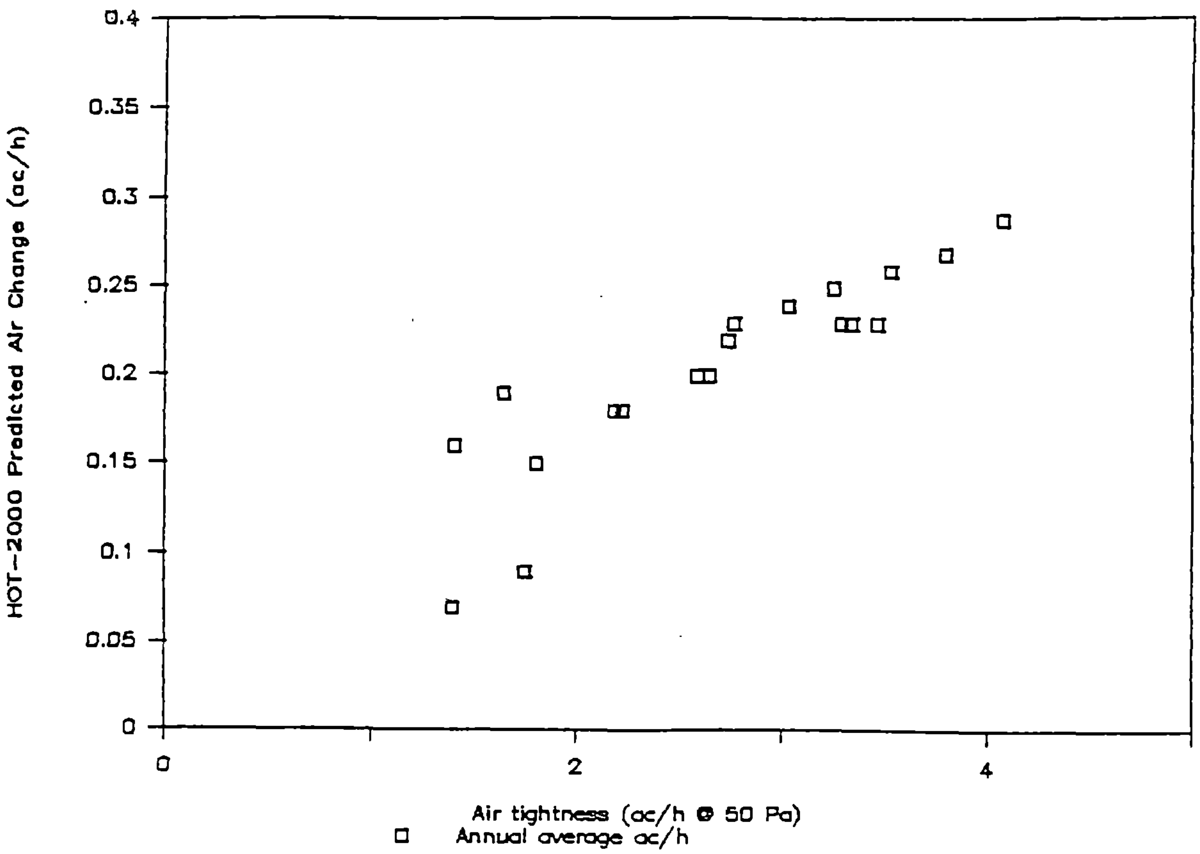


Figure 4. Predicted air change rates in 19 houses as a function of air tightness.

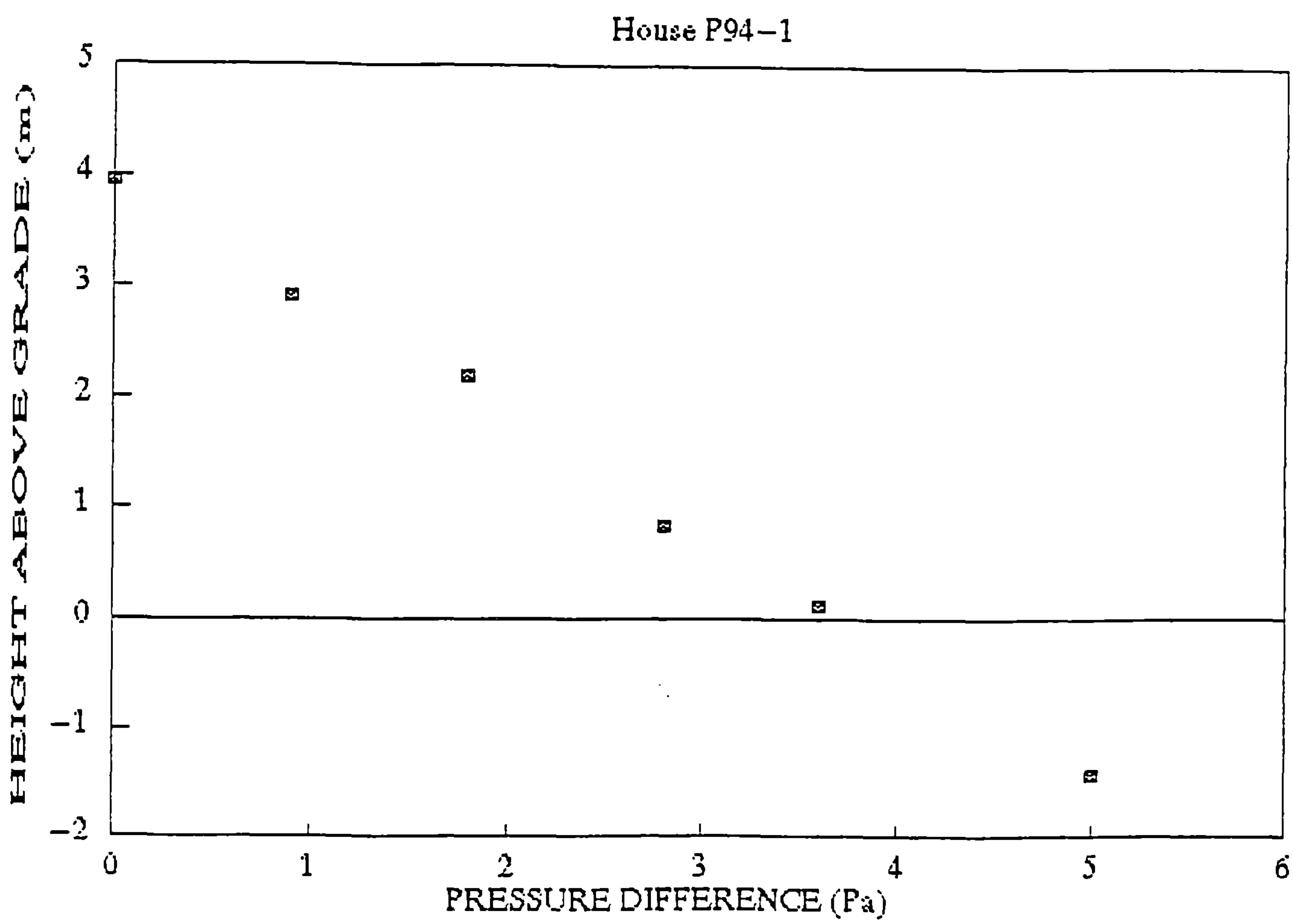


Figure 5. Neutral pressure plane measurement in House P94-1.

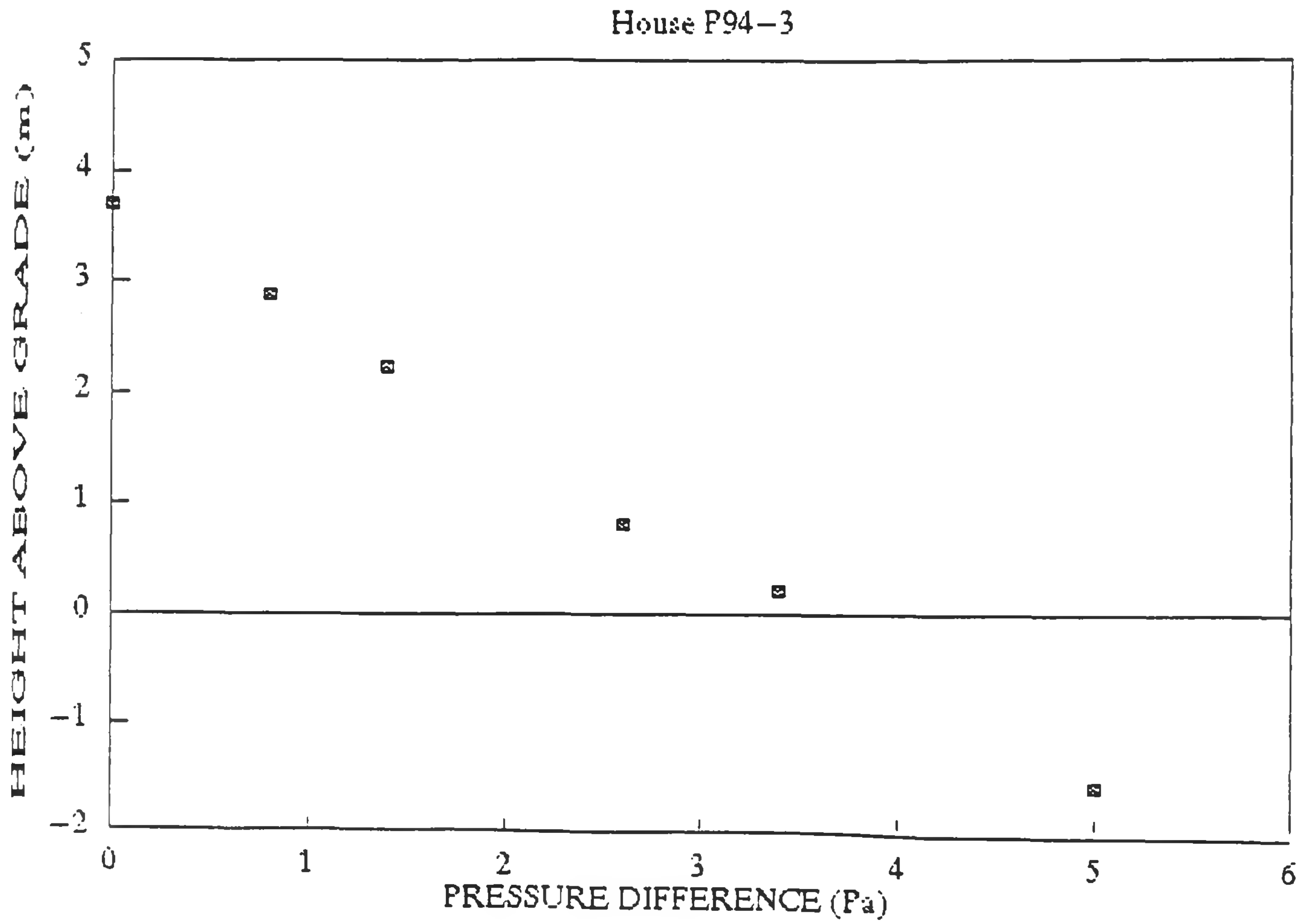


Figure 6. Neutral pressure plane measurement in House P94-3.

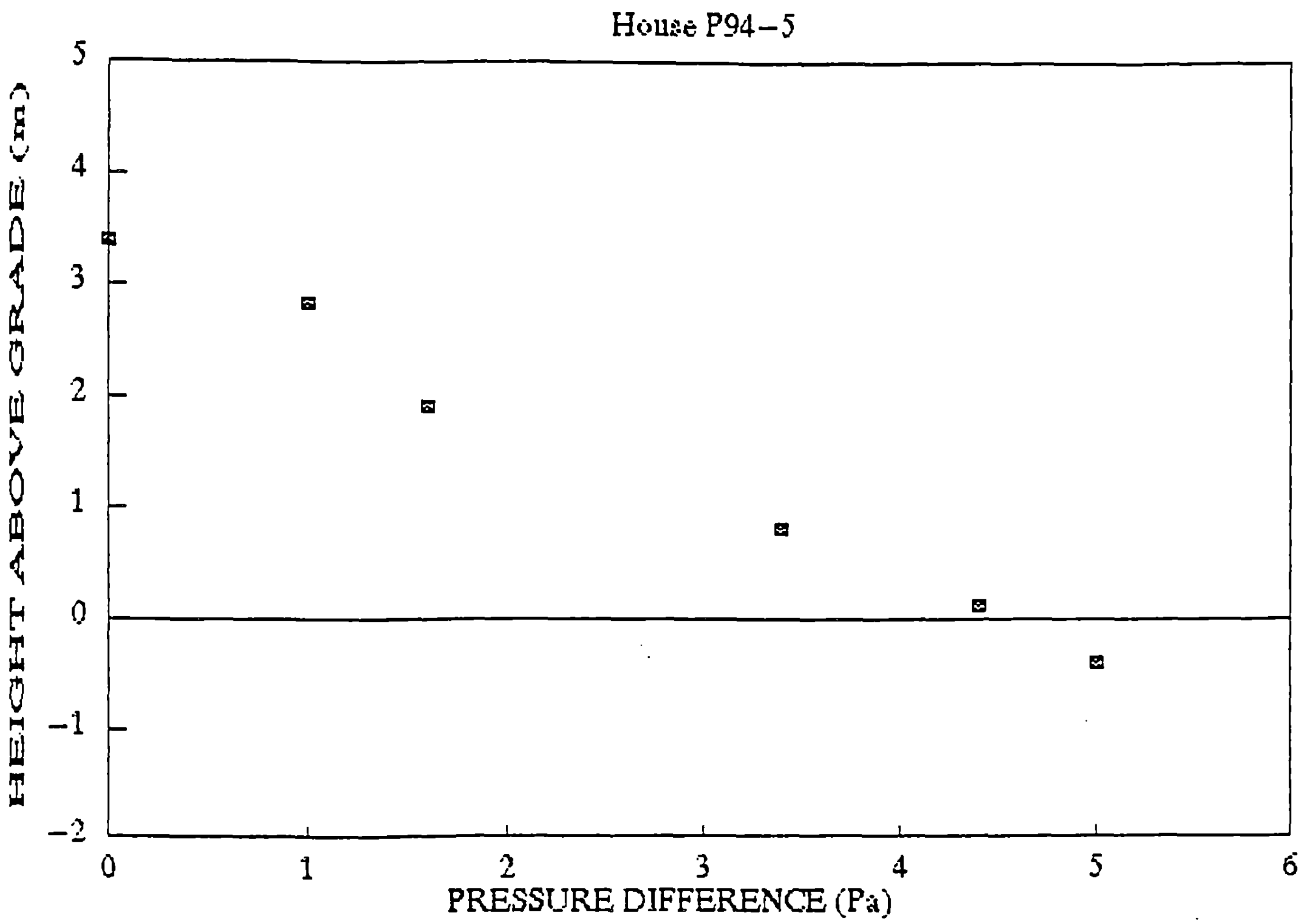


Figure 7. Neutral pressure plane measurement in House P94-5.

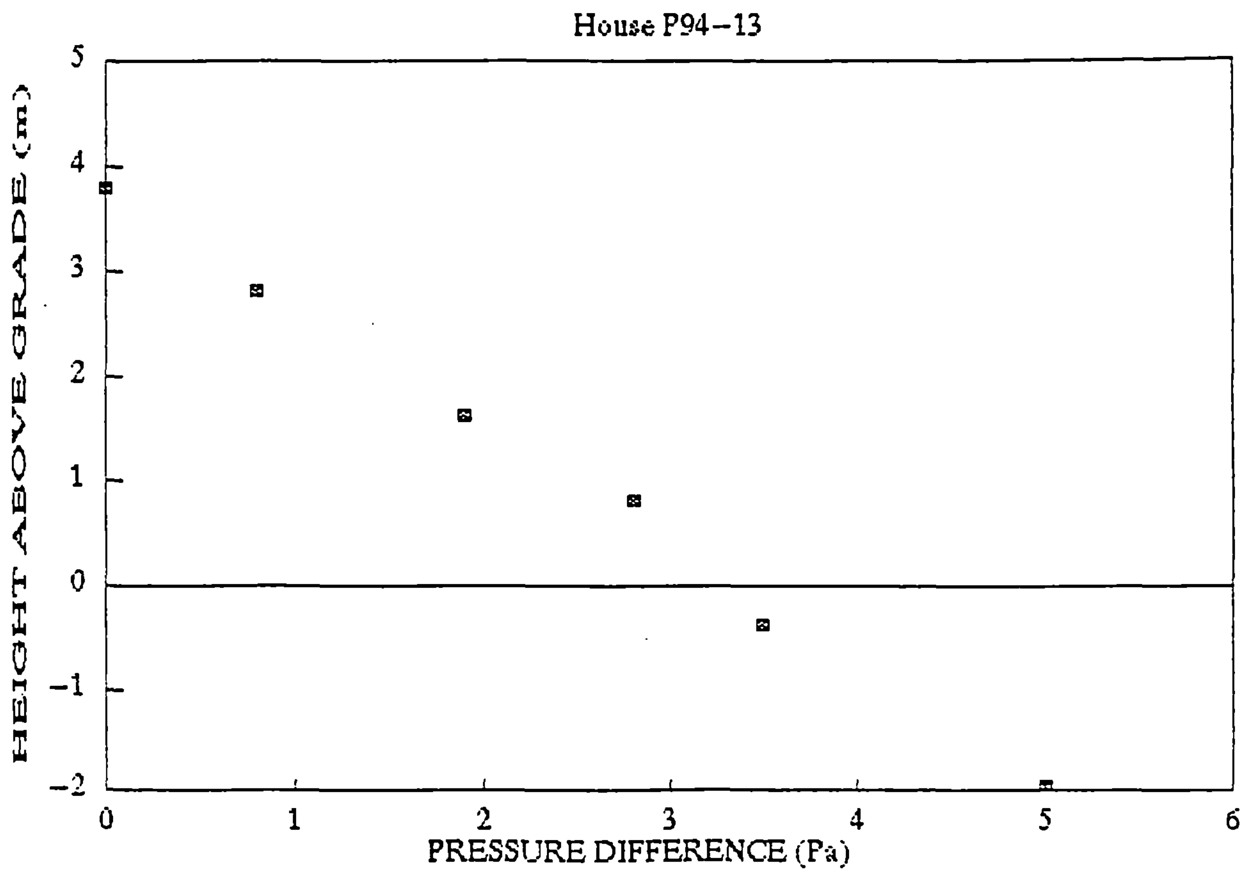


Figure 8. Neutral pressure plane measurement in House P94-13.

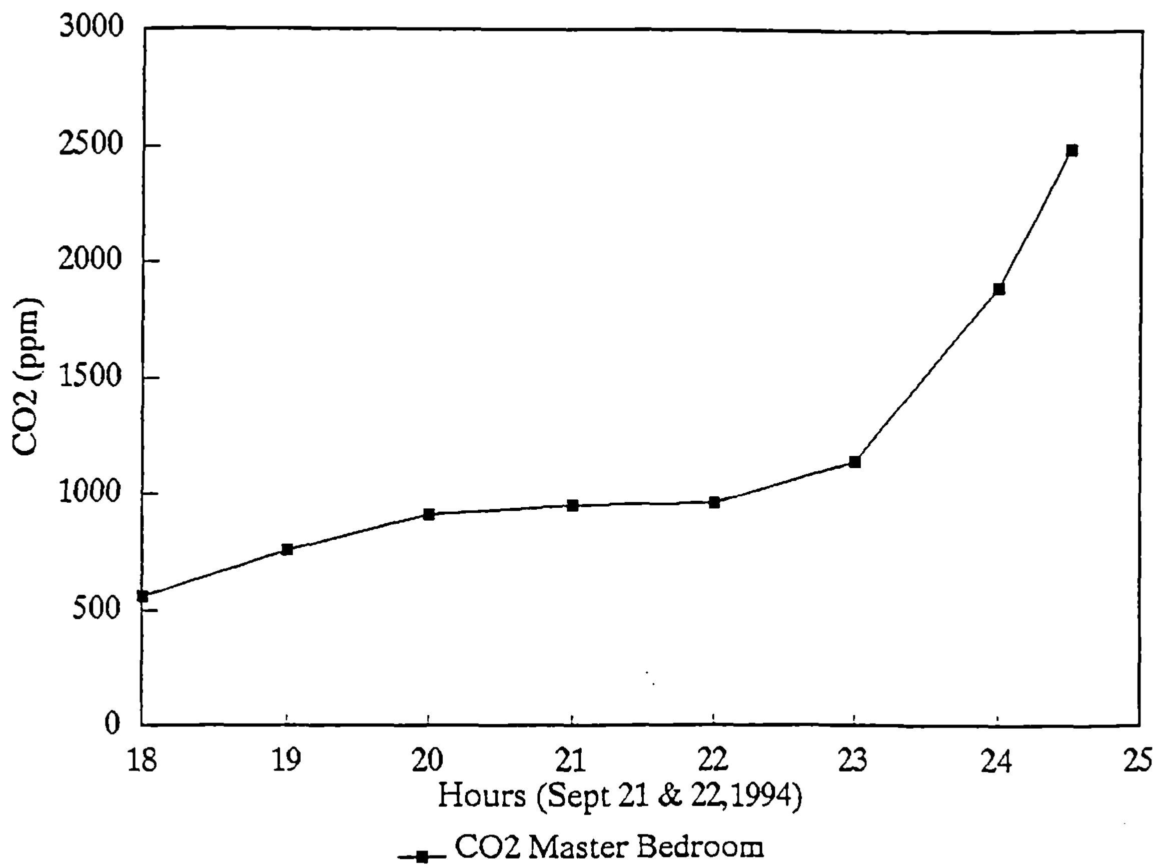


Figure 9. Carbon dioxide levels in bedroom in House P94-1.

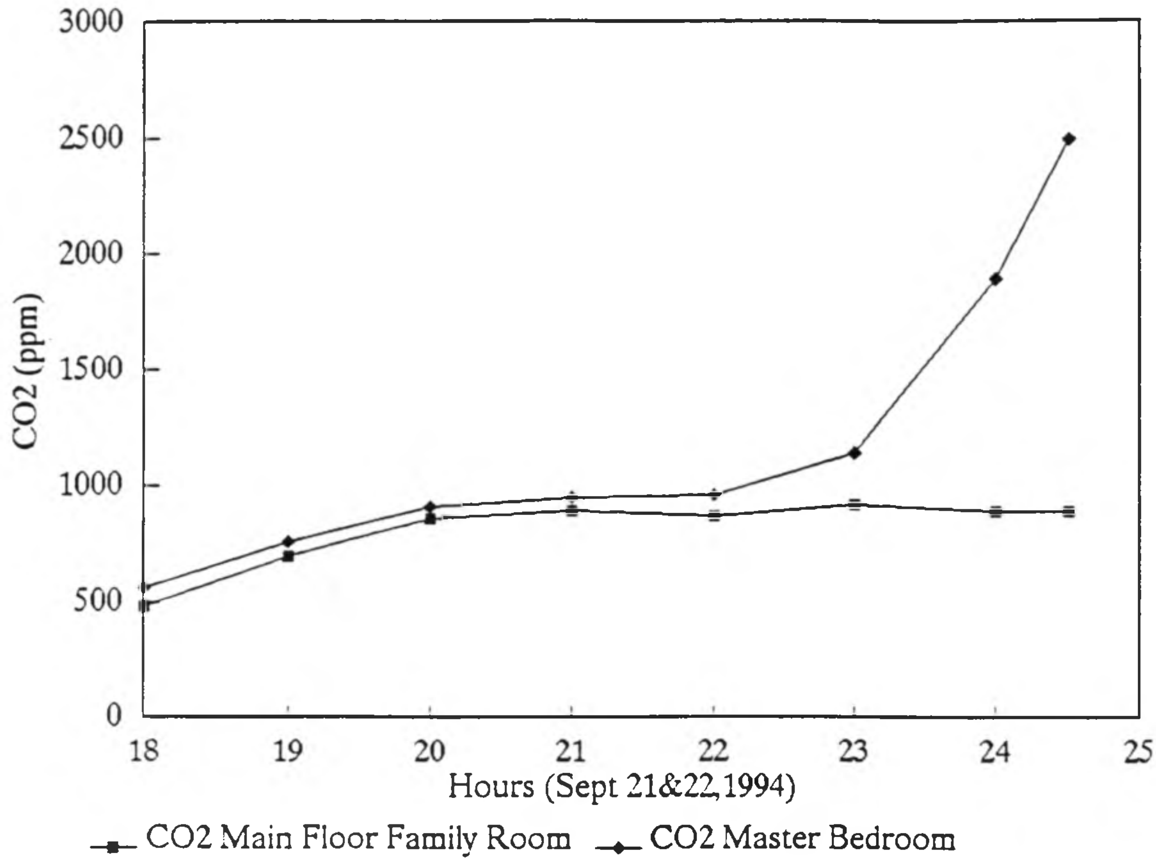
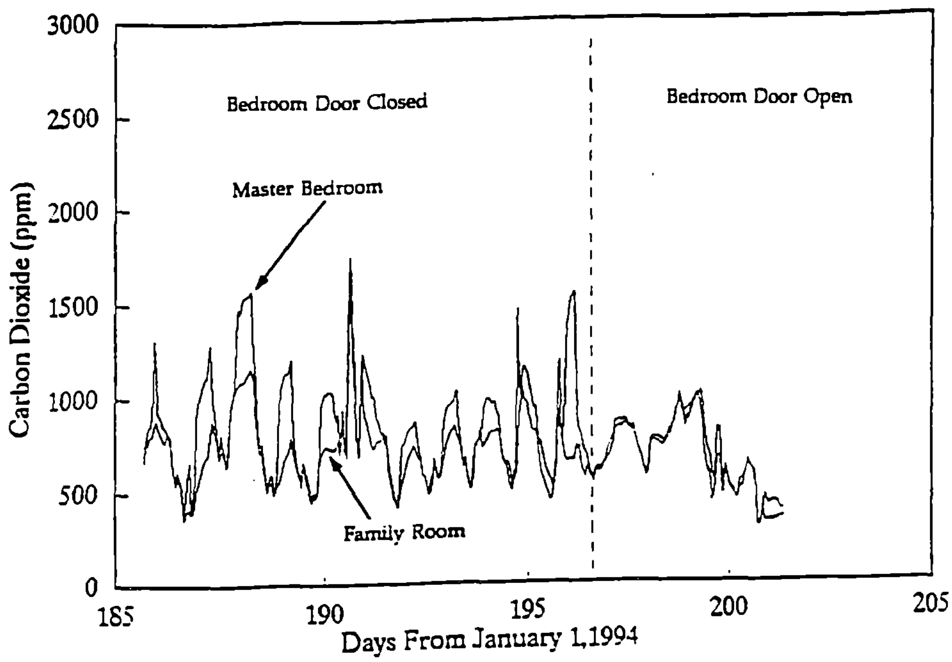


Figure 10. Carbon dioxide levels in bedroom and family room in House P94-1.



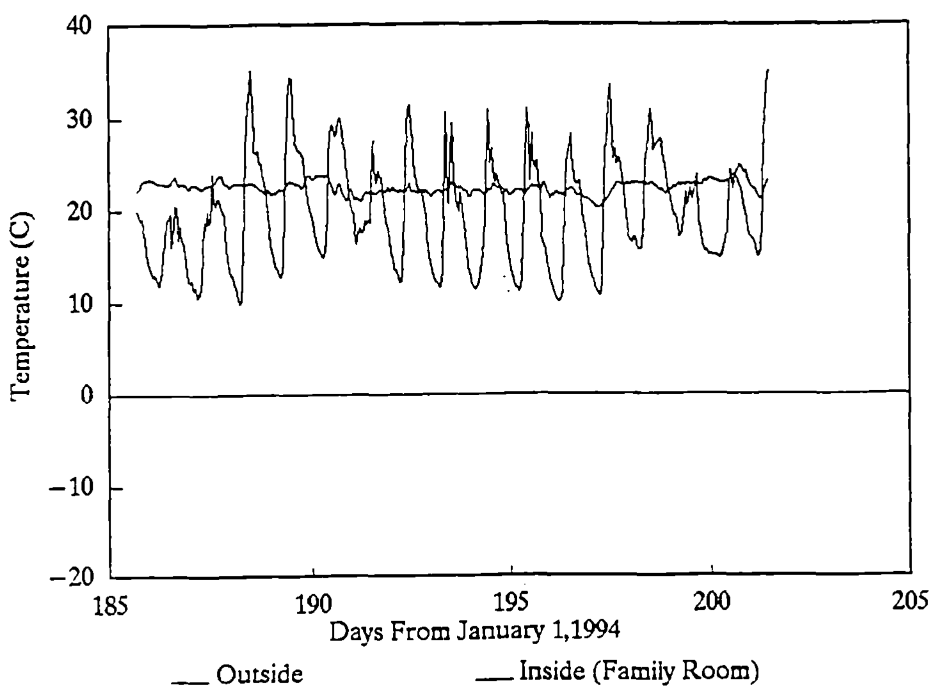


Figure 11. Carbon dioxide levels in bedroom and family room in House P94-1.

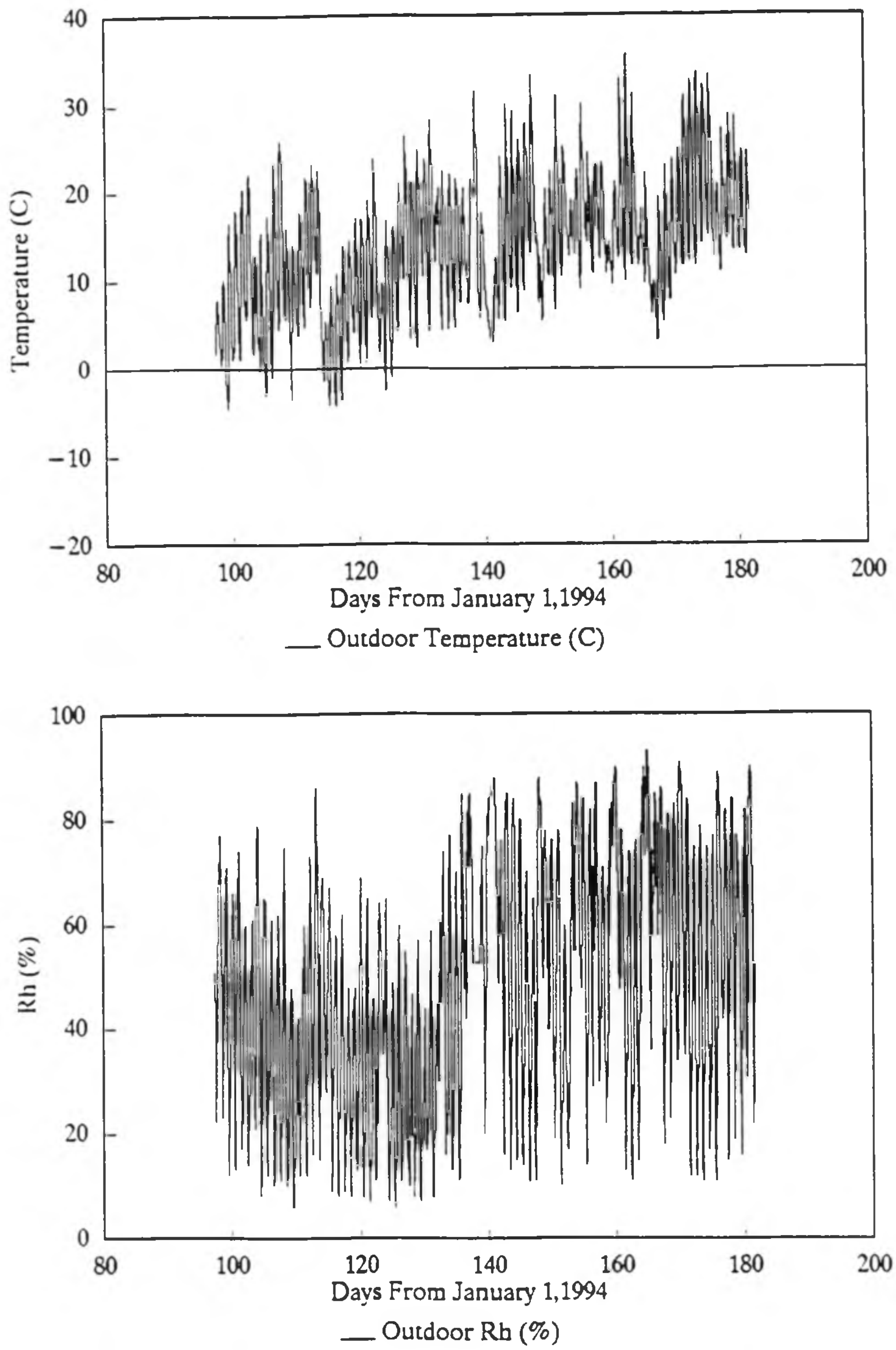


Figure 12. Outdoor air temperature and relative humidity.

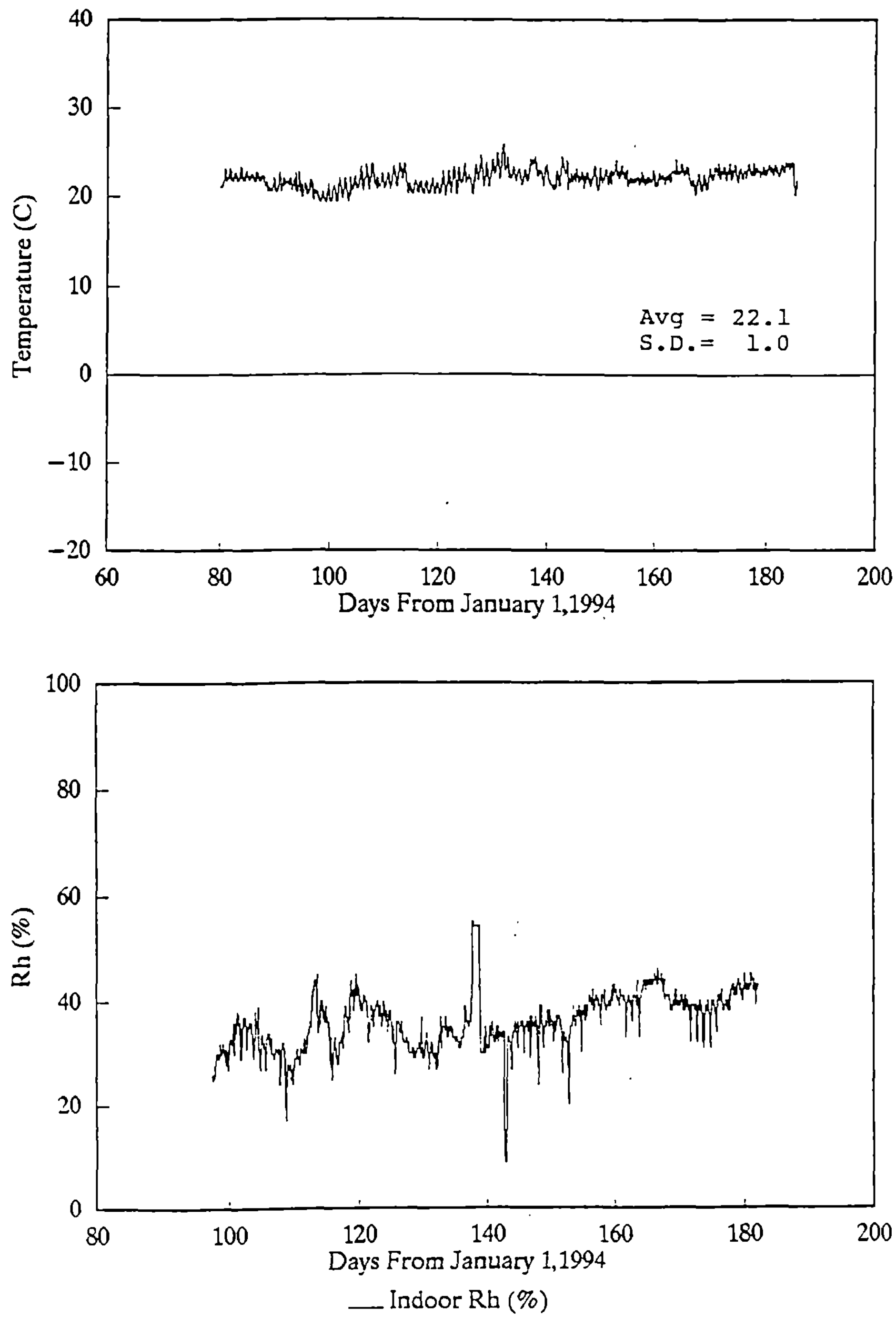


Figure 13. Indoor temperature and relative humidity in House P94-1.

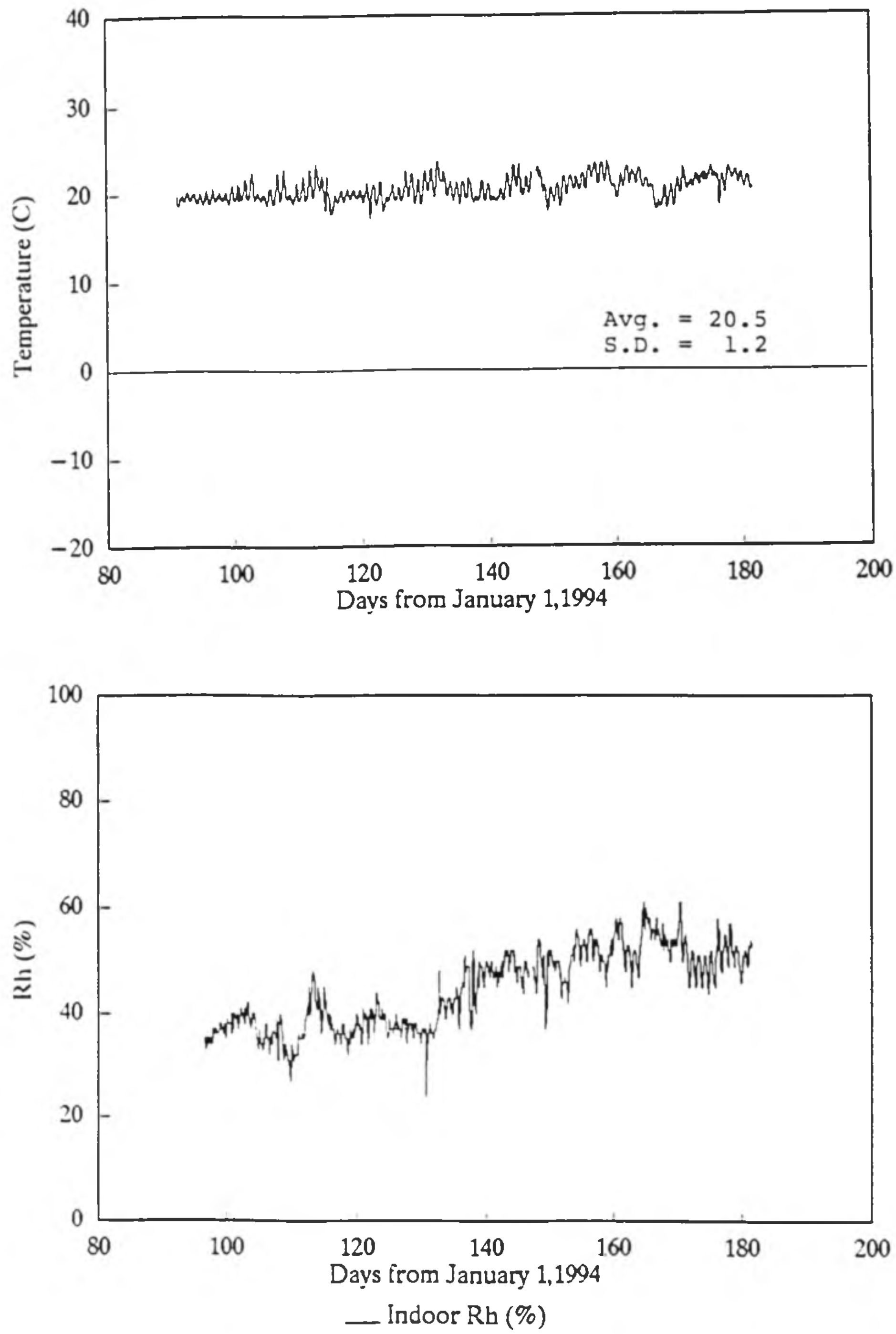
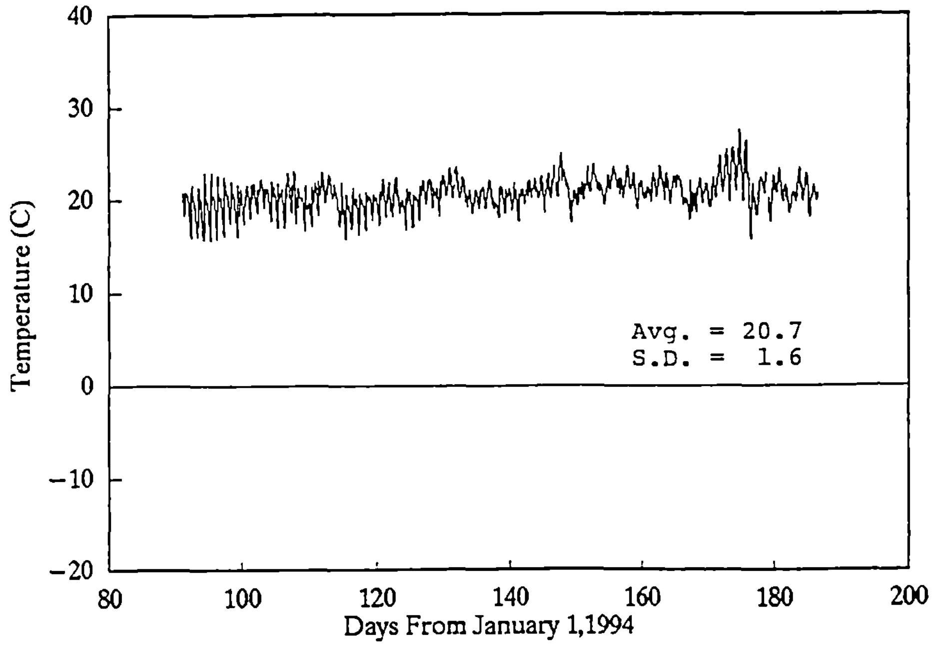


Figure 14. Indoor temperature and relative humidity in House P94-3.



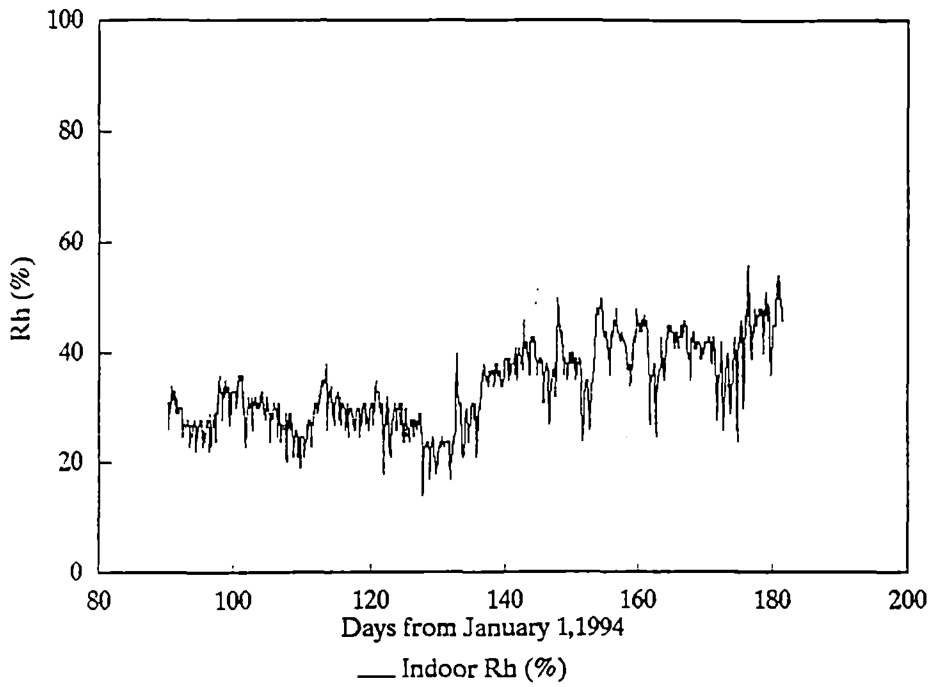
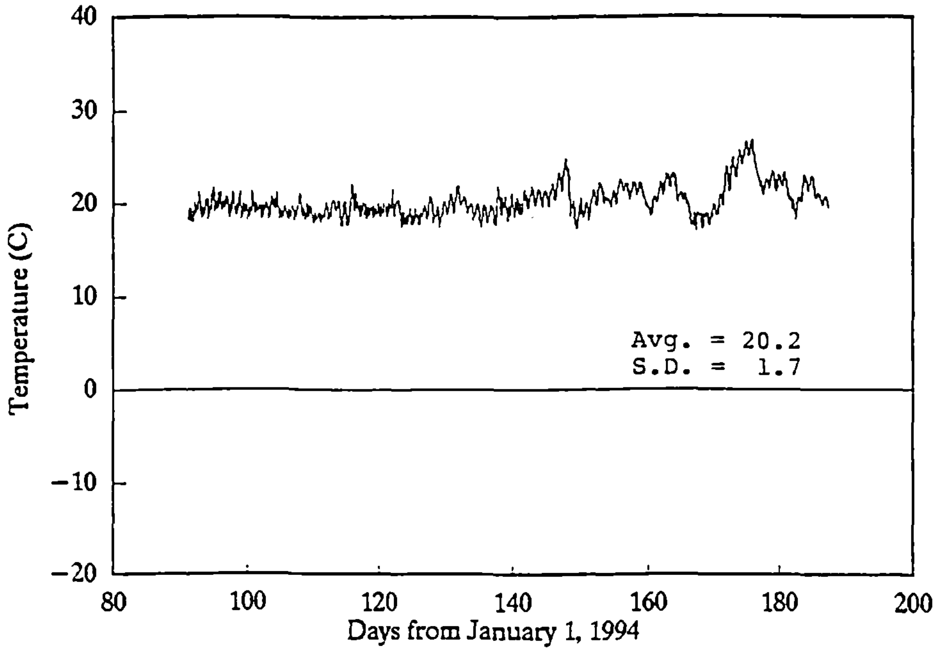


Figure 15. Indoor temperature and relative humidity in House P94-5.



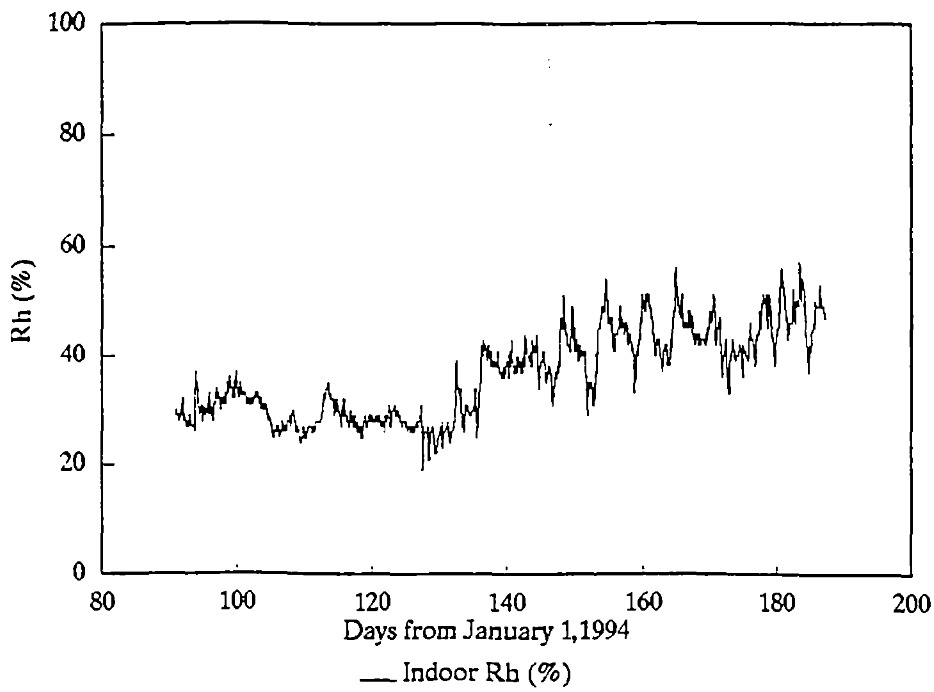


Figure 16. Indoor temperature and relative humidity in House P94-13.

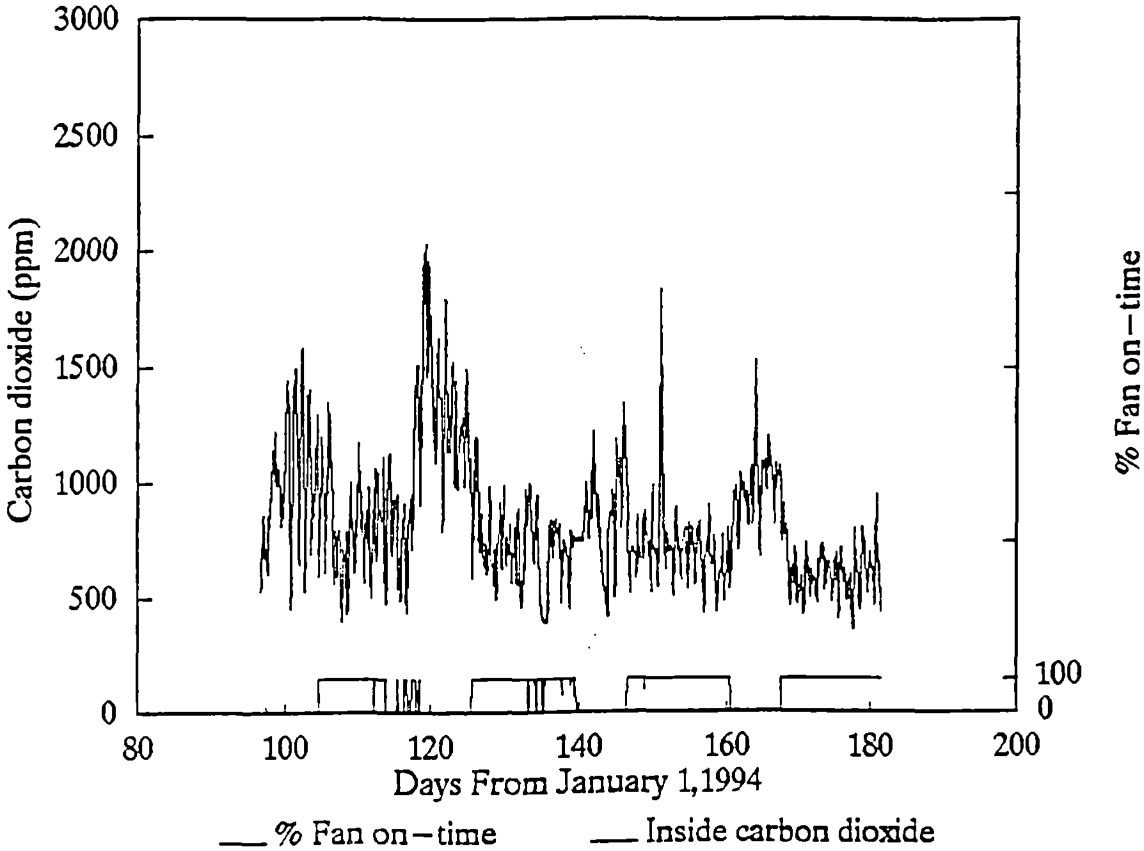


Figure 17. Carbon dioxide levels in House P94-1.

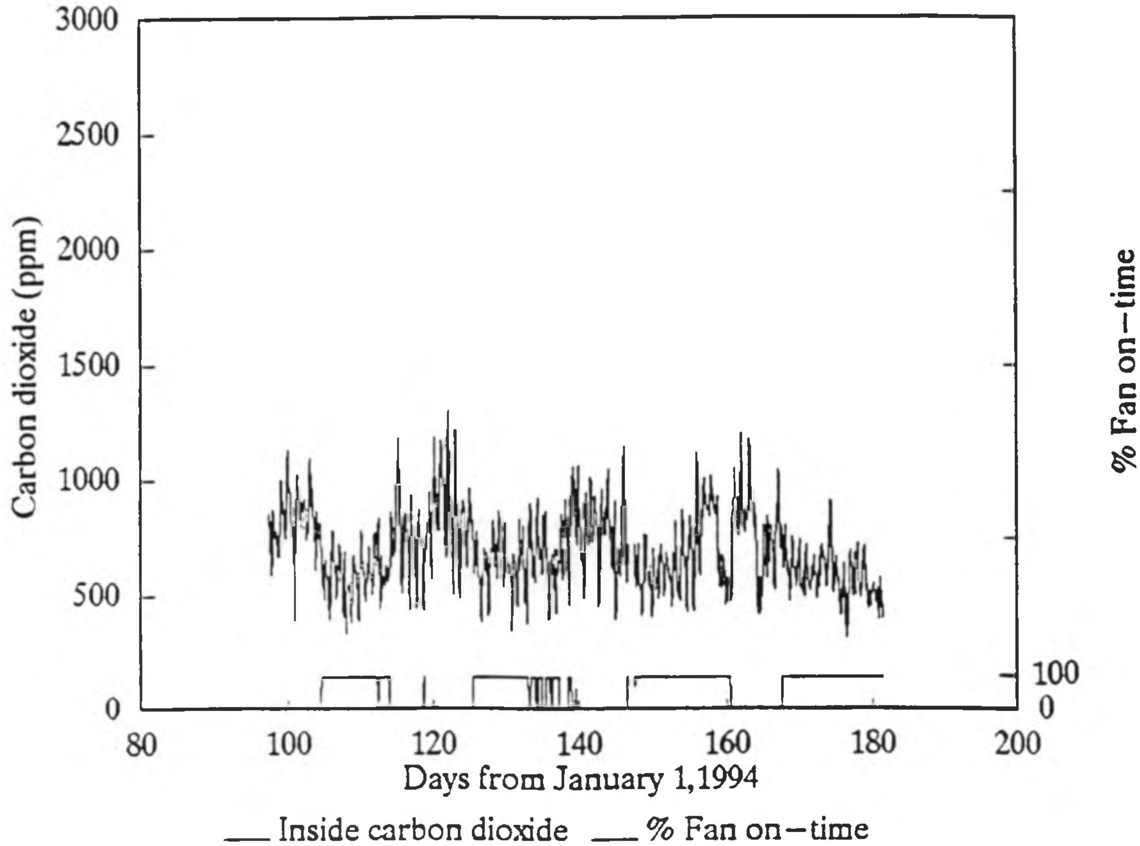


Figure 18. Carbon dioxide levels in House P94-3.

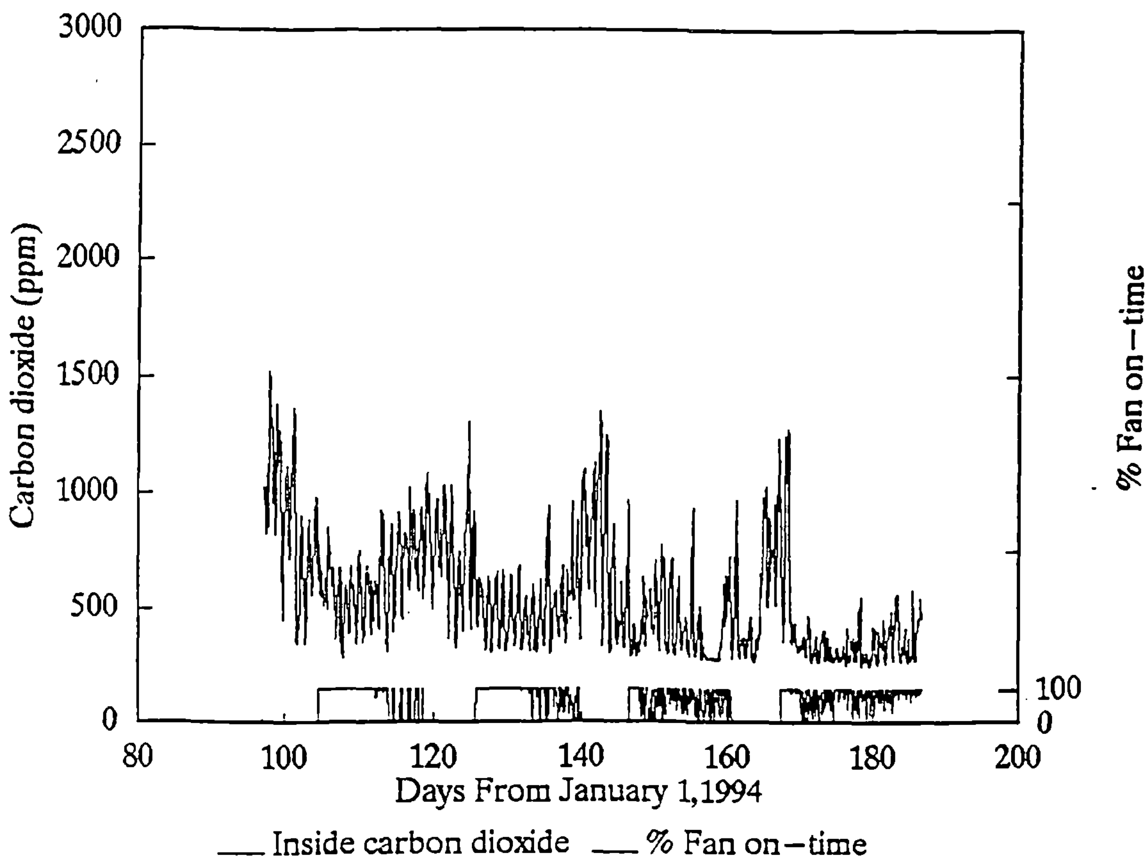


Figure 19. Carbon dioxide levels in House P94-5.

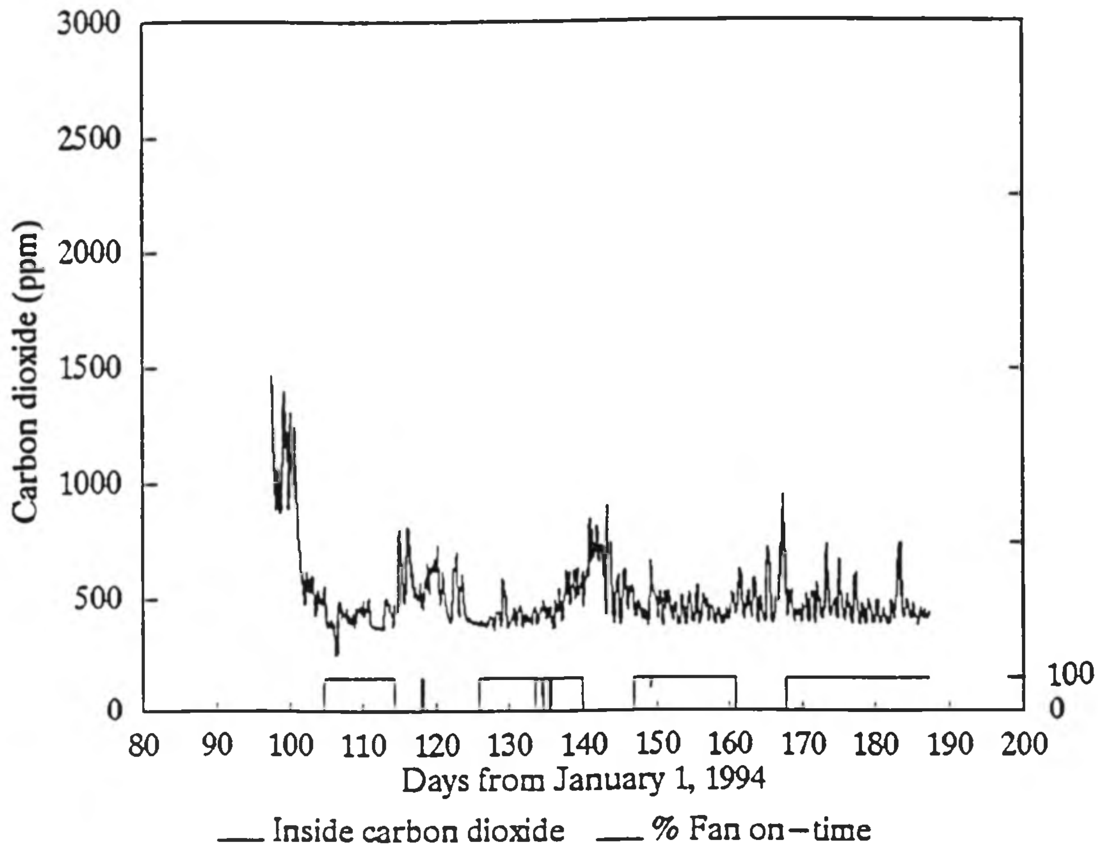


Figure 20. Carbon dioxide in levels in House P94-13.

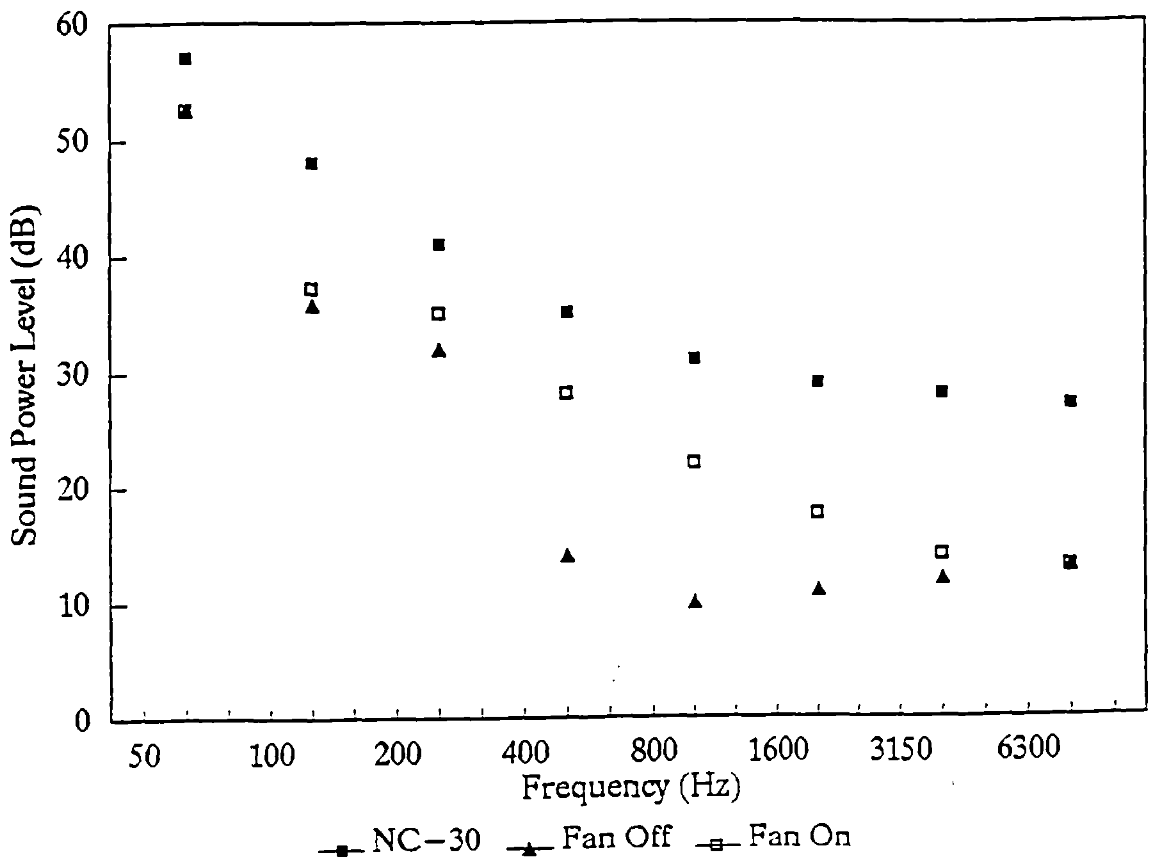


Figure 21. Sound pressure levels for OTCV fan in House P94-1.

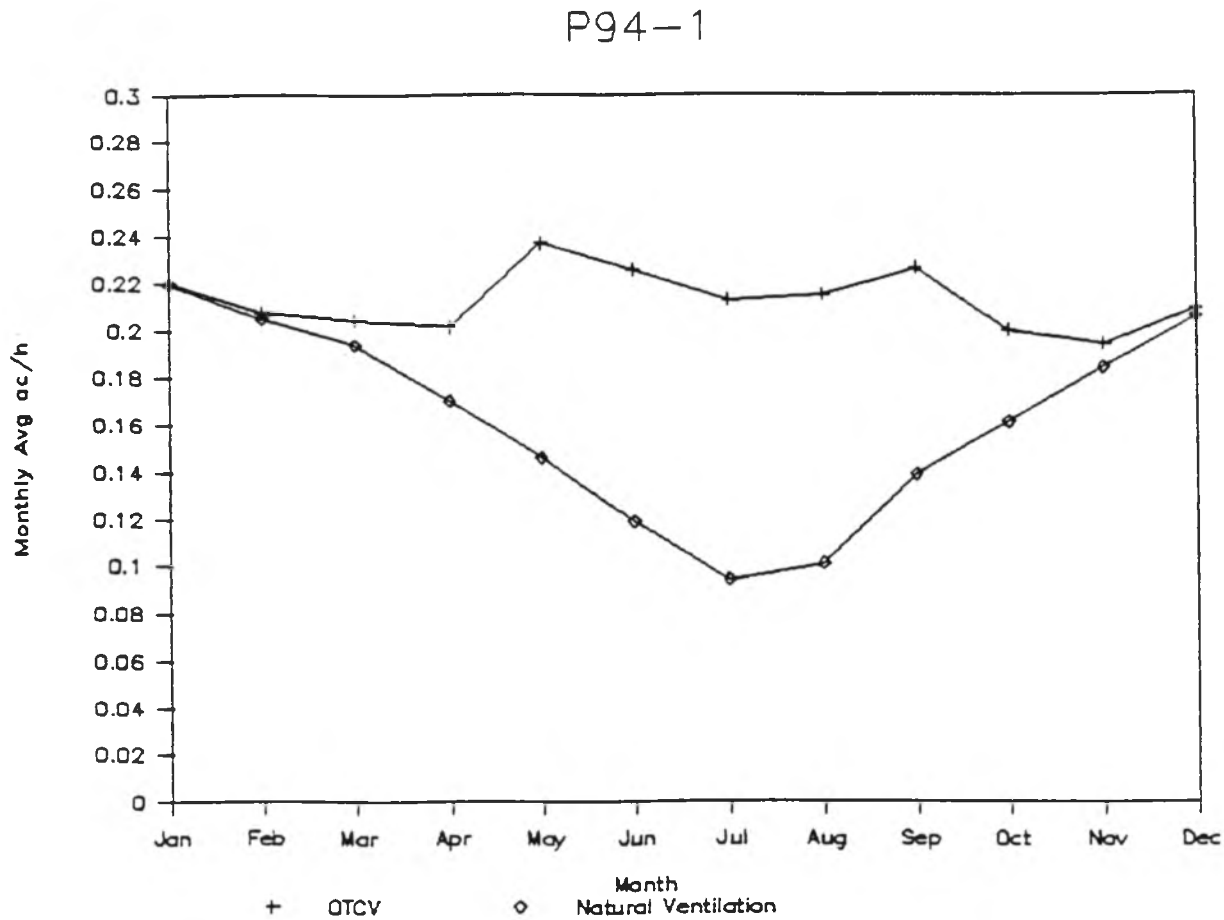


Figure 22. HOT 2000 simulation of OTCV and natural ventilation in House P94-1.

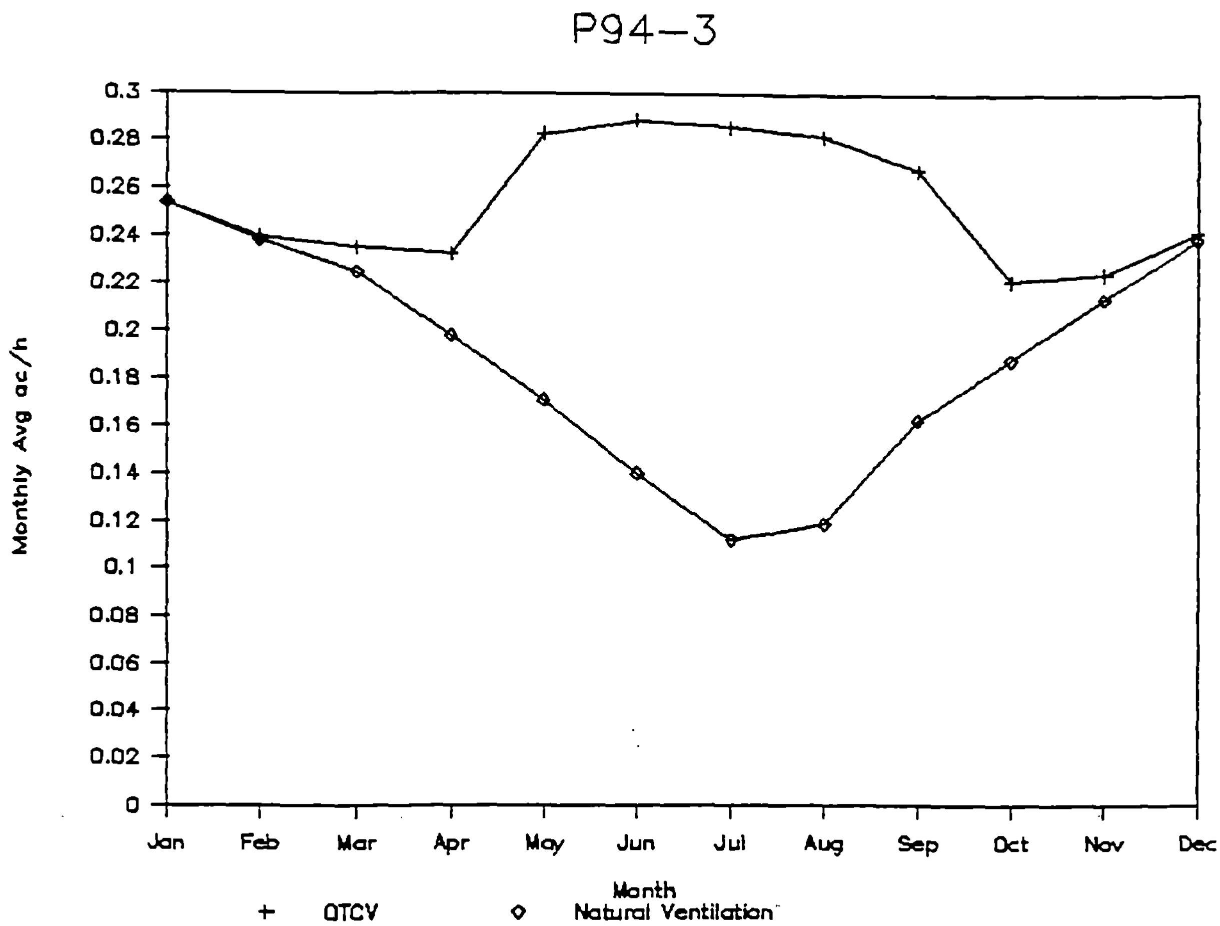


Figure 23. HOT 2000 simulation of OTCV and natural ventilation in House P94-3.

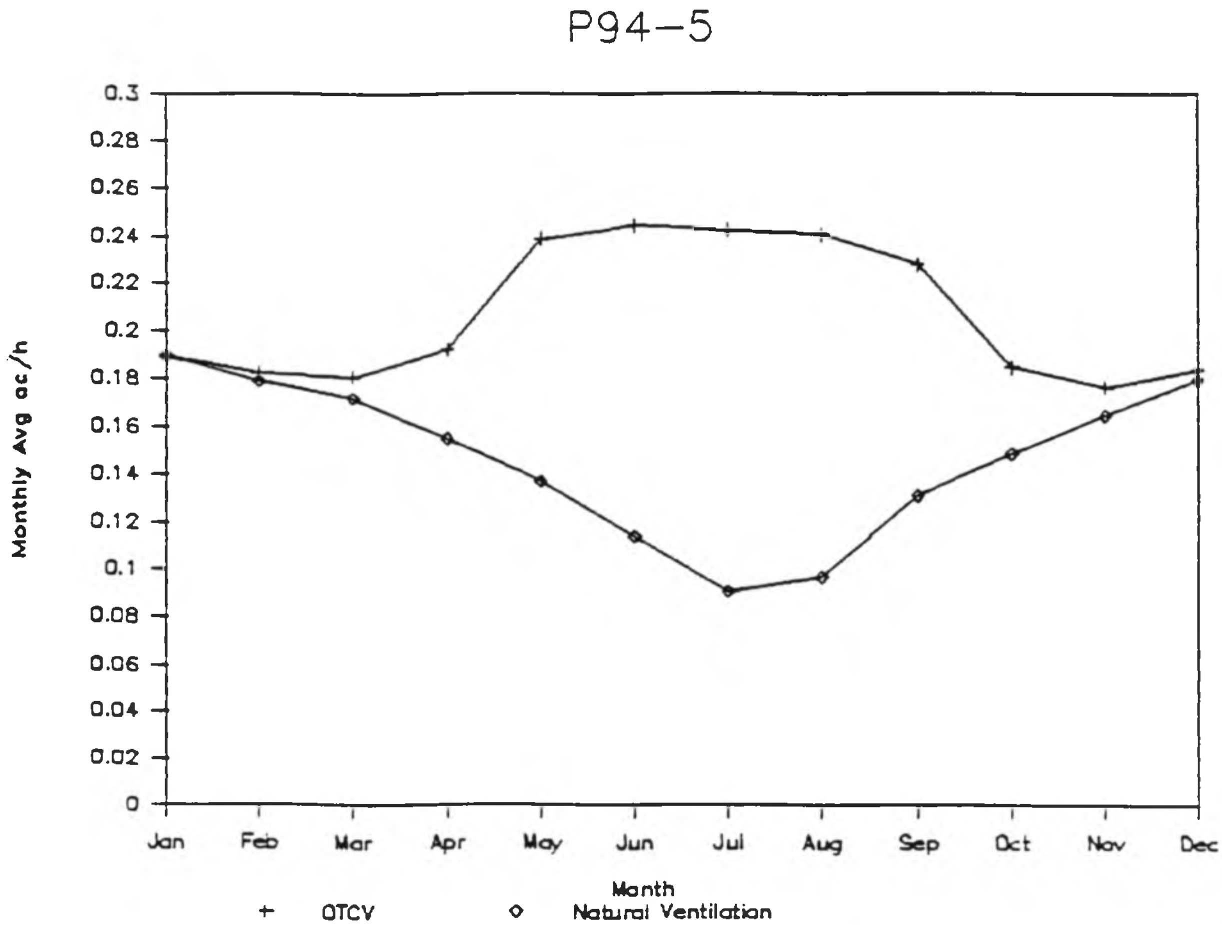


Figure 24. HOT 2000 simulation of OTCV and natural ventilation in House P94-5.

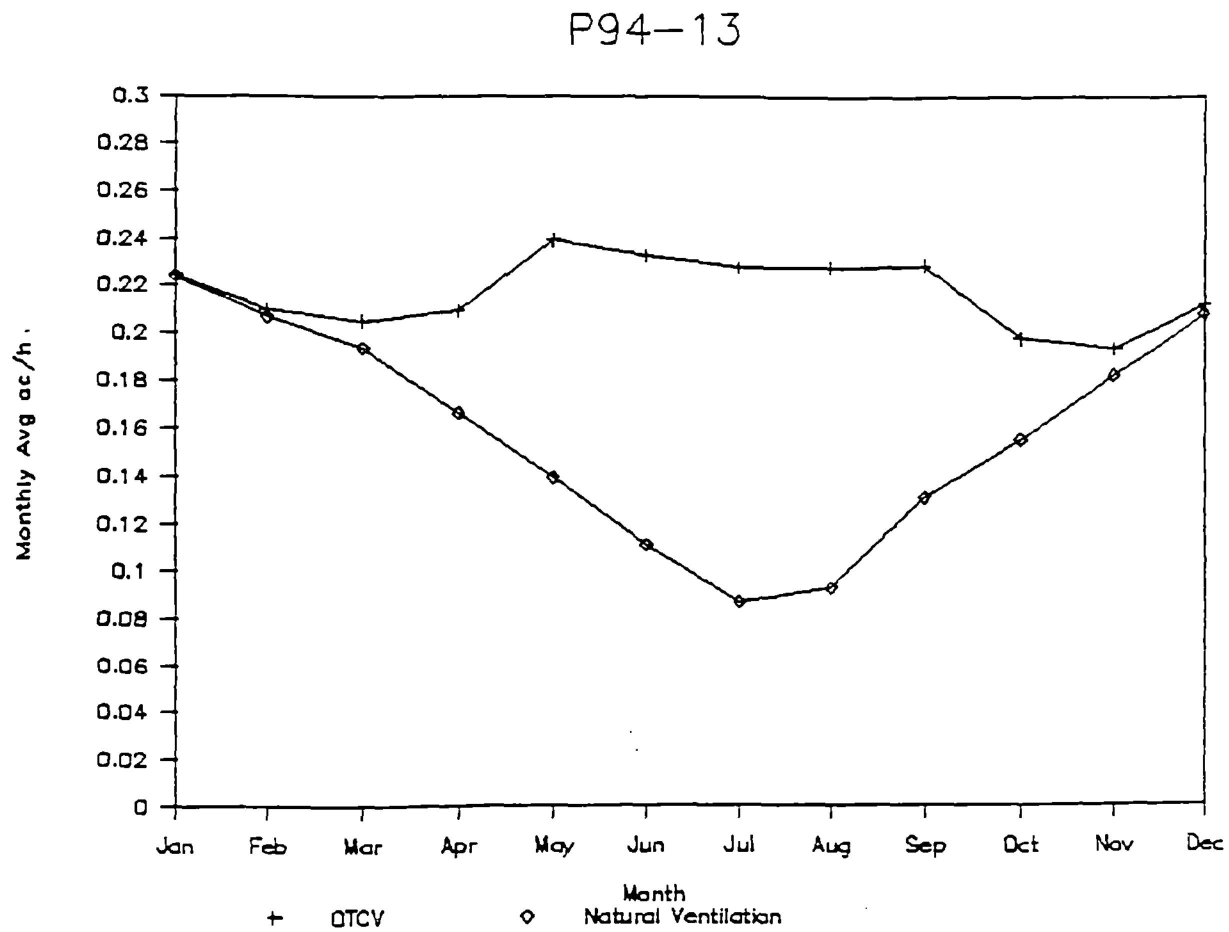


Figure 25. HOT 2000 simulation of OTCV and natural ventilation in house P94-13.

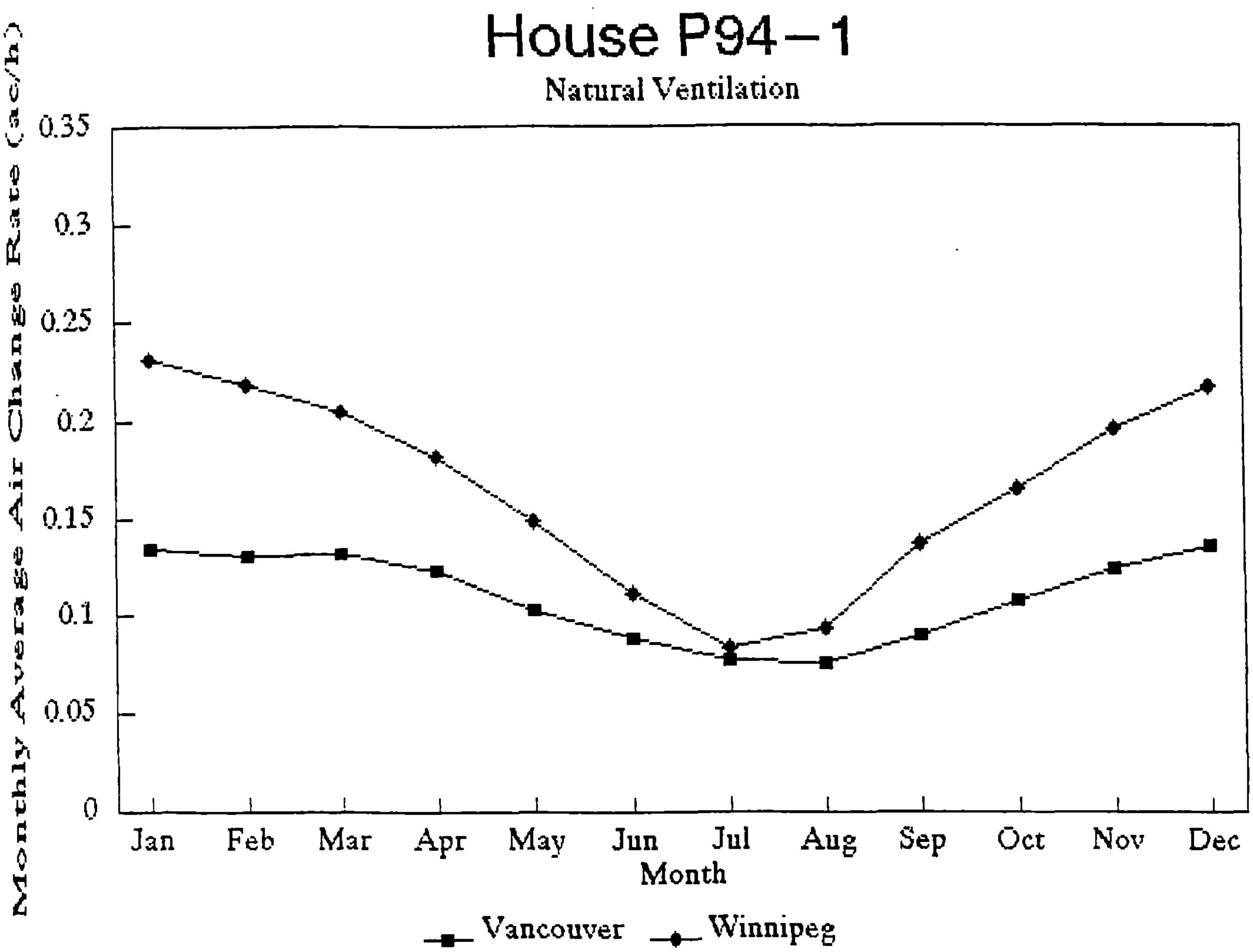


Figure 26. Calculated average monthly air change rates for house P94-1 when located in Vancouver and Winnipeg. Natural ventilation mode.

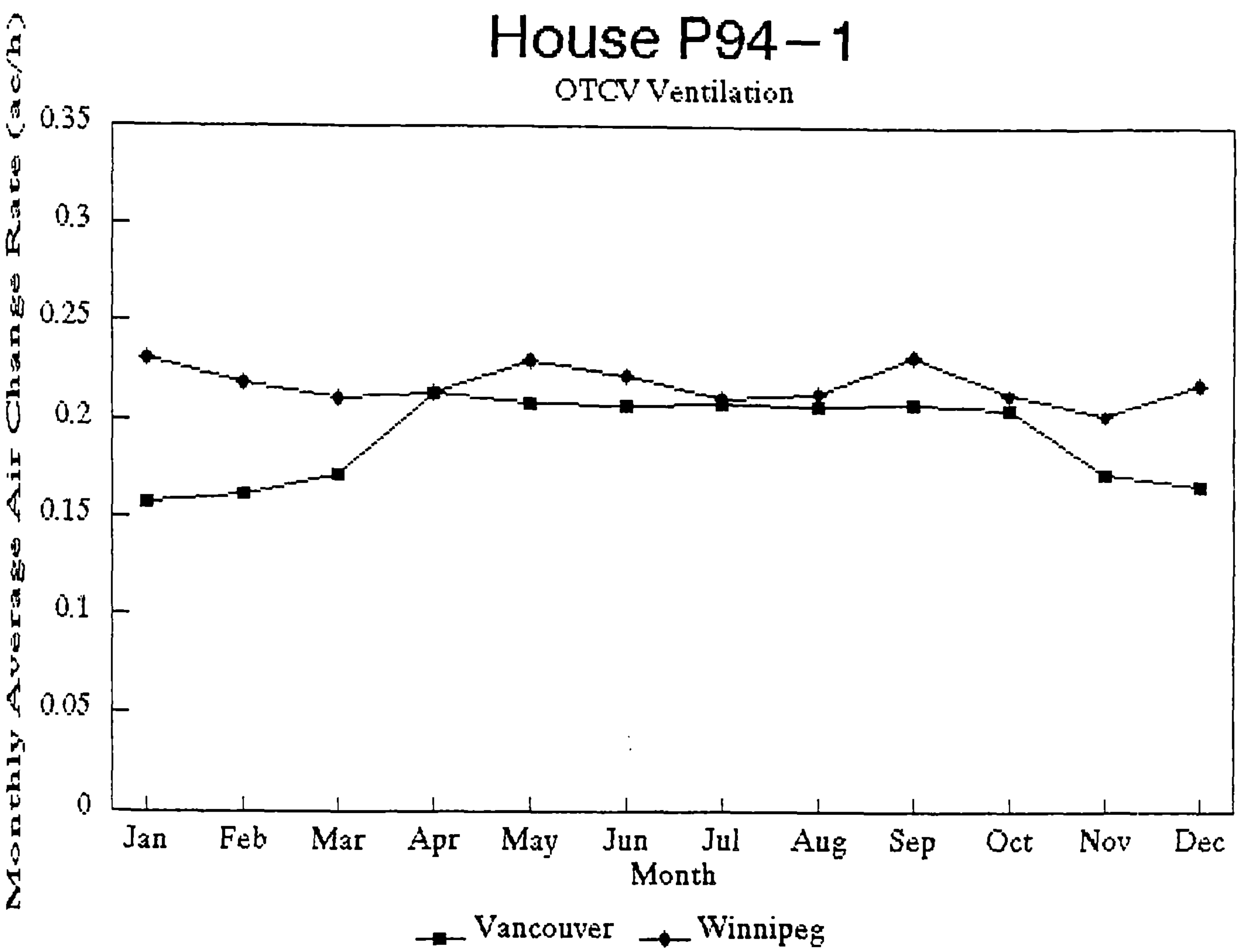


Figure 27. Calculated average monthly air change rates for house P94-1 when located in Vancouver and Winnipeg. OTCV ventilation mode.

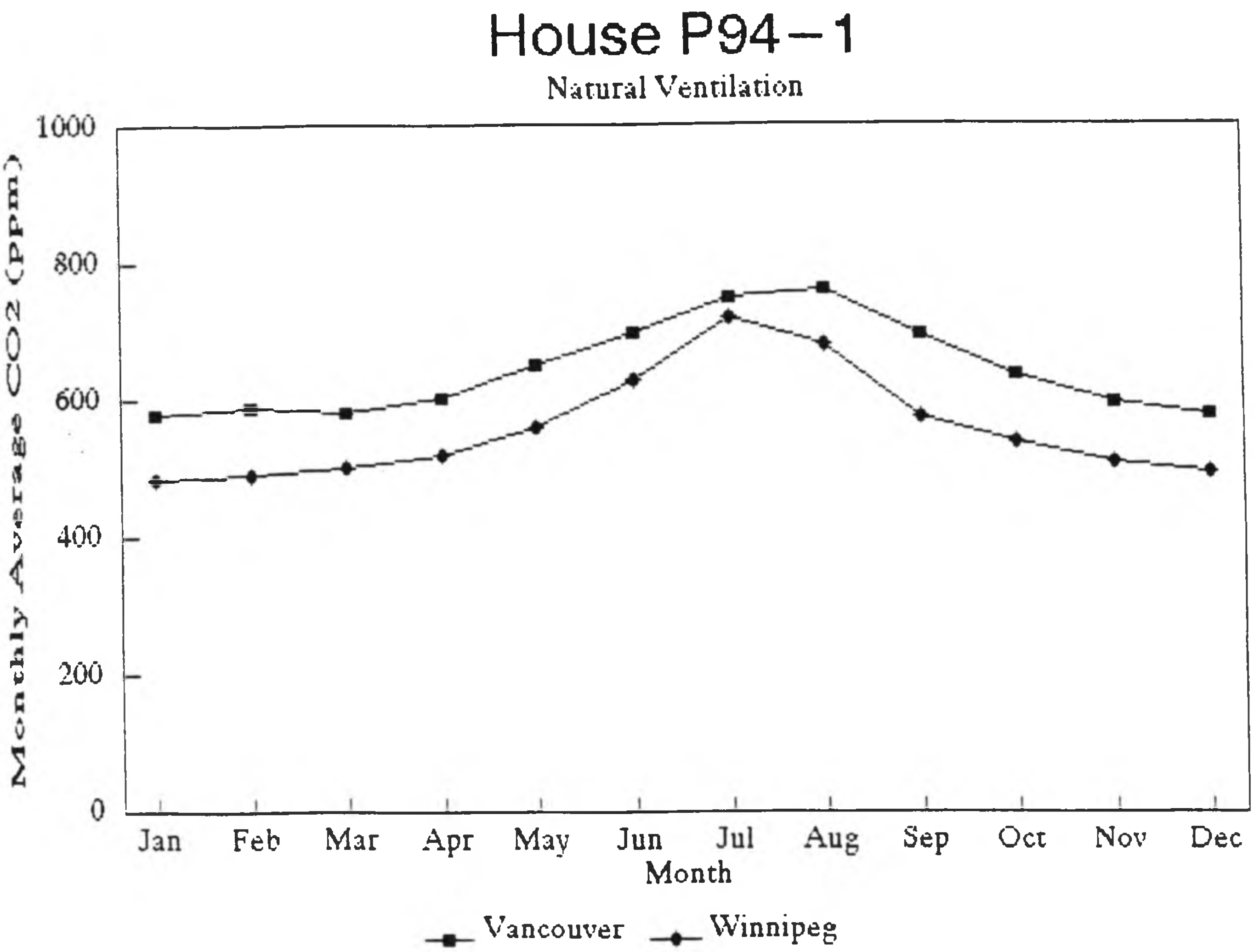


Figure 28. Calculated monthly average carbon dioxide values for house P94-1. Natural ventilation mode.

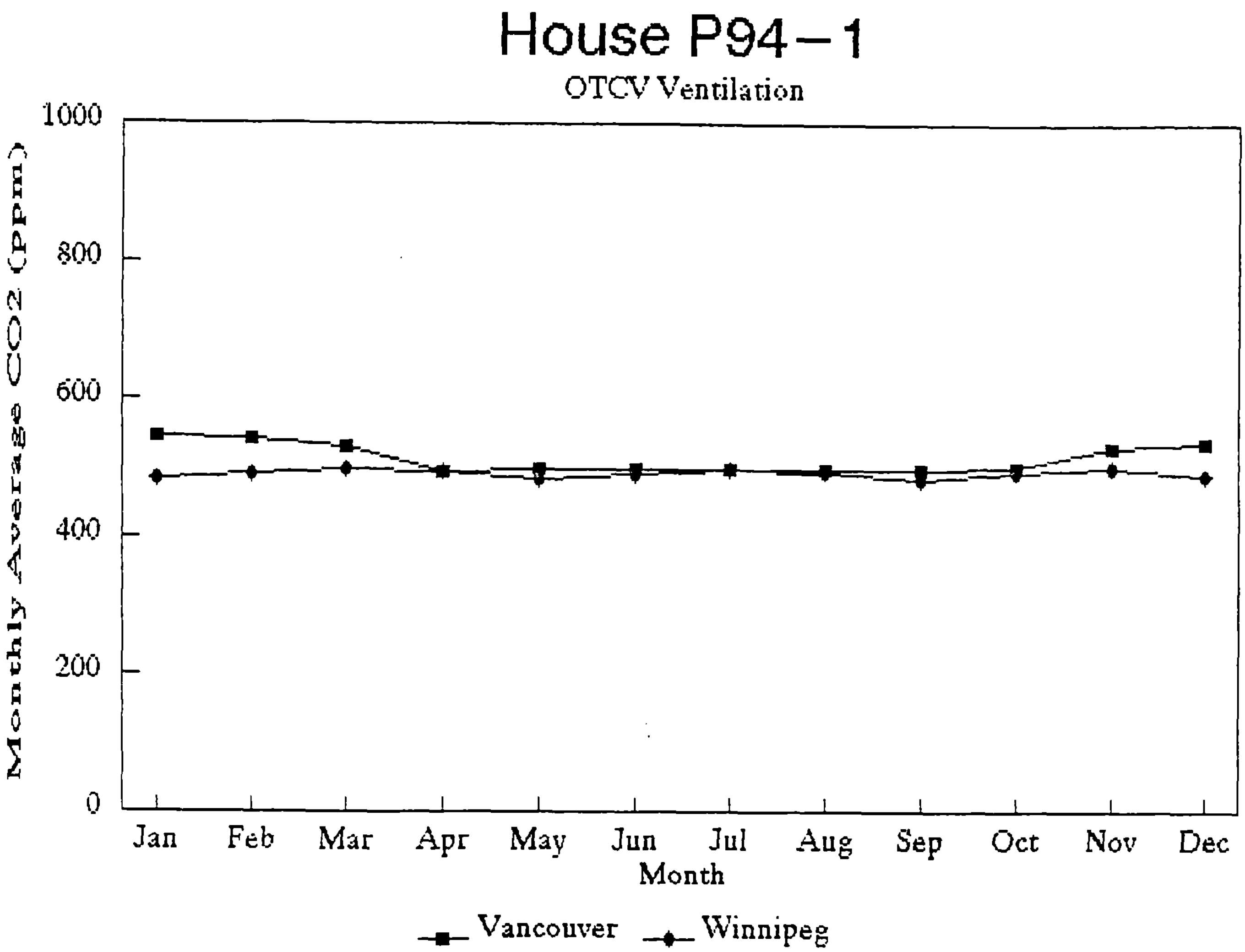


Figure 29. Calculated monthly average carbon dioxide values for house P94-1. OTCV ventilation mode.

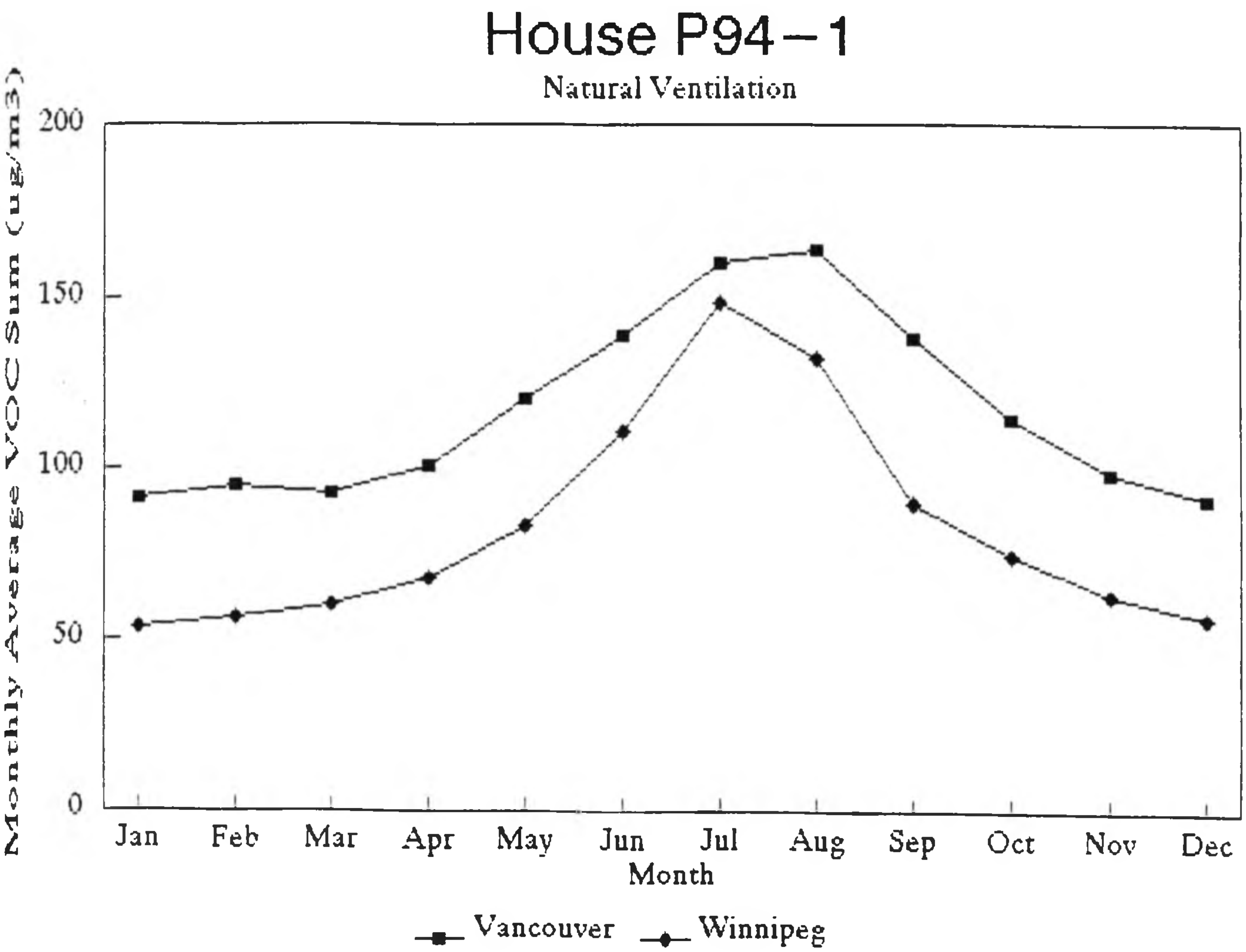


Figure 30. Calculated monthly average VOC sum values for house P94-1. Natural ventilation mode.

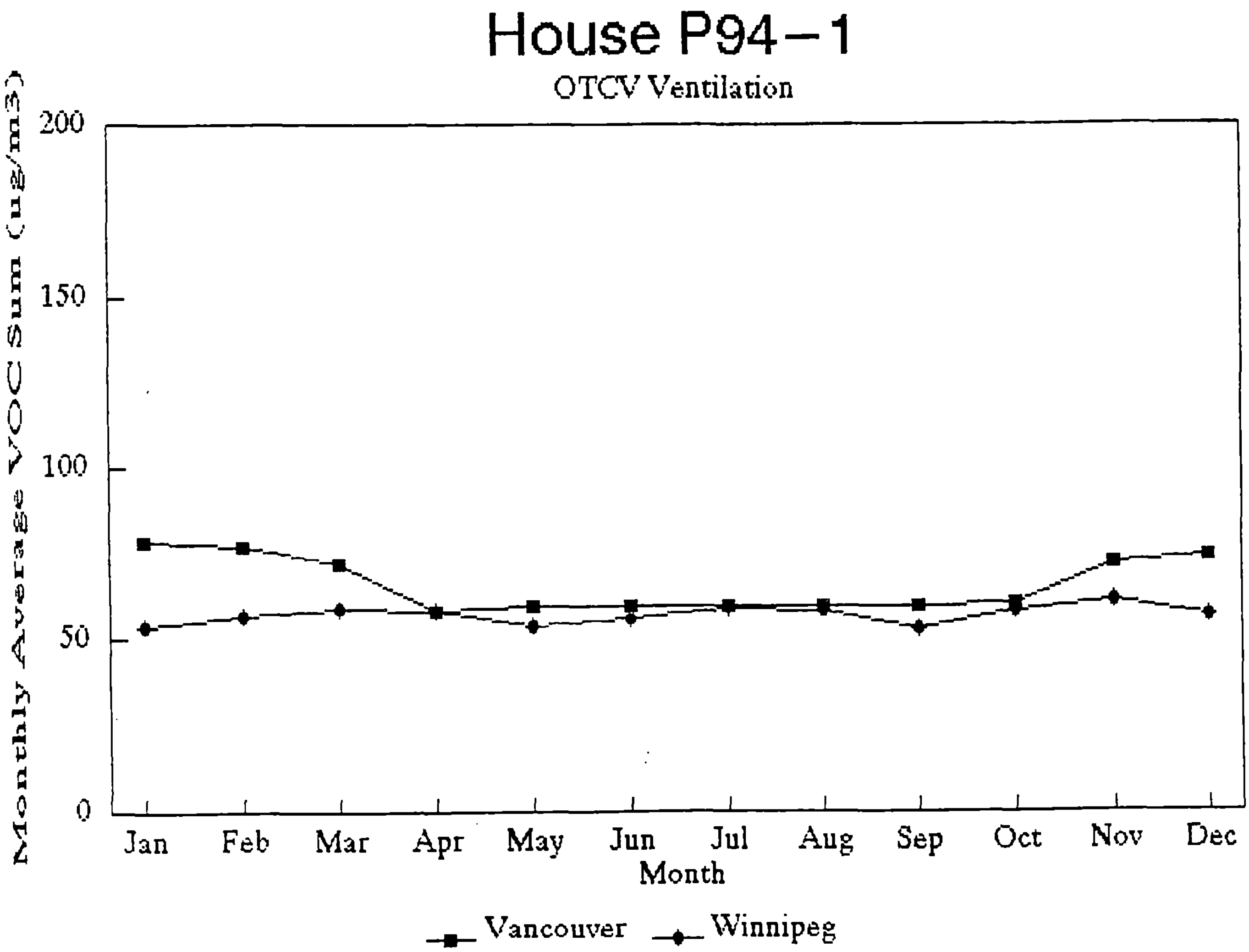


Figure 31. Calculated monthly average VOC sum values for house P94-1. OTCV ventilation mode.

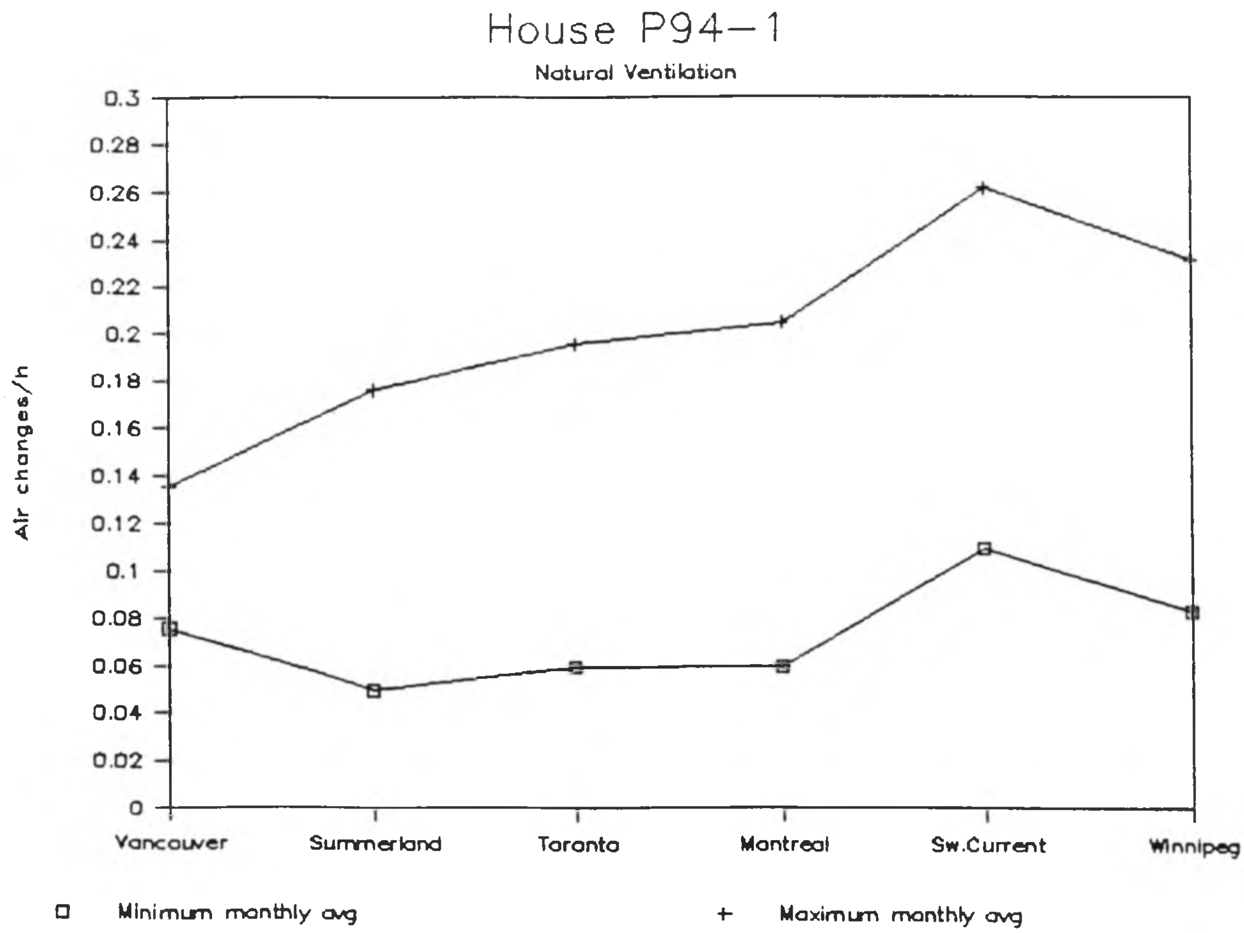


Figure 32. Minimum and maximum monthly average ventilation rates for house P94-1 when located in six cities across Canada. Natural ventilation mode.

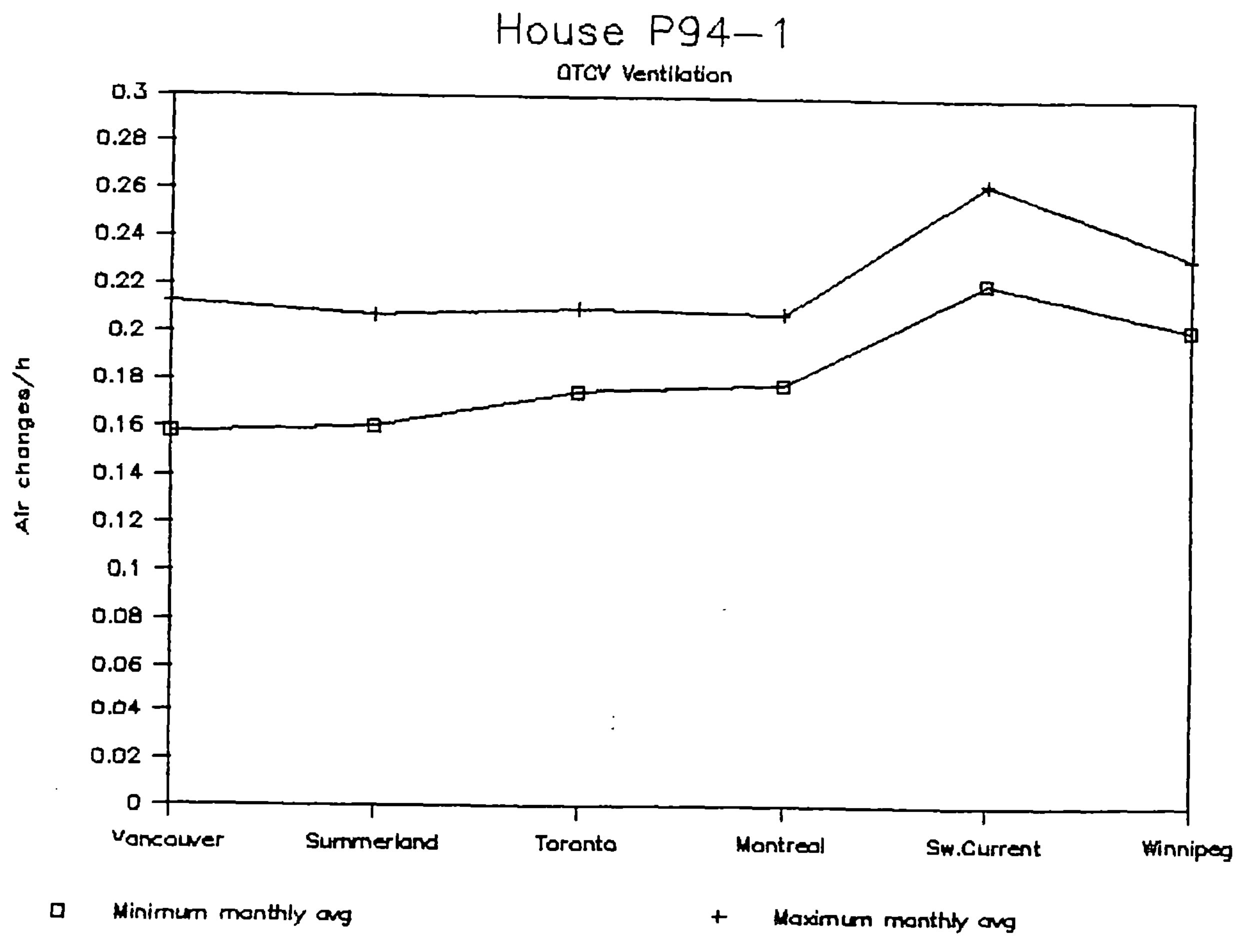


Figure 33. Minimum and maximum monthly average ventilation rates for house P94-1 when located in six cities across Canada. OTCV ventilation mode.

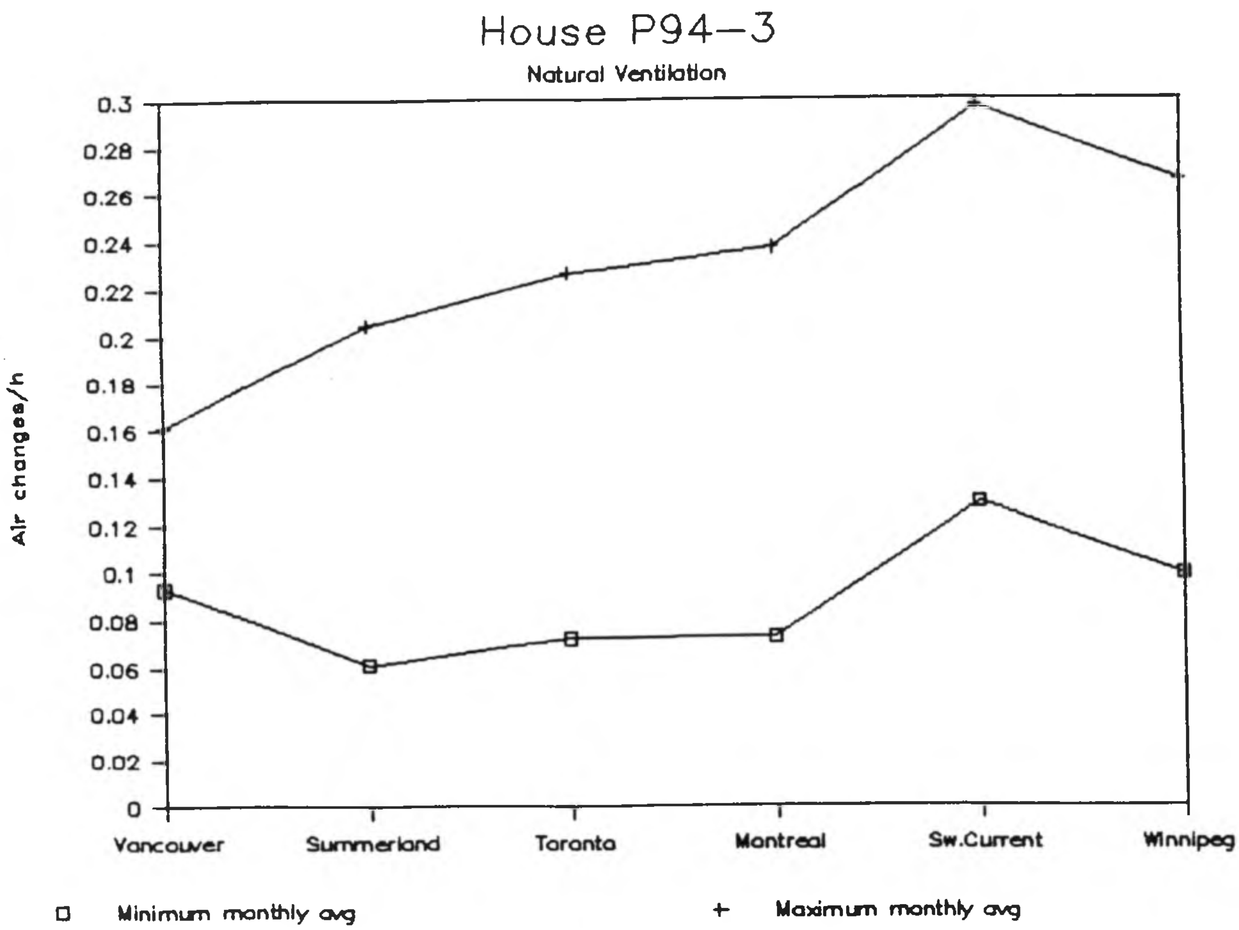


Figure 34. Minimum and maximum monthly average ventilation rates for house P94-3 when located in six cities across Canada. Natural ventilation mode.

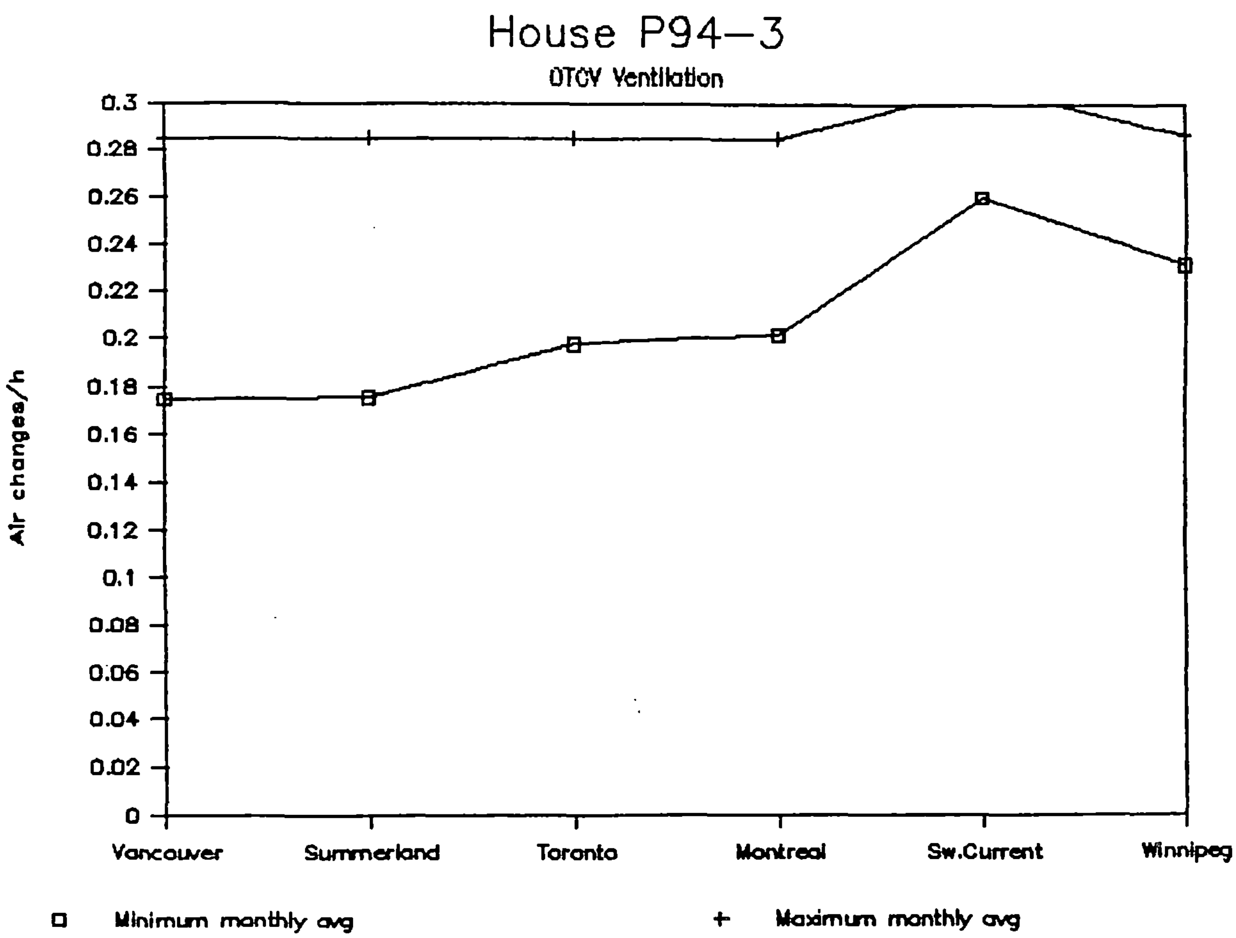


Figure 35. Minimum and maximum monthly average ventilation rates for house P94-3 when located in six cities across Canada. OTCV ventilation mode.

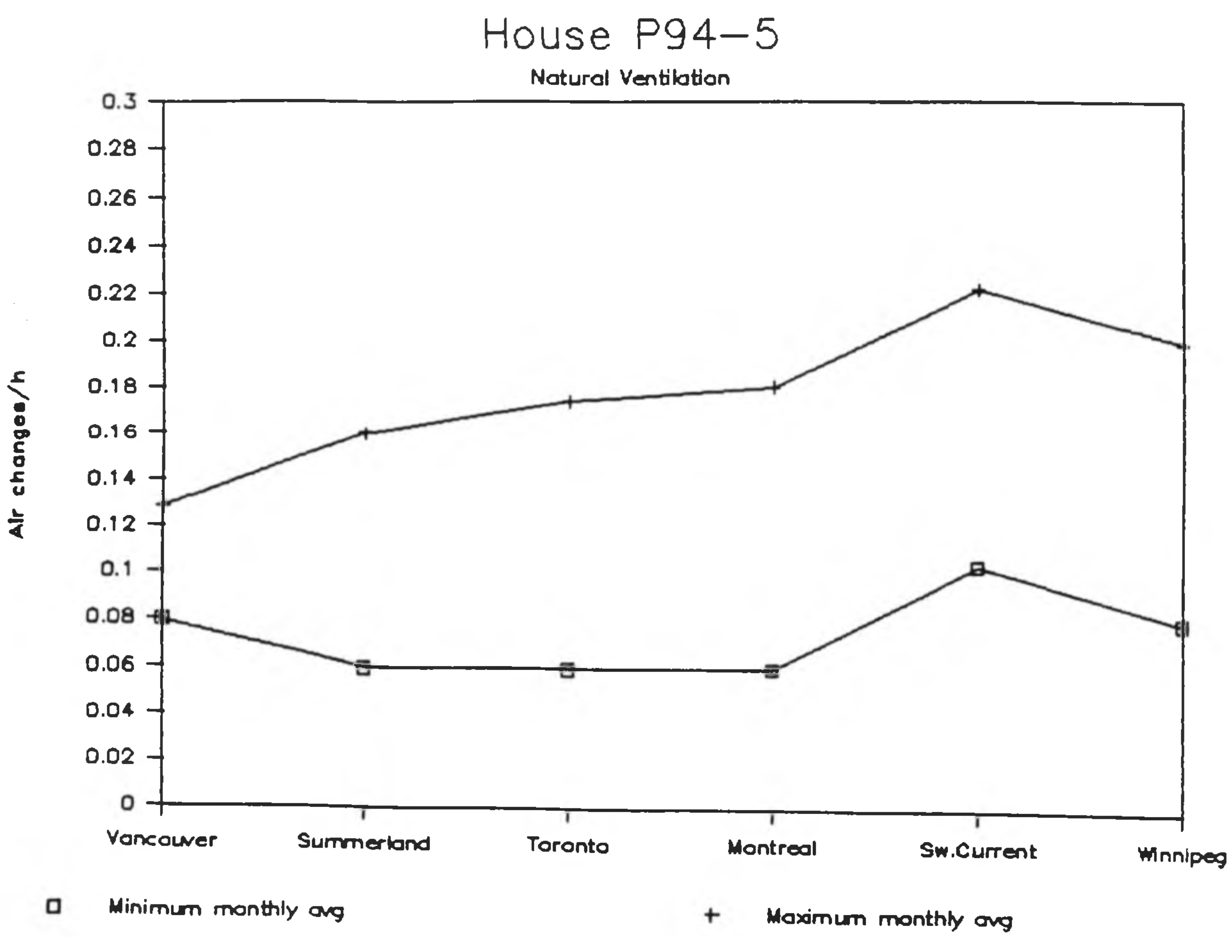


Figure 36. Minimum and maximum monthly average ventilation rates for house P94-5 when located in six cities across Canada. Natural ventilation mode.

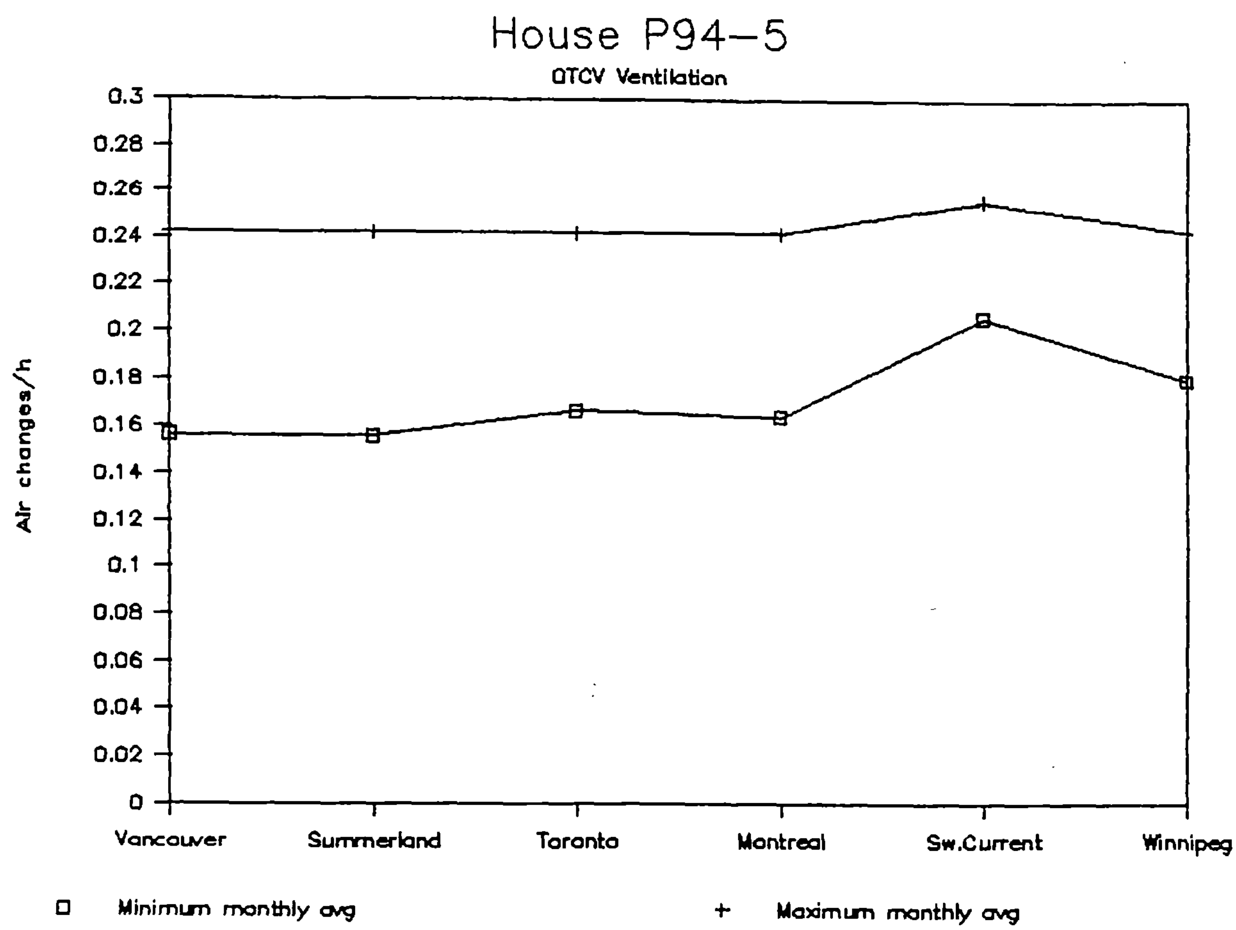


Figure 37. Minimum and maximum monthly average ventilation rates for house P94-5 when located in six cities across Canada. OTCV ventilation mode.

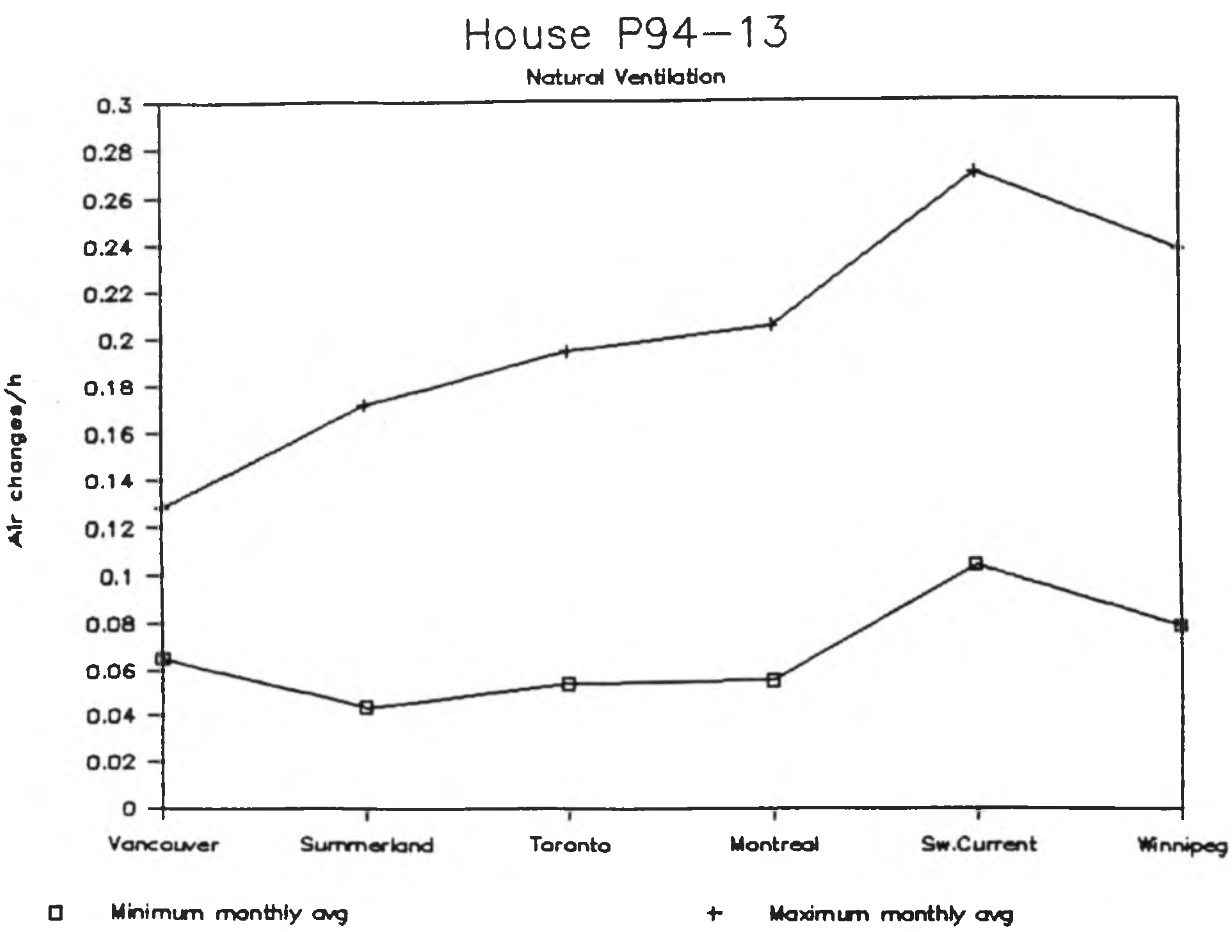


Figure 38. Minimum and maximum monthly average ventilation rates for house P94-13 when located in six cities across Canada. Natural ventilation mode.

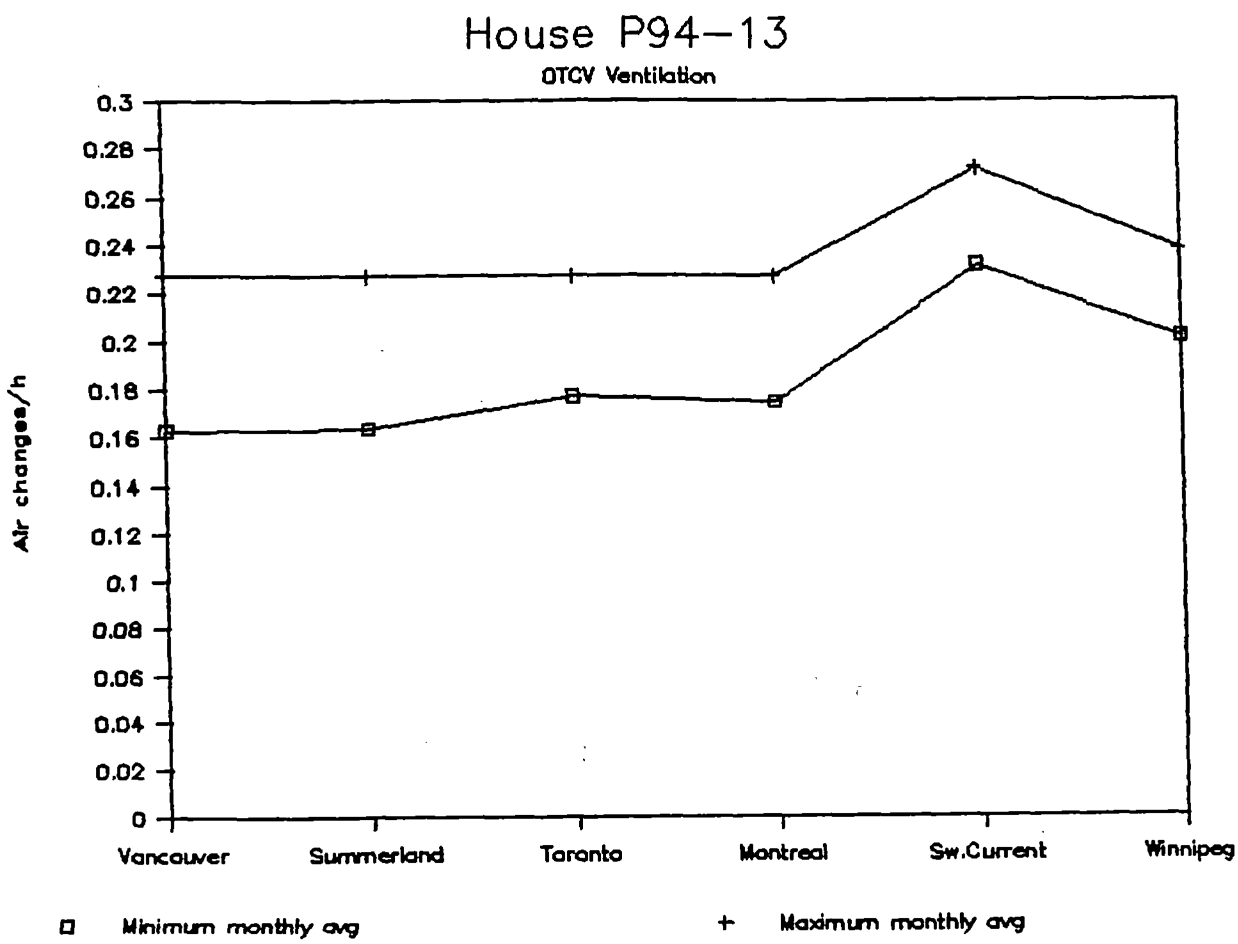


Figure 39. Minimum and maximum monthly average ventilation rates for house P94-13 when located in six cities across Canada. OTCV ventilation mode.