DEMAND CONTROLLED VENTILATION

FINAL REPORT

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Demand Controlled Ventilation

A Research Report
Submitted to:

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Canada Mortgage and Housing Corporation

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SUMMARY

This research project was completed for the Research Division of Canada Mortgage and Housing Corporation, and is part of Canada's contribution to an international research effort on Demand Control Ventilation (DCV). The research took place between September 1989 and December 1990.

The primary objective for the project was to determine if DCV can improve the way in which Canadian houses are ventilated, while lowering the operating or capital cost of ventilating systems. A further objective was to provide guidance for home builders and ventilation system designers on what DCV strategies might be most appropriate for near term applications.

The project was completed in five separate phases, which included a literature survey, the preparation of a Primer for home builders and system designers, extensive field research on five houses, computer simulations, and economic analysis. The results of the first two phases have been combined into a separate publication - *A DCV Primer for Home Builders and System Designers* which provides a popular explanation of ventilation strategies, and identifies many types of sensor technologies and DCV hardware that are currently available or under development.

The field investigations on the five research houses were intentionally designed to test ventilation systems compatible with the new F326 Ventilation Standard. The research houses were all energy efficient, low toxicity construction. The houses were located in both coastal and interior climatic zones. The variety of systems was intended to reflect the most common approaches applied in new energy efficient Canadian housing.

Summary Table 1 Description of ventilation systems in the Five Research Houses

Sue house	HRV with recirculating system
Jones house	HRV with no recirculating system
Smith house	Exhaust only with recirculating system
Morewood house	Exhaust only with no recirculating system
Helma house	Multiple sensor DCV system, HRV with recirculating system

The Sue, Jones and Smith houses were extensively monitored and retrofitted as part of the research. The Morewood house had an existing DCV system which was tested as found. The Helma house was new construction, and incorporated ventilation design specifications prepared as part of this project.

Field investigations began with extensive commissioning tests on existing ventilation systems, followed by minor upgrades and installation of long term monitoring equipment. After three months of monitoring house performance and air quality without DCV, each house was retrofitted with a new DCV system. The new DCV systems employed a variety of sensors, to permit continuous measurement of such parameters as CO_2 levels, pressure differentials, temperatures indoors and out, relative humidity, absolute humidity, air flow through the ventilation system, activity levels within the house, operation of heating equipment and clothes dryers, and air flows through variable exhaust equipment and furnace blowers. Several patented devices for gauging air quality measurement were also employed in the houses, including the Massawa Vital Air Purity meter (combining oxygen, particles and humidity), and the Halitech Sensor (for odours and combustibles). Different combinations of sensors were used in each house, as dictated by the type of systems. Spot measurements were also conducted for measuring formaldehyde, organics and other pollutants.

Intensive monitoring of activity scenarios was conducted in four of the research houses, to measure how the systems responded to very different kinds of activities within the home. The intensive monitoring included: a tracer gas growth test in each house, to measure ventilation effectiveness; a tracer gas decay test, to measure ventilation efficiency; a mass balance moisture test, to measure the capture efficiency of the exhaust inlets; and a multi-point absolute humidity test, to measure the moisture absorption and desorption rates of the entire house.

During the intensive monitoring, **Co-pilot**, a program designed for MS-DOS computers, was successfully used as a sophisticated controller and data acquisition system. Co-pilot was capable of simulating many different DCV control strategies.

An additional two months of monitoring was conducted, on the Sue, Jones and Smith houses, following the installation of DCV systems. This approach provided extensive data for comparison with the earlier pre-DCV configurations.

Summary Table 2 Low Level Monitoring

	DCV1: Sue house		DCV2: Jones house		DCV3: Smith house	
	Before	After	Before	After	Before	After
Control	RH	Activity	RH	CO_2	RH	Abs.Hum.
Hours of data	856	580	1,168	189	1,385	846
Outside Temperature (C)	3.8	10.5	2.7	NA	7.1	13.4
INSIDE:						
Temperature (C)	20.9	21.4	21.2	22.1	24.4	24.0
Relative Humidity (%)	40	42	38	NA	31	NA
Average CO_2 (ppm)	571	544	584	558	542	472
Max. hourly CO_2 (ppm)	2,250	948	996	726	2,767	1028
Vent. flow rate (L/s)	80	75	62	49	25	32
Vent. system time off (%)	0%	23%	0%	34%	0%	0%
Activity counts - fam. room	75	67	39	35	79	68
Activity counts - M.Bdrm.	4	4	15	13	4	5

With demand control, ventilation reductions of 6% to 21% resulted for the period monitored. This will result in a corresponding reduction in energy required to heat the ventilation air. In addition, fan electrical energy was reduced by from 23% to 34%[1]

While generally reducing energy use, all three DCV systems reduced CO_2 levels somewhat and significantly reduced the high peak CO_2 levels.

The combined **Enerpass/Contam87 program**, created for this project, was successfully used for calculating the energy operating savings of DCV in three different climate zones and for a variety of control strategies.

A series of hourly simulations were performed using the Enerpass/Contam87 program. The base house was a bungalow with full basement, 123 m^2 per floor. Simulations with continuous fan operation (base cases) and demand controlled ventilation (based on CO_2 level control) were carried out for Vancouver, Toronto and Winnipeg.

The results of the simulations for matching average carbon dioxide concentrations to the base case showed savings ranging from 3.2 GJ per year (Vancouver) to 5.6 GJ per year (Toronto) - equal to annual savings of from $19 to $37. Over a ten year period, this would translate into an allowable economic investment of from $200 to $400.

[1] Not counting the Smith house, which required increased ventilation rates to reduce very high peak CO_2 levels (over 2,500 ppm). Also, the system was not cycled off during periods of no occupancy due to the relatively low peak capacity of the system.

Matching **peak** carbon dioxide concentrations to the base case showed savings ranging from 9.6 GJ per year (Vancouver) to 15.7 GJ per year (Winnipeg) - equal to annual savings of from $46 to $66. Because of higher energy costs, the 11.8 GJ saved per year for Toronto translated into annual savings of $69. Over a ten year period, these savings would translate into an allowable economic investment of from $500 to $700.

Savings with DCV were comparable to savings predicted for conventional heat recovery ventilators and the installed cost of the simpler forms of DCV is likely to be significantly less than for HRV systems. Maintenance costs are also likely to be significantly less than for current HRV technology.

CONCLUSIONS and RECOMMENDATIONS:

- **DCV offers benefits only** when time-varying occupant generated pollutants exceed building related pollutants
- **Source control of building generated pollutants** at the construction stage is essential for applying DCV control strategies in new Canadian homes.
- **CO_2 is an excellent indicator of occupancy** and ventilation requirements in residential buildings. A small, moderately priced passive CO_2 gas analyzer performed well in three research houses.
- **Activity related pollutants** are best controlled by special purpose high capacity, directly vented, exhaust fans with high capture efficiencies.
- **Relative humidity is a poor indicator of occupancy.** Response times are slow and often there is no discernable change in RH despite major changes in occupancy and CO_2 concentrations. Absolute humidity is a much better indicator of occupancy than relative humidity but still displays a lag time that is due to absorption and desorption characteristics of the house. Ventilation control based on absolute humidity is limited to the heating season, and is best combined with a window inside surface temperature to provide condensation control.
- **The dehumidistats** commonly employed for RH control were found to be grossly inaccurate, as supplied by the manufacturers, subject to drift over time, and lacking any convenient means for re-calibration.
- **Passive Infra Red (PIR) activity sensors** proved low cost and reliable during the field trials. They have a poor short term correlation with CO_2 but excellent long term correlation. The poor short term correlation is due to the fact that activity is sensed instantly whereas pollutant concentrations

rise over time. Short term correlations could be improved with more sampling points, and a software program that is able to gauge the level of activity over time, and allow the system to respond to the rhythm of the house.

- **Semi-conductor sensors** (e.g. Figaro T68800) appear to have potential as an overall IAQ indicator if used in alternating operation with a breather that periodically flushes the sampling chamber to automatically zero the sensor.
- **High mixing rates in residential houses** are preferable to zoning and can greatly reduce the ventilation requirements on a room by room basis. In an energy efficient home, the ventilation requirements - not the heating load - should dominate the design specifications for air moving and distribution systems.
- **DCV systems** are particularly effective at **reducing peak pollutant** concentrations. This offers improved health and comfort, even if the mean level of pollutants are similar for systems without DCV.
- **Further research**, including theoretical work and chamber testing, is needed to develop a simple and reliable performance test capable of describing the effectiveness of fresh air distribution, and the response time of systems to fresh air demands. The development of these tests could greatly facilitate the evolution of ventilation systems, and the incorporation of minimum standards within the building codes.
- **Inlets equipped with humidity controlled bladders** were found to be particularly **ineffective** for DCV applications, both in a coastal climate and in central Canada.
- **DCV system design** can be simplified by defining the most common operating modes for the house, and configuring the air mixing and air change rates accordingly. Typical operating modes could be: standby (with timer activated intervals of operation); occupant arrival; high activity; odour control; and sleep.
- **A potential exists for lowering the capital costs** of sophisticated DCV systems by using a multipurpose home computer.
- **Occupants should not be relied upon** to optimize the operation of ventilation systems.
- **DCV systems** have the potential to become highly visible **sales features**, especially if occupants are provided with continuous feedback on indoor and outdoor environments.

RÉSUMÉ

CONCEPTS DE VENTILATION AUTORÉGLABLE

INTRODUCTION

La ventilation autoréglable (VA) permet de contrôler l'apport d'air de ventilation au taux minimal nécessaire pour maintenir la qualité de l'air dans les habitations. Ces systèmes peuvent réduire les besoins en énergie et ou améliorer la qualité de l'air ambiant. Les modèles examinés lors de cette étude sont principalement axés sur l'efficacité énergétique.

CONCEPTION DE LA RECHERCHE

Une recherche documentaire a été entreprise, pour obtenir autant de connaissances possibles sur la ventilation, les capteurs de qualité d'air ambiant et les stratégies de ventilation autoréglable. Des données sur les variations spatiales et temporelles de la qualité de l'air ambiant dans les maisons ont été recueillies sur place.

Des stratégies susceptibles de donner des résultats satisfaisants ont alors été élaborées, et ont été testées in situ. À partir des résultats de ces tests, on a effectué des simulations de rendement, heure par heure, de plusieurs systèmes de ventilation dans plusieurs climats canadiens. Les économies d'énergie ont ensuite été estimées pour la ventilation autoréglable, la ventilation à récupération de chaleur avec échangeurs de chaleur air à air, puis comparées à un système de ventilation à sortie continue utilisé comme référence. Tous les systèmes utilisaient la recirculation de l'air.

RÉSULTATS

Le contrôle de trois maisons occupées a fourni des données de référence sur la production de polluants et des informations sur le fonctionnement des systèmes de ventilation. Toutes les maisons étaient éco-énergétiques, avec des enveloppes relativement étanches et des systèmes de ventilation mécaniques. Plusieurs expériences portant sur le rendement du système de ventilation et la production de polluants ont indiqué que des volumes élevés (90 Ls) et des rendements de capture très efficaces sont nécessaires pour les hottes de cuisinières, afin d'éviter que les polluants ne se propagent à travers la maison. Les systèmes d'évacuation et d'admission d'air à humidité contrôlée ne semblaient pas réagir positivement aux changements d'humidité. L'une des maisons (VA3) avait une capacité insuffisante pour contrôler les polluants, aucune recirculation de l'air, et en conséquence, n'enregistrait aucune économie d'énergie avec une VA, bien que la qualité de l'air ambiant ait été améliorée. Ce cas n'a pas été considéré comme offrant une base de comparaison satisfaisante pour la conception de VA. Les deux autres maisons ont enregistré des économies grâce à la VA, de 6 et 21% pour l'écoulement d'air et de 23 et 34% pour l'énergie de ventilation.

Les incidences potentielles de modèles de VA furent généralisées dans une simulation horaire par ordinateur des diffusions de l'air et des niveaux de polluants, en utilisant des données typiques sur l'occupation des bureaux et le climat local pour Vancouver, Winnipeg et Toronto.

Une stratégie de ventilation autoréglable qui a conservé une qualité de l'air ambiant équivalente à une ventilation continue d'évacuation a été simulée en ajustant le point de demande de ventilation de CO^2 jusqu'à ce que des concentrations maximales de CO^2 soient atteintes dans les deux cas. La ventilation autoréglable a permis d'économiser de 9,6 Gjannée (Vancouver) à 15,7 Gjannée (Winnipeg). En se fondant sur les prix locaux de l'énergie, les économies ainsi réalisées allaient de 46 $ (Vancouver) à 69 $ (Toronto) par an, avec une perspective d'économies de 500 $ à 700 $ sur un investissement de dix ans. Ces économies sont environ les mêmes que celles offertes par les systèmes de ventilation à récupération de chaleur actuels utilisant des échangeurs de chaleur air à air.

Le cas de référence où la concentration de CO^2 était moyenne démontre que la VA peut améliorer le confort en réduisant les maxima de concentration, tout en permettant des économies.

CONSÉQUENCES

Les VA n'ont pas d'avenir à moins que l'on puisse réduire les polluants produits par la construction.

Si les polluants de construction sont réduits et les polluants résultant d'activités (comme la cuisine) sont effectivement évacués, la VA peut alors permettre de contrôler les polluants produits par l'occupant.

Cependant, il n'y aura pas d'économie d'énergie importante à moins que l'enveloppe de l'immeuble ne soit suffisamment étanche pour réduire les fuites d'air naturelles à environ 0,1 changement d'air par heure.

Les capteurs de gaz carbonique semblent être le meilleur contrôle pour les polluants produits par l'occupant. On a utilisé trois capteurs de CO^2 bon marché, et ils ont semblé fonctionner de façon satisfaisante. On prévoit que le coût de ce type de capteur par absorption à infra rouge baissera à environ 200 $.

Les capteurs d'activité, utilisés couramment pour les systèmes de sécurité se sont avérés de bons capteurs potentiels pour contrôler l'occupation des espaces autres que les chambres à coucher. Une minuterie pourrait contrôler la ventilation pendant la nuit.

On a constaté que l'humidité relative est un mauvais indicateur de l'occupation. L'humidité absolue était meilleure, mais il y avait un décalage de temps notable dû à l'absorption par la maison et son contenu. Les déshumidostates ne se sont pas révélés fiables.

La recirculation de l'air dans les logements fait baisser la concentration locale de polluants produits par l'occupant et réduit ainsi la quantité de ventilation nécessaire. Ce ne serait pas vrai dans les logements classiques avec une quantité élevée de polluants générés par la construction. Les prises passives, avec des ouvertures contrôlées par l'humidité, se sont avérées inefficaces pour la distribution de la ventilation d'air.

Il serait possible de réduire le coût des contrôleurs de Va en les intégrant aux thermostats et aux systèmes de sécurité domiciliaires. Les systèmes de VA devront être commandés et entretenus par des experts. La VA pourrait devenir un élément à haut profil pour la vente des maisons, particulièrement si les occupants reçoivent une rétroinformation continuelle sur l'environnement intérieur et extérieur.

Ce projet a été partiellement financé par le Groupe d'experts pour le développement et la recherche énergétique et constituait une partie de la contribution du Canada à l'Agence internationale pour l'énergie. Le travail a été effectué par Peter Moffatt, et Sebastian Moffatt de Sheltair Scientific Limited, Ken Cooper de SAR Engineering Limited, avec Tom Hamlin de la Société canadienne d'hypothèques et de logement.

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1 INTRODUCTION

Background

The following project was completed for CMHC and is part of Canada's contribution to an international research effort on **Demand Controlled Ventilation (DCV).**[2]

DCV systems attempt to minimize the volume of air flow required by ventilating when and where needed in order to maintain indoor air quality. Reductions in air flow translate into lower operating costs for the heating and ventilating systems. DCV systems are intelligent and therefore have the potential to improve the efficiency and effectiveness of ventilation systems in houses.

DCV systems use technological advances in computer control and electronic and biological sensors to minimize the volume of fresh air flow required to maintain indoor air quality. DCV systems only have potential for saving energy when the pollutant load being monitored varies by location within a building or varies hour by hour according to the level of occupancy in the building. Direct sensing of pollutant load allows fine tuning of the forced ventilation rate to closely match the varying demand.

An evaluation of DCV systems must be predicated on two basic assumptions:

- **occupant related pollutants dominate building related pollutants; and**
- **the building envelope is sufficiently air-tight that forced ventilation is required.**

This study therefore applies to a small but growing subset of Canadian housing stock. Most houses are currently quite toxic and require continuous high rates of ventilation to control the off-gassing from building materials[3]. A considerable effort will be required by the building industry to reduce building pollutants at source. However the extra effort may bring significant rewards.

The extra ventilation required to control building related pollutants has reached the point where ventilation the costs in energy efficient houses comprise 50% of the total energy used for space heating and cooling. Simply put, to avoid pollution indoors we are consuming more energy and thereby contributing to pollution outdoors.

[2] The International Energy Agency (IEA) has a Program on Energy Conservation in Buildings and Community Systems. Annex 19 of this program is responsible for coordinating the effort on DCV by a number of participating countries.

[3] Even with 0.3 ach air change rate, a significant number of conventional houses exceed the Health and Welfare formaldehyde target level of 0.05 ppm according to the CMHC study "Ventilation and Airtightness in New Detached Houses", May 1980, by Tom Hamlin et al (survey of 194 new houses across Canada).

The escalating costs for ventilation are of special concern to Canada's housing industry. Continuous mechanical ventilation systems are being installed in an increasing number of homes. With the likelihood that building codes will adopt new ventilation standards, such as the CSA F326, the number of ventilation systems can be expected to increase even more rapidly, this in turn will lead to concerns about increasing capital and operating costs.

Another concern is the inefficiencies of many current ventilation system designs. Unresponsive systems can result in high peaks for pollutants with variable emission rates. The result is more occupant discomfort or ill health, despite high average air change rates.

This report describes how DCV systems may reduce the environmental impact of housing, lower heating and cooling costs, and improve occupant comfort and health. The first step in this direction is the control of building related pollutants at the time of construction.

2 RESEARCH OBJECTIVES

The objectives of this project are as follows:

- to determine if DCV can improve upon the way we are ventilating our houses and meet performance criteria for an optimum ventilation system;
- to measure if DCV can lower operating or capital costs of ventilation systems;
- to establish when a DCV strategy best fits into the design of a new house; and,
- to indicate directions for future research and to identify current barriers to DCV applications.

3 FRAMEWORK FOR ANALYZING VENTILATION STRATEGIES

Our first step in evaluating DCV was to construct a conceptual framework to examine "why we ventilate houses". This framework is crucial to understanding both our approach to this research and our conclusions. Consequently, we have included a brief description at this time.

Very simply, we ventilate houses to keep indoor air quality as good or better than outdoor conditions and to avoid condensation problems from excess indoor humidity. We used three distinct categories of indoor pollutants in order to define the most appropriate ventilation strategy for controlling the pollutants.

Building Ventilation

The first task of a ventilation system is to control building generated pollutants for health-related concerns. Examples are toluene and other solvents, formaldehyde and other aldehydes, and soil gases such as radon and water vapour. In new Canadian houses, the generation of building pollutants is usually relatively constant and widespread throughout the house. Source control would include careful selection of materials, containment techniques, and construction practices that isolate outdoor sources. A steady-state ventilation system operating at a high capacity is appropriate for houses with little or no source control. Even with elaborate source control some minimum continuous ventilation will be required to control building generated pollutants.

Occupant Ventilation

The second task of a ventilation system is to control occupant generated pollutants such as carbon dioxide, moisture, and bioeffluents. Occupant related pollutants are concentrated on a room by room basis, vary depending on the time of day and number of adults and children at home, and are obviously not a concern if the house is unoccupied. A intelligent system based on sensors and computer control is the most appropriate for occupant generated pollutants. The system can combine mixing of air from occupied and unoccupied rooms in order to dilute pollutants and minimize the requirement for outdoor air.

Event-related Ventilation

The third task of a ventilation system is to control event-related pollutants such as the odours, moisture and particulates generated by cooking and bathing activities or hobbies. Event generated pollutants tend to be very localized both in time and space. Powerful direct exhaust fans controlled by occupants or sensors are the most appropriate system for dealing with event related pollutants. Exhaust fans with high capture rates will prevent the pollutants from spreading throughout the house.

If a ventilation system is to be acceptable to occupants, it must accomplish the above tasks without causing discomfort in terms of cold drafts and noise and without excessive heating cost or condensation problems.

Ventilation systems can also be used for purposes other than the removal of pollutants. For example, ventilation systems can be used to remove dust and pollens from outdoor air, or to heat and cool the house. Ventilation systems can avoid creating excessive house depressurization and to provide adequate make-up air for vented combustion appliances. These are not ventilation issues but are factors that may have to be considered in the overall design of a ventilation system. Ultimately a ventilation system design must be based on a number of parameters such as those listed in Table 3.1. It is this complexity of issues that makes an evaluation of DCV difficult.

Table 3.1
Parameters that influence ventilation system design

The presence of an air mixing and distribution system
Effect of ventilation system on house pressures
Pressure sensitivity of combustion equipment
Building pollutant load
Occupant pollutant load
Activity pollutant load
Envelope thermal efficiency
Envelope air tightness
Severity of climate
Outdoor pollutants
Fuel cost for electricity and heating fuel
Capital budget for building systems
Filtration requirements for occupants

Different packages of houses and ventilation systems will work well together. A list of criteria for evaluating ventilation systems is included in Table 3.2. As our houses become less toxic and more energy efficient, ventilation systems can be designed more to optimize ventilation requirements than as an adjunct to heating, cooling, or heat recovery systems. In these advanced houses, DCV strategies have the greatest potential for lowering costs and improving the effectiveness of the ventilation systems.

Table 3.2 Criteria for evaluating Ventilation Systems
Comfort
Health
Safety
Noise
Maintenance Requirements
Durability
Operating cost
Ease of installation
Size of equipment
Availability of equipment and local expertise
Track record
Complexity
Failure detection and diagnosis

In this report, the term **ventilation** refers to the exchange of indoor air with outdoor air. Mixing of air within a dwelling is a function of **circulation** systems as opposed to ventilation systems.

4 RESEARCH PLAN

The DCV research plan breaks down into five separate phases, as described as follows:

- a literature survey;
- the preparation of a primer for designers and builders of DCV systems;
- field research and data collection, including
  - commissioning of ventilation systems,
  - low level monitoring (before and after DCV), and
  - intensive monitoring of activity scenarios;
- computer simulations; and,
- economic analysis.

4.1 Literature Survey

The intention of the literature survey was to inform and guide research in further phases of the project. A large number of on-line computer databases were accessed for published materials and conference proceedings. Both North American and European papers were ordered for review.

Much of the previous work on DCV control has focussed on commercial applications and was not transferable to residential buildings. The emphasis has been on CO_2 detection as a basis for ventilation control. Some interesting work has been done on moisture loading and moisture control measures. Research on the effectiveness and efficiency of ventilation systems and establishing criteria for rating systems is sorely lacking. Many of the better papers are referenced in the Primer for Builders and Designers of DCV systems (see below).

4.2 DCV Primer for Home Builders and System Designers

The Primer is a catalog of tools and strategies that builders and designers can use to apply DCV. The products that are listed are not intended to be comprehensive. Instead we have emphasized products that are new or innovative, or that may have potential in the future if prices fall with advances in technology. Some products may already be used in a limited capacity and warrant more attention by the ventilation and housing industries.

The Primer is divided into five chapters with the following headings:

Table 4.1 DCV Primer Outline
Chapter 1: Ventilation Overview Chapter 2: DCV Strategies Chapter 3: Primary Sensor Technology Chapter 4: Secondary Sensor Technology Chapter 5: DCV hardware

Ventilation overview presents the terms and concepts that we use to address DCV issues.

DCV Strategies describes innovative ways to apply sensors, hardware or duct layout to achieve lower ventilation rates and more effective ventilation.

Primary sensor technology describes devices with sensors that enable us to detect occupant or event related pollutants.

Secondary sensor technology describes devices with sensors that enable us to detect conditions that are **related to** conditions or events that correspond with the production of occupant or event related pollutants.

DCV hardware describes equipment that allows the ventilation system to respond to pollutants detected by primary and secondary sensors.

Two important assumptions have been made as part of producing a Primer on DCV. The first assumption is that future houses will have some kind of sophisticated computer controller (i.e. such as an alarm system, Smart House, or Cebus) that can serve a dual purpose by incorporating DCV control. The second assumption is that houses will be built using "good building practice" particularly in regards to controlling pollutants at their source.

4.3 Field Research and Data Collection

The field investigations involved testing five research houses. The houses were located in different climate zones representing the extremes of weather conditions for Canadian houses. The five houses had a variety of ventilation systems compatible with the new CSA F326 standard. The differences between the homes were intended to reflect the range of designs commonly found in new energy efficient housing.

A description of the ventilation systems in the five houses is listed in Table 4.2.

Table 4.2 Description of ventilation systems[4] in the Five Research Houses

Sue house	HRV with recirculating system
Jones house	HRV with no recirculating system
Smith house	Exhaust only with recirculating system
Morewood house	Exhaust only with no recirculating system
Helma house	Multiple sensor DCV system, HRV with recirculating system

The first three houses were subjected to low level, long term monitoring with the intention of comparing DCV strategies with more conventional continuous ventilation strategies. The houses are labeled with the homeowner's last names: Sue house, Jones house, and Smith house. Special measures had been taken by the builders during construction to reduce building generated pollutants in these three research houses, making them particularly suitable for DCV.

The fourth house was part of another project designed to evaluate the applicability of the Aereco ventilation system in the harsh Canadian climate. Scanada Consultants Limited had completed this evaluation as part of a separate contract with Energy, Mines and Resources Canada. The house takes its label from the small community where it is located: the Morewood house.[5]As part of this DCV project additional intensive monitoring was carried out with the intent of gauging how well the ventilation system and house respond to increases and decreases in humidity.

[4] Note: The Sue and Jones houses are actively controlled by a humidity sensor and the Smith and Morewood houses have passively controlled humidity sensitive control valves. Only the Helma house uses DCV controls other than humidity.

[5] Described more fully in the EMR report: "Operating Characteristics and Performance of the AERECO Humidity-Controlled Ventilation System, Phase II, Monitoring and Performance Analysis", July 1990, by Scanada Consultants Limited.

The fifth house was built during the course of the project, by Helma Construction, and is aptly called the Helma house. At the construction stage of the Helma house, the research team attempted to demonstrate an affordable DCV strategy, using current knowledge and technology. An elaborate computerized DCV control system was installed permanently in this new house. Duct work and fans were specified to take best advantage of DCV.

Field investigations took place in five stages:

Table 4.3 Steps in Field Investigations

Commissioning Ventilation Systems	(3 houses)
Pre DCV low level monitoring	(3 houses)
Intensive monitoring	(5 houses)
Post DCV low level monitoring	(3 houses)
Analysis and simulation	(5 houses)

4.3.1 Commissioning Ventilation Systems

Table 4.4 lists the steps taken during the commissioning of the three houses subjected to long-term monitoring. More detailed procedures and results are presented in the Appendix, sections 10.1, 10.2 and 10.3. The commissioning tests uncovered some very interesting situations, and some of the highlights are included in the main body of this report. To our knowledge this kind of analysis has not been done before on energy efficient houses in Canada. Extensive commissioning was required in order to fully understand how each house operated and to recognize areas requiring improvement or more thorough investigation.

Where a major problem was uncovered, the problem was remedied only if it was not felt to be typical of current installation practices. Dehumidistats were calibrated, booster fans were added to the ventilation system to balance flows, and dampers were adjusted to insure systems were operating as intended.

Table 4.4 Steps involved in commissioning of the Sue, Jones, and Smith houses

1. Calculate F326 and/or R-2000 Ventilation requirements in effect when house was built
2. Measure the air flows from inlets and outlets on a room by room basis[6]
3. Measure the total flow in and out of the house*
4. Collect information on envelope thermal efficiency and air tightness
5. Inspect operation of combustion equipment
6. Interview homeowner on operation of house
7. Measure flows from direct vent exhaust equipment*
8. Calibrate dehumidistat and thermostat
9. Clean filters and intake hoods and fine tune ventilation and heating systems
10. Document how house operates and describe any major deficiencies
11. Retrofit those problems judged atypical for the average Energy Efficient house

[6] *The Duct Test Rig (DTR) was an essential tool used for accurately measuring air flows (see CMHC report on the development of the DTR).

4.3.2 Low Level Monitoring of Homes Without DCV

The intent of the low-level monitoring was to obtain a clear picture of how the house was operating with a system providing continuous ventilation.

Campbell Scientific CR21 data loggers were installed in three houses in late November, 1989. Data was processed for the winter period from November through April, 1990. Processed data is available for over four months, however some sensors were late arriving or failed initial calibration tests, so not all data is available for the complete period (see Tables in Appendix, sections 10.1.2, 10.2.2 and 10.3.2.).

Low level monitoring, in all three houses, continued through the intensive monitoring period and then through to mid April, following the installation of demand controlled ventilation systems in the three houses.

The sensors that were employed in each of the houses are listed in Table 4.5. The types of sensors used were slightly different in each house because of the different ventilating and heating equipment.

Table 4.5
Measurement Systems in the Sue, Jones and Smith houses

Measurement	Description of Equipment	Sue	Jones	Smith
Carbon dioxide levels	Nova Passive Carbon Dioxide infra red gas analyzer	1	1	1
Pressure difference across the envelope and air flow through the ventilation system	Modus Electronic Pressure transducer		1	1
Temperature indoors and outdoors	Fenwal Temperature sensing thermistors	2	2	2
Relative humidity indoors	Physchem relative humidity sensor	1	1	1
Air flow through the ventilation system	Mitsubishi air flow sensor	1	1	1
Level of activity and occupancy in living area and bedroom	Passive infra red security sensors	2	2	2
Operation of heating equipment and dryer	Snap thermo disk switches	1	1	1
Air flow through other variable exhaust equipment and furnace blower	Dual Gang linear potentiometers	1		
Outside absolute humidity	Mitsubishi absolute humidity sensor	1		

In all houses, the activity of occupants was detected using simple Passive Infra Red (PIR) sensors developed for the security industry. This technique appeared to be low cost and reliable. Pulses were sent to and counted by the data logger, in proportion to the level of activity with sight of the PIR. In bedrooms, the PIR sensors would sometimes detect a sleeping person rolling over in the night. A high level of activity "counts" could be an indication of one individual constantly moving about the house, or a group of people visiting together.

Site visits were made, approximately on a weekly basis, in order to check operation of the monitoring units; to take manual readings of energy meters, and to complete sensor calibration checks.

4.3.3 Intensive Monitoring of Activity Scenarios

Intensive monitoring of activity scenarios was conducted in four of the research houses to evaluate the performance of ventilation systems. The purpose was to simulate activity scenarios in order to quantify how the ventilation systems controlled the build-up of occupant, building, and activity related pollutants. The four tests listed in Table 4.6 were developed.

Table 4.6 Intensive Monitoring Test Descriptions
Ventilation Effectiveness Test A tracer gas growth test to measure the effectiveness of the ventilation system in the Sue house.
Ventilation Efficiency Test A tracer gas decay test to measure the efficiency of the whole house ventilation system in the Sue house.
Exhaust Inlet Capture Efficiency Test A mass balance moisture test to measure the capture efficiency of HRV exhaust inlets and kitchen range hood fans in the Jones house.
Moisture Absorption and Desorption Test A multi-point absolute humidity test to measure the moisture absorption and desorption rates of an entire house in the Smith and Morewood houses.

Prior to the intensive monitoring, air flows were determined using the Duct Test Rig (DTR)[7].

Effectiveness and Efficiency test were performed on the Sue, Jones, and Smith houses to measure how effectively fresh air was distributed through the house. Due to budget limitations and for the sake of brevity only the results are presented for the Sue house. The Sue house was chosen because it had a complete data set and representative of the other tests conducted on the Jones and Smith houses. Comments are included on the Jones and Smith house where appropriate.

Inlet Capture Efficiency Tests were conducted on the bathroom HRV inlet and the kitchen range hood in the Jones house, the bathroom inlet in the Sue house, and the bathroom Aereco extractor and kitchen range hood fan in the Smith house. Again due to budget and space limitations only the results for the Jones house have been presented. The results for the Jones house were chosen because there was a complete data set and the results were representative of the results from the other two houses. Comments on testing the other houses are included where appropriate.

Moisture absorption and desorption tests were only done on the Morewood and Smith houses.

4.3.4 Low Level Monitoring of Houses With DCV

DCV strategies were implemented in the Sue, Jones, and Smith houses. The work broke down into four distinct, tasks as described in the following table.

Table 4.7 Breakdown of Tasks

Task 1	Select control equipment and program software for DCV
Task 2	Select control sensors
Task 3	Design and install DCV control strategies in each house
Task 4	Conduct spot measurements of air quality during DCV operation

[7] The DTR is a portable flow chamber that was developed by Sheltair for CMHC research applications. It is equipped with flow hoods and a compensating fan, and is designed to measure air flows between 2 L/s and 350 L/s with an accuracy of ±5%.

Task 1 Select control equipment and program software for DCV

The CR21 data loggers had some abilities to act as intelligent controllers. Up to four output channels operate as on/off switches, and can be programmed to respond to information collected on any of the nine input channels. By using more than one control channel, multiple set-point bands, responding to several input variables are possible.

The ability to program in more complex DCV strategies could only be accomplished by developing a sophisticated program for this purpose. As part of this project, Gorden Howell of Howell, Mayhew Engineering, revised their Co-Pilot monitoring control software to operate a Sciemetrics Labmate data logger as both an intelligent controller and data acquisition system. A Proportional Integral Derivative (PID) control module was added which would allow the program to estimate the generation rate of pollutants and to quickly search out a ventilation rate that would maintain pollutants below a predetermined set-point.

Figure 4.1 shows the revised Co-pilot program acting as a DCV controller in the Jones House. This trial of the software shows that the feedback gain set for the ventilation system controller was too high, causing an erratic fluctuation in the ventilation rates. Further experimentation was required to obtain a smooth transition.

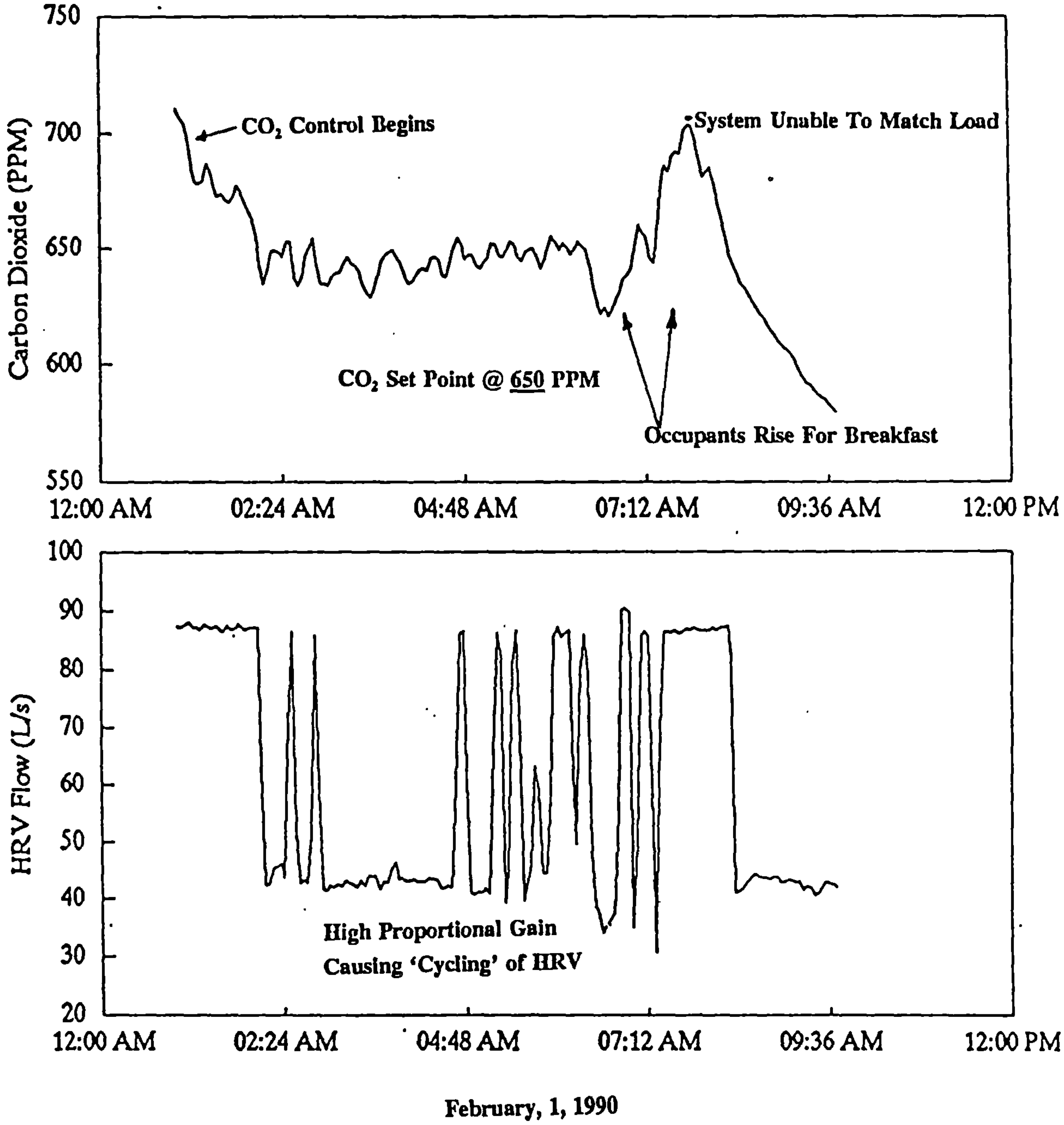

Figure 4.1 Co-Pilot CO_2 DCV Control - Jones house

Task 2 Select control sensors

The occupant generated pollutant CO_2 was selected as a primary control variable. However, because of the high cost of CO_2 sensors, secondary control sensors were selected by performing an analysis of low level monitoring data and by conducting preliminary tests to determine how well absolute humidity and activity correlated with CO_2.

Intensive monitoring was conducted in the Jones house to determine if **absolute humidity** could be used as a DCV control mechanism. A correlation was needed between moisture generation[8] and CO_2 production. Relative humidity was discounted as a control variable because it depends on both moisture generation and temperature. Indoor temperatures in occupied houses vary unpredictably and thus influence the relative humidity in ways that are not related to pollutant generation.

Figure 4.2 presents the pre-design data from the Jones house, and indicates a rough correlation exists between absolute humidity and CO_2 levels. Humidity and CO_2 peaks tend to coincide, however the CO_2 peaks are usually one to three hours later. During unoccupied periods, CO_2 concentrations drop from peaks of 800 - 900 ppm to 500 - 600 ppm (about 35%). For the same periods, humidity drops about 15% to 20%. At night, when the six occupants are sleeping, CO_2 concentration remains relatively stable, while the absolute humidity falls slightly - due to absorption into the building structure. Changes in outdoor absolute humidity will influence indoor humidity.

Both relative and absolute humidity are also influenced by non-pollutant influencing factors such as watering of plants and changes in outdoor humidity.

Data from the Sue house was analyzed to determine if **occupant activity**, as detected by Passive Infra Red (PIR) sensors, could be used for DCV. Figure 4.3 shows the results of this analysis. Over a seven day period there appears to be a rough correlation between pulses received from the PIR sensors and CO_2 levels. CO_2 levels are always elevated above ambient when there are a high number of pulses recorded. However, there are times when there are no or few pulses recorded and CO_2 levels are high.

[8] Occupant related activities often produce moisture in conjunction with pollutants.

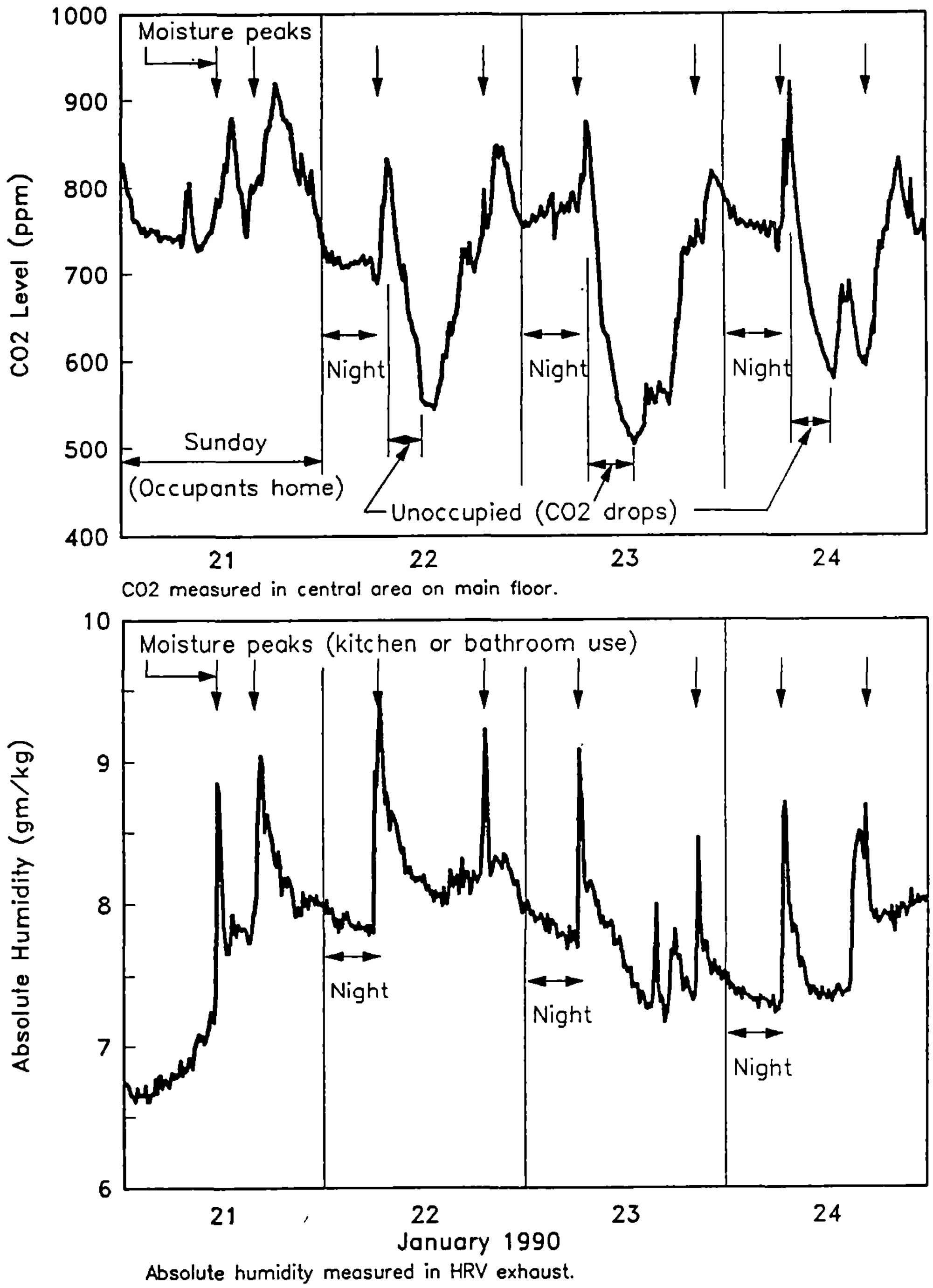

Figure 4.2 Evaluation of Absolute Humidity Sensor for DCV control (Jones house)

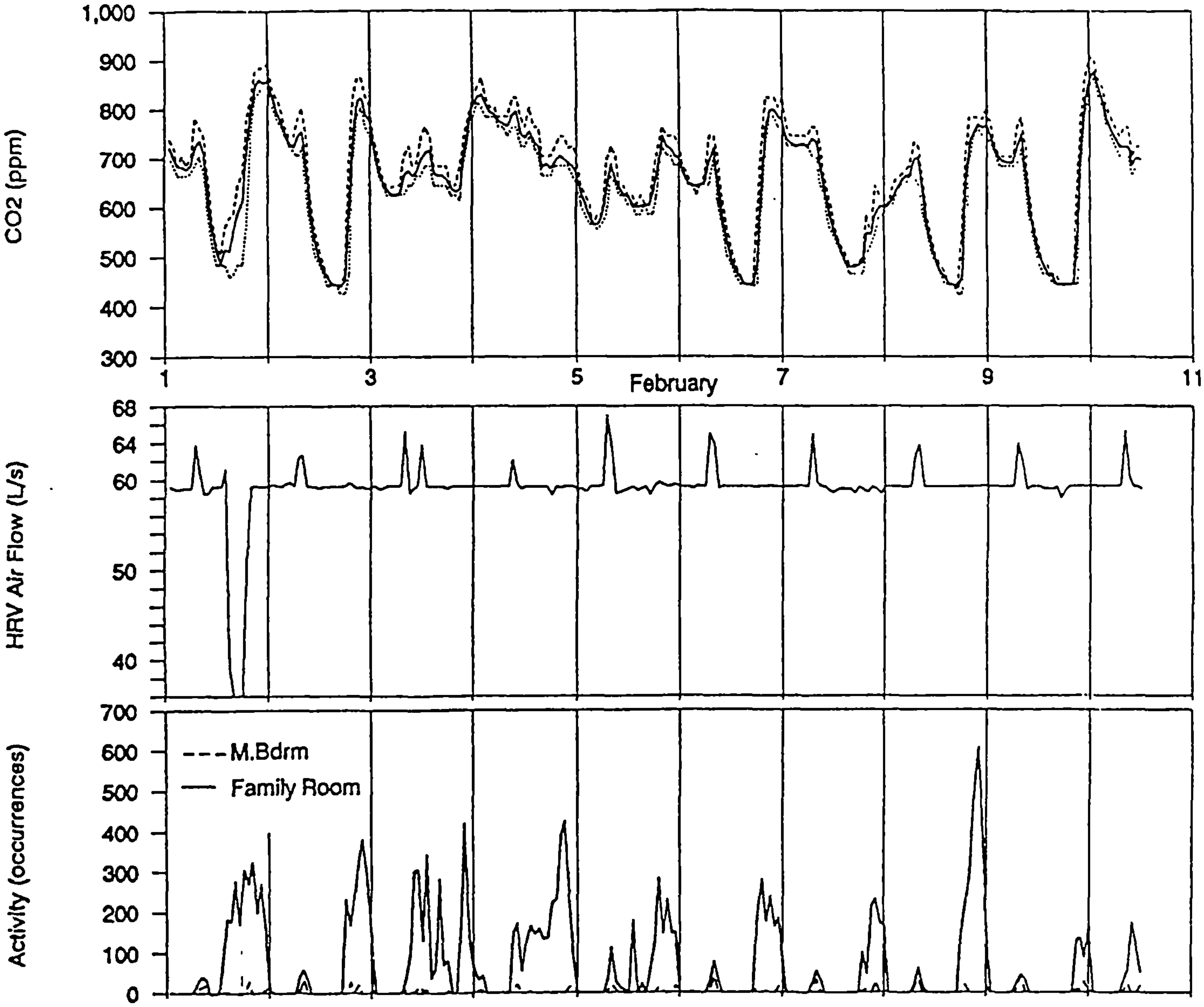

Figure 4.3 Edvaluation of Activity Sensors for DCV control (Sue house)

An imperfect correlation between activity and CO_2 is to be expected over the short term. With only two activity sensors there will be times when occupants are not within sight of the PIR's and no activity will be detected. Even when the occupants are in sight, the PIR sensor will not easily detect a person sitting very still or sleeping.

Because the PIR sensors respond immediately to changes in activity their activity counts always precede the rise in pollutant concentrations within the house. A CO_2 analyzer, for example, will experience delays as the CO_2 diffuses through the house, and a further delay due to the response time of the equipment.

Task 3 Design and install DCV control strategies in each house.

The Sue house used PIR sensors as a DCV control device using the Co-pilot software and Sciemetrics equipment. The features that were later designed into the Helma house controller were pioneered in the Sue house. This included the integration of a standby mode, a sleep mode, and an occupant arrival mode (Refer to section 7.5 for descriptions of these modes of operation). These modes allowed the system to anticipate the requirements for ventilation, based on the history of activity in the house.

A DCV system based on CO_2 sensors was tested in the Jones house. The system used a CR21 data logger as a controller with two set-point bands to operate the HRV fans in three modes. The results of this strategy are presented in section 5.2.4.

The Smith house already used a partial DCV system, with passive bladders that respond to rises in relative humidity. However, as we have indicated, relative humidity is not a good control variable for pollutant sensitive DCV.

Two different strategies were experimented with in the Smith house. The first DCV application used a Massawa integrated controller manufactured in Japan and connected to the range hood exhaust fan. The device outputs an Indoor Air Quality (IAQ) index on a scale from one to nine - one indicating very poor air quality and nine indicating very good air quality. The index is based on a combination of measurements of oxygen content, dust particles and relative humidity. For more information on the Massawa controller, please refer to the Appendix, section 10.3.

The second strategy for the Smith house was to use an absolute humidity set point band to turn the central exhaust ventilator on or off. The Aereco humidity controlled bladders were taped open during this period.

Task 4 Conduct spot measurements of air quality during DCV

The three research houses were monitored for specific air pollutants during the low level monitoring period. Four tests were completed on each house. A two hour **formaldehyde** impinger measurement was taken to compare levels with Health and Welfare guidelines (target level of 0.05 ppm). An air bag sample was taken to measure **Total Volatile Organic Compounds (TVOCs)** as methane equivalents. Although there is no Canadian standard, we expected levels to be below 2 mg/m^3. A charcoal tube sample was taken and run through the Gas Chromatograph Mass Spectrometer (GCMS) for **n-decane.** N-decane was shown to be the best indicator for TVOCs in a large German study involving 500 houses[9]. Finally, a Halitec gas analyzer using a Figaro TGS 800 was used to indicate the relative quality of air in the houses.

The Figaro sensor is a metal oxide semiconductor which can be used to detect certain volatile organic compounds found in indoor air. The total conductivity of the metal strip changes due to the reaction of reactive gases with chemisorbed oxygen on the surface. By thermal modulation, non-linearities in the sensor reponse are then analyzed using various algorithms including Fast Fourier Transforms (FFT) and empirical curve fits. The Figaro sensor was used as a generic air quality monitor. Increases in both the 1st harmonic and/or the phase angle are interpreted as an increase in the presence of detectable gases (i.e.: air quality decreases).

This information would later be used to establish set points for the controller in the Helma house. The air sampling results are presented with the low level monitoring results for each house (sections 5.1.4, 5.2.4, and 5.3.4).

4.4 Computer Modelling and Economic Analysis

As part of this project, Enermodal Engineering was contracted to combine their Enerpass hourly thermal simulation program with the National Institute of Standards and Technology CONTAM87 contaminant simulation program. The result was a multipurpose simulation program referred to as Enerpass/Contam.

The main use for this new program, was to enable monitored DCV results on a few houses and locations to be extrapolated to a wider range of locations and ventilation configurations. Also, the input parameters had to be standardized to enable economic comparisons of different systems.

[9] Christian Krause et al, "Occurence of Volatile Organic Compounds in the Air of 500 Homes in the Federal Republic of Germany", in Indoor Air '87, Volume 1. Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Institute for Water, Soil and Air Hygiene, Berlin, pp. 102-106. B. Seifert et al Ed.

The program was configured to allow a consistent menu input of thermal parameters, mechanical system characteristics and up to two contaminant characteristics. Input parameters and monthly summary output was possible directly from the program. In addition, hourly contaminant concentrations and air flows were output in the form of ASCII data files. These files were then imported into spreadsheets for further analysis.

The program also allowed the ventilation system to be controlled by concentration levels for up to two contaminants.

Because two large, complex programs were merged and had to pass data between them, the combined program was very slow. While Enerpass, the thermal simulation, took about six minutes to run a full year, the combined contaminant simulation program took about **ten minutes to run one day**. This fact imposed a restriction on the number of cases investigated and also meant that most runs were restricted to a maximum of a few months.

Runs were carried out to ensure that the contaminant model resulted in carbon dioxide concentrations consistent with those measured during the low level monitoring.

Runs were performed for Vancouver, Winnipeg and Toronto, for a Base house (continuous exhaust), Continuous HRV and Demand Controlled Exhaust Ventilation (carbon dioxide concentration control). Some DCV HRV systems were also simulated. Runs were performed with three and six occupants and for two DCV control modes - match average and match peak. The **match average mode** consisted of performing multiple DCV runs to find carbon dioxide concentration set-point that would result in the same heating season **average** carbon dioxide concentration as the base case. Similarly, for the **match peak mode** of control, multiple runs were carried out to find the set-point to match DCV peak concentrations with those for the non-DCV base case.

The decision to match averages and peaks to the base case was based on the assumption that "acceptable" CO_2 levels lie somewhere in this range. A DCV system with matched average CO_2 is a conservative comparison which results in an environment with the same average CO_2 levels and reduced peaks - a more comfortable environment than the original. A matched peak mode allows the DCV system to achieve significantly greater cost savings by reducing ventilation rates at all times, except during periods with highest pollutant activity or occupancy.

Operating cost savings were determined from savings due to reduced overall ventilation and also due to reduced fan operating time.

5 COMMISSIONING AND LOW LEVEL MONITORING RESULTS

5.1 DCV House #1 (Sue)

5.1.1 Sue House Description

A young couple with a single baby live in the Sue house. The family spends time mostly in the family room because the house is only partly furnished. This two storey house has an unfinished basement, used for storage. Both adults work outside the home on weekdays (an accountant and a school teacher). The house is located on an in-fill lot on a slight rise between Burnaby and Vancouver. The house was built for and designed by the Sue family. Table 5.1 lists the house characteristics, also see Appendix section 10.1.1.

Table 5.1 Sue House Description (HRV with recirculating system)
Homeowner: Henry Sue Burnaby, B.C. **House Description:** HRV with exhaust air ducted separately Sealed combustion gas fireplace Aereco mid-efficiency gas forced air furnace 297 m^2 heated floor area Two floors plus a full basement Mechanical equipment is located in the basement Registered R-2000 house Stick frame construction

5.1.2 Sue House Commissioning Highlights

The commissioning procedures conducted on the Sue house were essential for interpreting the results of data collected during the low level monitoring. Refer to Table 4.4 for the full commissioning procedure. The most important results are listed below in point form. The rather long list of operational difficulties is not necessarily a reflection of poor workmanship or design. Rather it reflects the state-of-the-art for new heating and ventilating systems in Canada.

- The HRV supply air duct was intentionally uncoupled from the return air plenum of the furnace. This caused major spillage of fresh air into the basement. Leakage from the duct was estimated at between 30% and 60% depending on the speed of the furnace recirculating blower.
- A 100 mm diameter make-up air duct connected to the return air plenum was found to be unnecessary for controlling house pressures or supply of combustion air. The duct installation imposes an unnecessary energy penalty. The air flow through the duct was between 4 and 6 L/s (depending upon blower speed) and causes the house to be slightly pressurized.
- The mid-efficiency horizontally vented furnace was found to be constantly spilling combustion gases primarily through the fan axle hole. This is a common design flaw with mid-efficiency furnaces. In the Sue house, the spillage places an extra load on the ventilation system and contributes to higher CO2 levels.
- The supply and return ducts of the forced air furnace were found to be leaky. Holes in sheet metal plenums, of about 50 cm_2, were observed. Total leakage from the system was estimated at 30% to 40%.
- The householder adjusts the speed of the HRV on entering and leaving the house. The householder also increases the speed of the furnace blower during the summer for the purpose of mixing cool basement air with the air in the rest of the house.
- The householder expressed concern that not enough fresh air reaches the master bedroom and that the second floor does not receive enough heat. In the winter there is marked stratification between floors.
- The fireplace, the DHW tank, and the furnace are all side vented and share the same exterior wall as the HRV and combustion air intake. With the wind and temperature conditions prevailing at the time of testing, combustion gases were observed entering the HRV supply inlet.
- The forced air distribution system was well balanced. Low speed was 166 L/s and high speed was 244 L/s.
- The ventilation system fails to meet the R-2000 design guidelines current at the time of construction[10]. The HRV

[10] R-2000 ventilation guidelines have changed from year to year. Recently, they have been brought in line with the new F326 standard.

flows were balanced at 78.7 L/s at high speed and slightly unbalanced at 41.7 L/s at low speed. R-2000 requires 95 L/s.

- Table 5.2 presents the air flow measurement results. The ventilation exhaust ducts were much tighter than the distribution duct work for the heating system. The total exhaust flow from wet rooms was 65.4 L/s. The exhaust flows were unbalanced and the duct work had a leakage of 17%. The flow from the kitchen is 56% less than R-2000 requirements.

Only minor refinements were performed on the ventilating and heating system in the Sue house prior to commencing the long term monitoring. The furnace venting system was tightened to reduce combustion gas spillage. Filters and hoods were cleaned. After the long term monitoring, the owner requested a relocation of the HRV supply to another exterior wall.

The Sue house would have benefitted from substituting a direct vent exhaust fan for the recirculating range hood. A booster fan or new larger ducting on the HRV exhaust duct from the kitchen would also have improved ventilation performance in the kitchen. However the field research team felt this was, in many respects, a typical installation and that the house should be tested as found.

Table 5.2 R-2000 Guidelines and Measured Air Flows: Sue House

Room Description	Required Supply Ventilation (L/s)	Required Exhaust Capacity (L/s)	Measured Maximum Flow Supply (L/s)	Measured Exhaust (L/s)
Bedroom	5		4	
Sewing room	5		6	
Master Bedroom	5		9	
Ensuite	5	25	6	17
Bathroom #2	5	25	3	12
Living Room	5		18	
Dining Room	5		6	
Kitchen	5	50	3	22
Family Room	5		5	
Guest Room	5		3	
Bathroom #1	5	25	6	15
Computer Room	5		6	
Basement	10		5	
Leakage in Ducts				12
Make-up Air Duct			6	
Total Continuous Capacity	70			
Add. Peak Capacity	25			
Total Continuous Capacity	95	95	84	78
Add. Peak Capacity		30		0
Total Capacity	95	125	84	78

5.1.3 Sue House Without DCV

Data on CO_2 was collected after January 13th. Weekdays, there is generally no one home between 9 AM and 4 PM. Inside temperatures drop during the day to about 18C to 19C from an evening/overnite level of just over 21C.

The heat recovery ventilator (HRV) typically operates in the 50 L/s to 60 L/s range for most of the time - moving just over 200 cubic meters of air per hour. Around 8 AM each morning, the HRV switches to high speed.

Outside absolute humidity was measured at the Sue house. The outdoor humidity data is assumed to be applicable to conditions at the Jones and Smith houses as well.

Hourly results for three days are shown graphically in the Appendix (section 10.1.2) for the period prior to installation of demand controlled ventilation. Results for a typical working day are also shown in Figure 5.1. Note that no CO_2 measurements were available at that time.

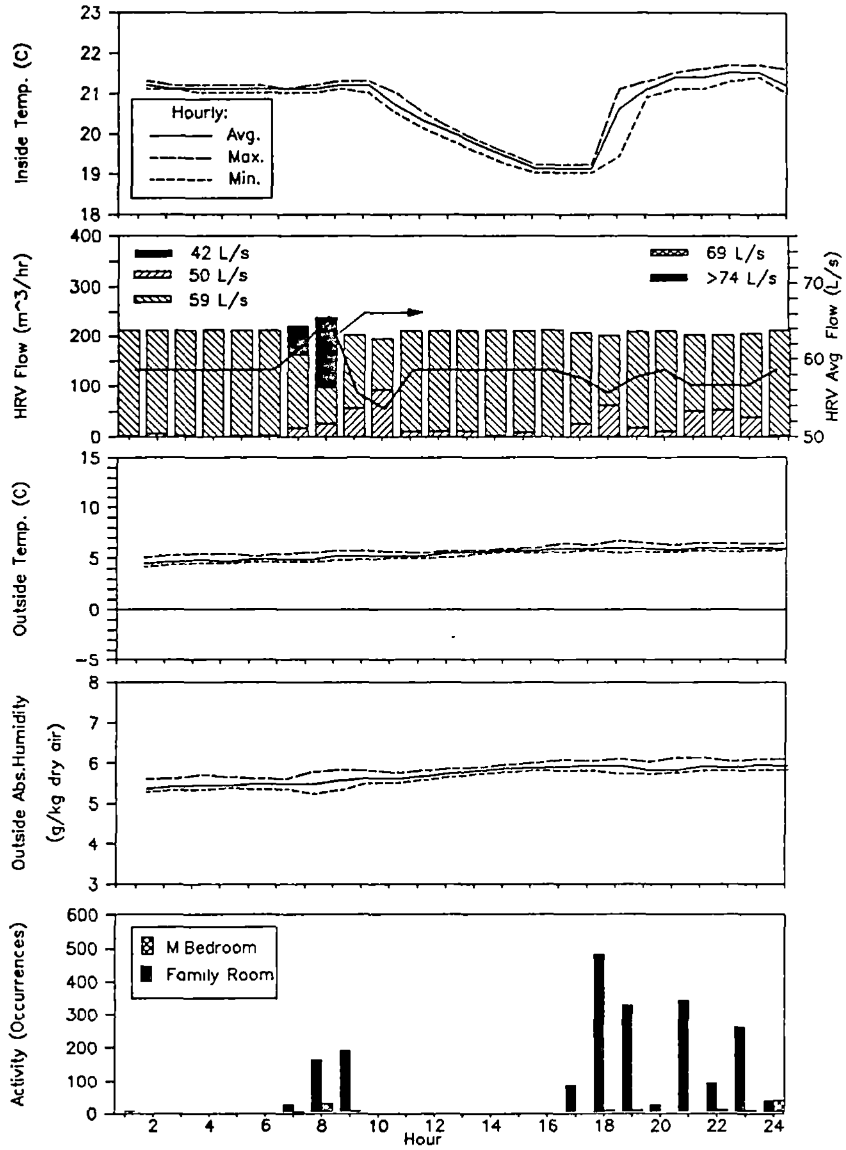

Figure 5.1 Sue house: No DCV on a working day (29 Dec 89)

5.1.4 Sue House With DCV

Activity sensor DCV was installed in the Sue house during the first week of March, 1990 and remained in operation for about five weeks until the end of monitoring. The system used a Proportional Integral Derivative (PID) Sciemetrics Labmate-based controller to interpret the activity counts and calculate optimum ventilation rates.

Figure 5.2 shows hourly operation for six days in April with DCV in operation. CO_2 stayed within a 400 ppm to 900 ppm range throughout the period (average 554 ppm). There is no discernible correlation between HRV fan air flow maxima and CO_2 maxima. With outside temperatures averaging over 13 C, there was likely very little natural infiltration.

Figure 5.3 shows a reduction in ventilation flow from 58 L/s to 53 L/s with a slight reduction in CO_2 levels. The amount of time in the 600 to 700 ppm and 700 to 800 ppm CO_2 concentration bands was significantly reduced. However, there was also a slight increase in the percentage of hours above 800 ppm CO_2 concentration. This increased duration in peak CO_2, and the tendency for the highest HRV flow rates to occur at mid levels of CO_2 concentration, indicates a poor correlation between CO_2 concentration and activity - at least as the sensing system was configured (for more details refer to section 10.1.2).

Ventilation fans were off about 24% of the time - for a corresponding saving in fan operating costs.

Air quality measurements on the Sue house with DCV recorded formaldehyde below the Health and Welfare target level of 0.05 ppm (Table 5.3). The local laboratory had difficulty detecting low levels of hydrocarbons and N-decane. Based on this experience, we recommend that a specialized laboratory be used in the future (i.e. one that has experience measuring background volatile organics in house environments). The Halitec IAQ instrument rated the air quality as average, somewhere between the Jones and Smith houses.

Table 5.3 Indoor Air Quality Test Results - Sue House

Formaldehyde	0.042 ppm
Total Hydrocarbons	<0.40 ppm
N-decane	<0.24 ppm
Halitec Instrument:	
1st Harmonic	9.8
Phase Angle	-65.0

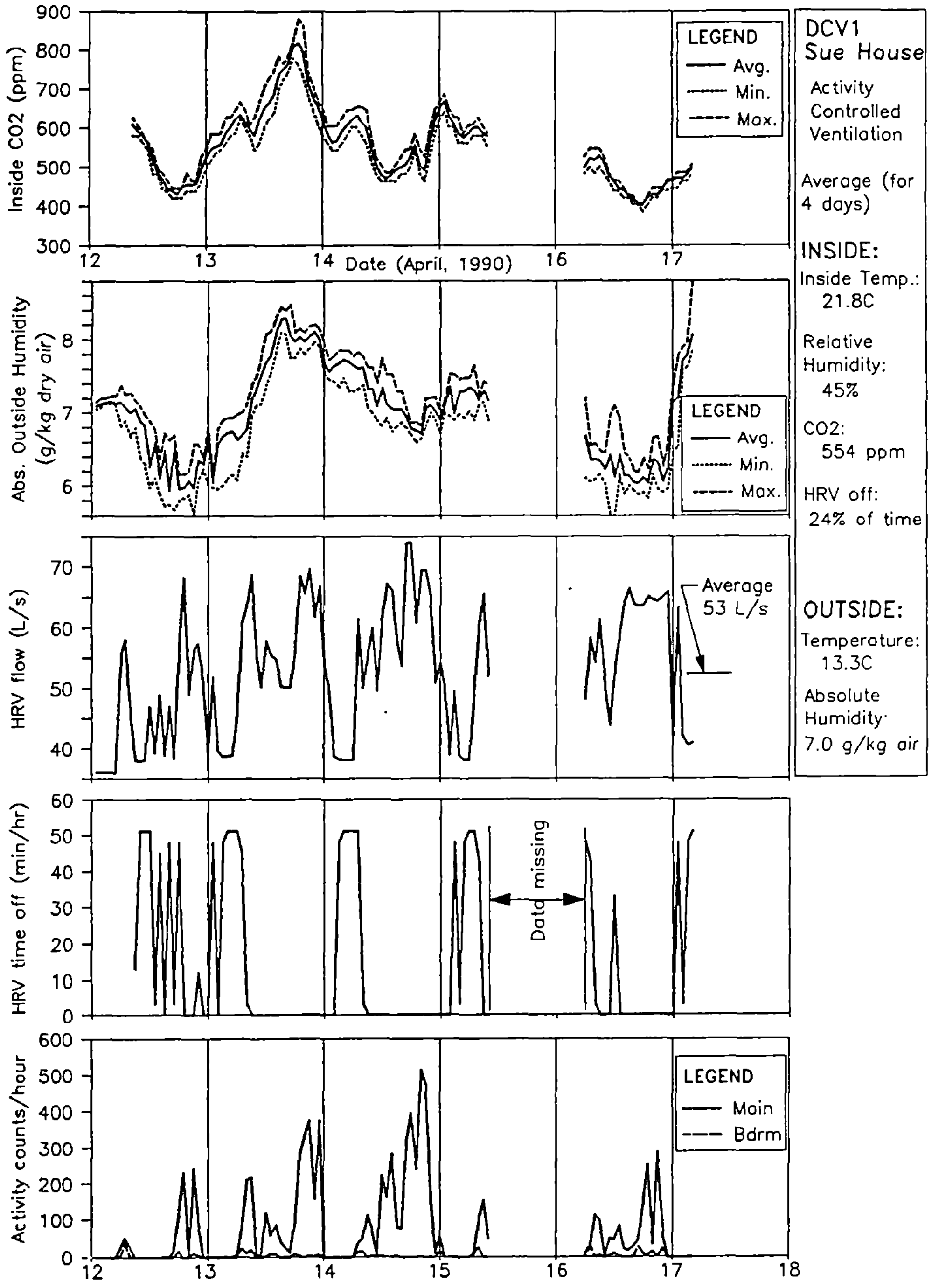

Figure 5.2 Activity Controlled DCV Operation (Sue house)

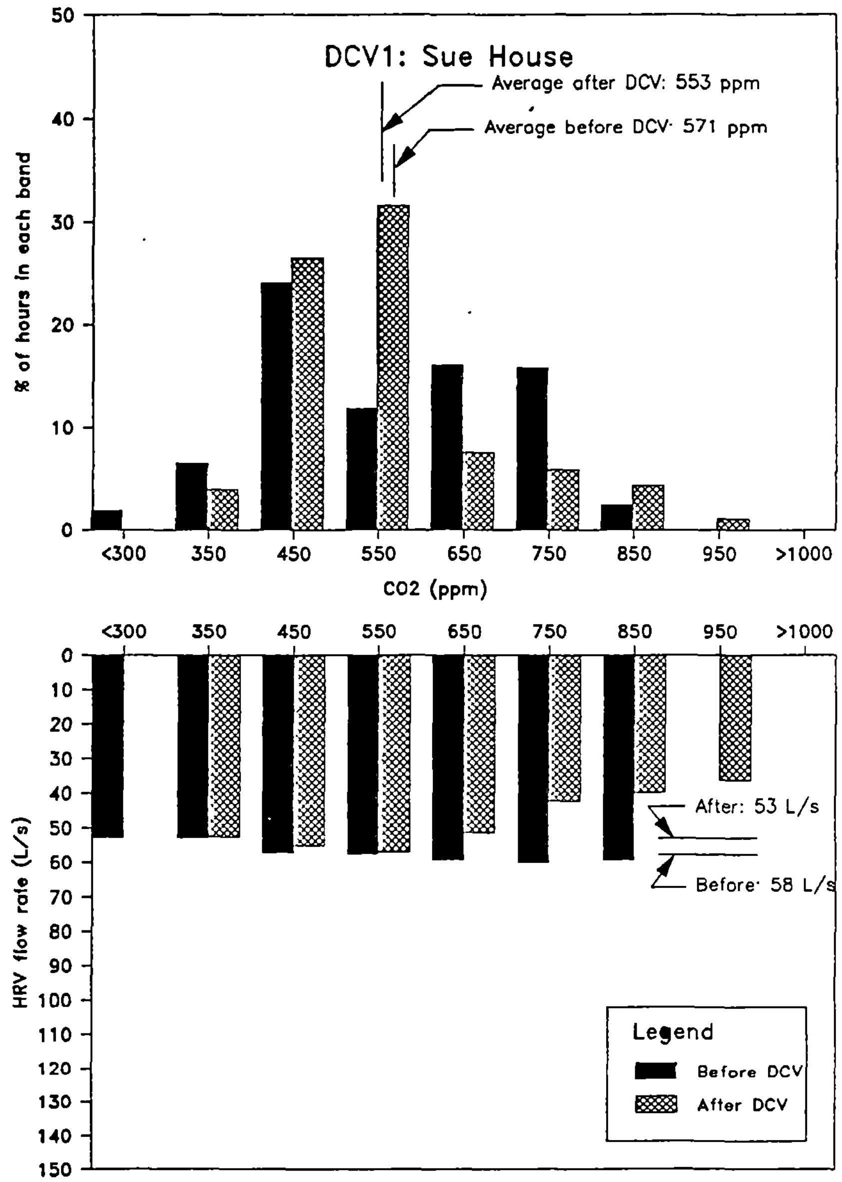

Figure 5.3 Ventilation System Performance with and without DCV (Sue house)

5.2 DCV House #2 (Jones)

5.2.1 Jones House Description

Two middle aged adults and four children live in the Jones house. The house has two full storeys over a finished, above-grade basement. During the monitoring period, the man of the family was often travelling as part of his job (mining engineer). The mother works at a nearby school and the children are all school age. The house is located on Capital hill in Burnaby with a panoramic view of the city and harbour. Table 5.3 lists the house characteristics (also see Appendix section 10.2.1).

Table 5.3 Jones House Description (HRV with no recirculating system)
Homeowner: Gary Jones Burnaby, B.C. ***House Description:*** Fully ducted HRV (VanEE 2000) Hot water radiant boiler (Allied Engineering) 335 m^2 heated floor area Two floors plus a full basement Mechanical equipment is located in the garage Registered R-2000 house Stick frame construction

5.2.2 Jones House Commissioning

The commissioning procedures conducted on the Jones house were essential for interpreting the results of data collected during the low level monitoring. The eleven steps involved in the commissioning procedure are listed in Table 4.4. The most important results are listed below in point form.

- The HRV was found to be unbalanced by 21 L/s when measured with the Duct Test Rig (DTR)[11]. Flow calibration grids which were poorly installed in the HRV showed the system to be balanced.

[11] The DTR accurately measures low air flows (down to 2 L/s).

- The interior wall stud cavities are used as ducts to transport fresh air. The leakage from these supply air ducts was 30 L/s or 33% of total flow. The exhaust ducts only exhibited a leakage of 11 L/s, or 12% of total exhaust flow.

- A hydronic pre-heat coil had been installed on the supply air of the HRV, and appeared to perform satisfactorily.

- The Kitchen range hood flows varied from 20.3 to 91.4 L/s depending on the speed setting.

- Table 5.4 lists the R-2000 ventilation guidelines and the actual measured flows for each room in the house. Capacity air flows were approximately 20 L/s below requirements.

- It is worth noting that the combustion air supply duct into the garage had been intentionally plugged with insulation, by the homeowner. The gas boiler was found to continuously spill combustion gases into the garage, similar to many other mid-efficiency boilers of recent manufacture.

- Both the dehumidistat in the laundry room and the dehumidistat installed in the HRV cabinet, were out of calibration by approximately 12%. Lock tight had been applied to the calibration screw on the HRV dehumidistat. The dehumidistat was set at 29% relative humidity. This permanent setting had caused the HRV to run continuously at high speed during most of the year.

- Occupants complained that when family room doors are shut the room air becomes stale.

- An access hole to the attic was pre-built to allow the addition of a booster fan if the householder found the master bedroom needed more fresh air.

- A maintenance check prior to measuring air flows on the HRV discovered that the blower wheels were coated with dirt over 5 mm thick.

It was decided that the imbalanced HRV would effect long term monitoring. A 200 cm diameter booster fan was added to the exhaust duct work down stream of the HRV. The exhaust flows increased to within 3% of supply flows and a balanced system was achieved without any reduction in total air flows. Filters, hoods, and blower wheels were cleaned and motors were lubricated. No air flows were adjusted.

Table 5.5 R-2000 Guidelines and Measured Air Flows: Jones House

Room Description	Minimum Required Supply (L/s)	Required Exhaust Capacity (L/s)	Measured Maximum Flow Supply (L/s)	Measured Exhaust (L/s)
Central Basement	5		5	
Bdrm N. Bsmt	5		5	
Bdrm E. Bsmt	5		3	
Master Bedroom	10		9	
Bdrm E. 2nd floor	5		2	
Bdrm S. 2nd floor	5		8	
Family room	5		9	
Bdrm S. Main floor	5		8	
Living Room	5		4	
Library	5		9	
Bathroom, Bsmt.				6
Bath, 2nd floor	5	25		15
Ensuite	5	25		17
Kitchen	5	50		11
Bath Main floor	5	25		15
Laundry	10	25		16
Duct Leakage			30	11
Total Continuous Capacity	85			
Add. Peak Capacity	25			
System Continuous Capacity	110	110	92	91
Add. Exhaust Intermittent		40		91
Total Exhaust Capacity		150		182

5.2.3 Jones House Without DCV

During the day, inside temperatures are typically about 21.5C to 22C - set back to 21C at night (just over 20C when unoccupied).

HRV air flow averages about 60 L/s, usually with morning and evening peaks of 80 L/s to 90 L/s.

Hourly results for three days are shown graphically in the Appendix (section 10.2.2), for the period prior to installation of demand controlled ventilation. Results for one day are also shown in Figure 5.4. This day, at the beginning of their holiday, is interesting in that it shows the CO_2 decaying from just under 700 ppm to equilibrium over a period of about six hours.

The evening of January 10th there is a noticeable lag of several hours between activity and the peak CO_2 readings (section 10.2.2).

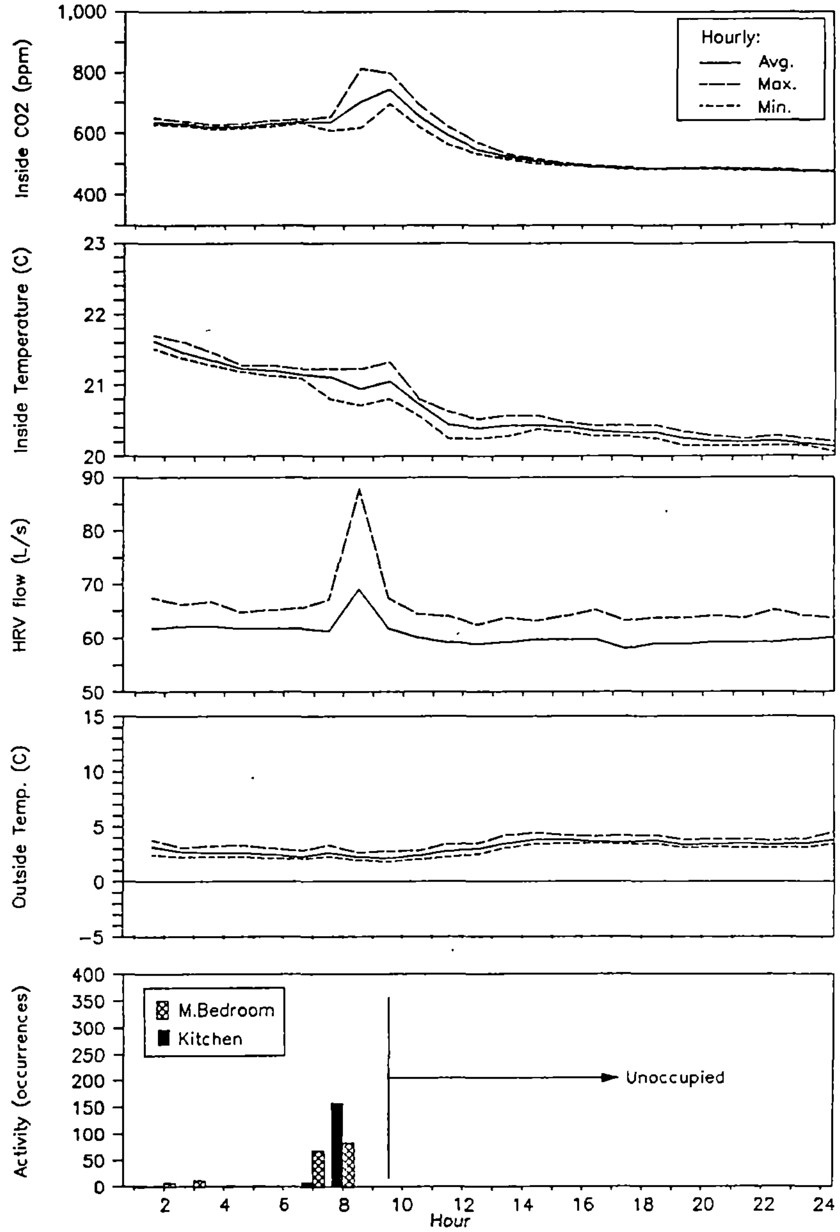

Figure 5.4 Jones house - Leaving on holidays (28 Dec 89)

5.2.4 Jones House With DCV

Demand controlled ventilation, based on CO_2, was installed in mid February and operated through to mid April when monitoring was halted. The system used a Campbell Scientific CR21 data logger as a controller, operating with two set-point bands to operate the heat recovery ventilator fans in three modes - off, low flow and maximum flow.

Figure 5.5 shows typical hourly operating characteristics over an eight day period. The house was unoccupied for the first two days - resulting in the system being off for 50 minutes out of each hour (the system was programmed to operate a minimum of 10 minutes out of each hour).

Figure 5.6 shows a slight reduction in average CO_2 (from 584 ppm to 558 ppm) with **lower average ventilation rates** - dropped from an average of 62 L/s to 49 L/s. This would result in a saving of 21% for the heating of ventilation air. In addition, the fans were typically off 24% of the time - resulting in a further saving in fan operating energy. Note that with CO_2 controlled ventilation, there is a match between high ventilation flow rates and high CO_2 levels (Figure 5.6). Also, after DCV, there are no occurrences of CO_2 concentration above 800 ppm.

Air quality measurements on the Jones house with DCV recorded formaldehyde below the Health and Welfare Canada target level of 0.05 ppm (Table 5.6). The very high reading of total hydrocarbons is interesting but is very likely an error in analysis, given the laboratory's lack of experience in this area. The Jones house had the best air quality of the three houses based on the Halitec instrument.

Table 5.6 Indoor Air Quality Test Results - Jones House

Formaldehyde	0.040 ppm
Total Hydrocarbons	4.7 ppm
N-decane	<0.24 ppm
Halitec Instrument:	
1st Harmonic	13.1
Phase Angle	-69.0

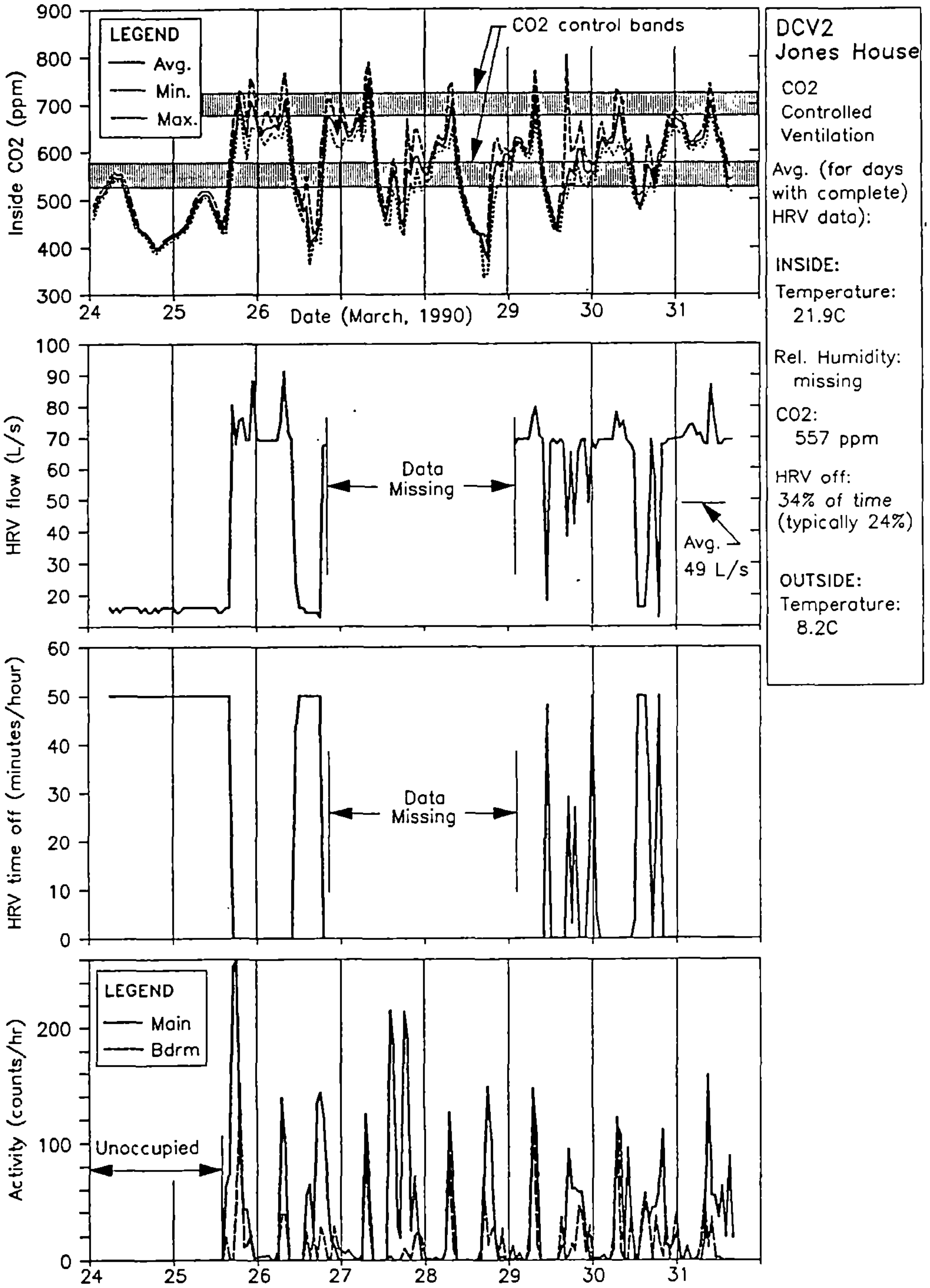

Figure 5.5 CO_2 controlled DCV operation

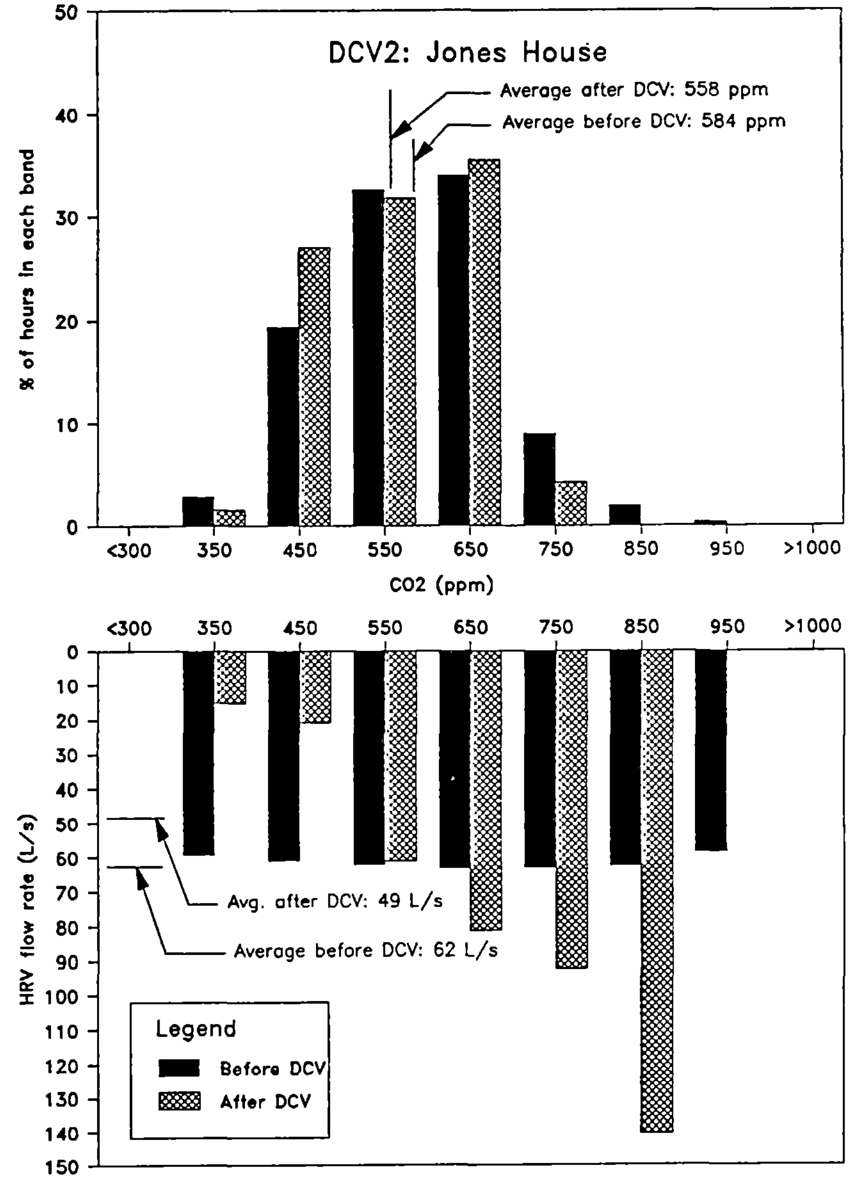

Figure 5.6 Ventilation Performance with and without DCV (Jones house)

5.3 DCV House #3 (Smith)

5.3.1 Smith House Description

The Smith's are almost at retirement age and chose to build their new home in rancher style, with one level throughout. The wife is a heavy smoker and spends most of the day indoors. The husband works as a hydro engineer, but is no longer required to travel. The house is located in a new subdivision in Ladner, on the delta between the north and south arms of the Fraser River. Table 5.7 lists the house characteristics (also see Appendix section 10.3.1).

Table 5.7 Smith House Description (CEV with recirculating system)

Homeowner:
Parker & Marilyn Smith
Ladner, B.C.

House Description:
One Range hood fan
Two Aereco bathroom extractors with manual override
One Aereco kitchen extractor with manual override
Sealed combustion gas fireplace
Forced air mixing and filtration system
Sealed combustion gas boiler
Heating coil in air mixing system supplying heat to bedrooms and living rooms through ceiling grills
Hydronic radiant heating in entrances, bathrooms, kitchen (non carpeted areas)
232 m^2 heated floor area
One floor, slab on grade with attached garage
Mechanical equipment is located in the basement
B.C. Hydro Quality Plus provisional house
Stick frame construction

5.3.2 Smith House Commissioning

The commissioning procedure conducted on the Smith house was essential for interpreting the results of data collected during the low level monitoring. The eleven steps involved in the commissioning procedure are listed in Table 4.4. The most important results are listed below in point form.

- There are two sources of fresh air supply to this house. The first source is from natural leaks in the envelope. The amount of fresh air varies according to house depressurization caused by a variable exhaust system. The rate of flow from the exhaust system is controlled by three humidity sensitive bladders installed at the kitchen and bathroom exhaust ducts. Maximum flow can be obtained from these extractors by depressing a pneumatic switch that opens a bypass shutter for 30 minutes. The maximum exhaust flow is 57 L/s. This creates a house depressurization of 5.5 Pascals. Fresh air supplied from infiltration through leaks in the building envelope amounts to 40 L/s.
- The second source of fresh air, a duct from outdoors, connected to the recirculation system, makes up the remaining 17 L/s. Air is drawn through the duct primarily by the pressure drop induced by the recirculation blower.
- The range hood exhaust fan is capable of exhausting 71 L/s of air and causes the house to be depressurized to 15 Pascals. All combustion equipment in this house is sealed, and no combustion gas spillage was evident.
- The recirculation system constantly moves 250 L/s of air through the house. This air flow is equivalent to 2 air changes per hour (ach). The rancher style of construction requires that ducts pass through the attic. The ducts appeared well sealed and insulated. The outlet registers are Swedish-style whisper grills, installed in the middle of rooms, at the ceiling level. Return air grills are located at high wall locations in hallways. The installation of a hydronic coil in the recirculation system gives the house a partial forced air heating system. The gas boiler supplies hot water to the air-tempering coil whenever the house drops below its balance temperature.
- Radiant hot water pipes in the slab warm the uncarpetted areas of the home (kitchen, bathrooms and the front entrance).
- The house meets the R-2000 ventilation requirements. Table 5.6 presents the air flow measured data on the ventilation and heating system and compares the flows to R-2000 requirements. The house requires 60 L/s of supply and exhaust air. The installed exhaust capacity was 57 L/s.
- The house had experienced boiler room depressurization before occupancy. The cause was leaky recirculation plenums in the boiler room that were difficult to seal. The solution was to install a relief air duct between the boiler room and the house.

- The house was initially commissioned by the ventilation equipment distributor. The house was set-up for zero pressure difference across the envelope with the ventilation system operating at its minimum exhaust flow rate of 17 L/s. This was verified by the research technician. Any increase in exhaust, above the 17 L/s minimum, caused the house to be depressurized.
- The mechanical system had already been retrofitted by the builder, prior to the DCV research. Waste heat from the recirculating blower caused the house to over-heat in the shoulder seasons. The system blower was replaced with a more efficient model which dropped power consumption significantly. During commissioning the new system performed satisfactorily.

No refinements or tune-up measures were made to the Smith house. However, it did take some time to understand fully how the designer of the system intended the system to work.

Table 5.8 R-2000 Guidelines and Measured Air Flows: Smith House

Room Description	Required Supply Ventilation (L/s)	Required Exhaust Capacity (L/s)	Measured Maximum Flow Supply (L/s)	Measured Exhaust (L/s)
Guest Bedroom	5		6	
Family room	5		8	
Bedroom #2	5		6	
Living room	5		6	
Dining room	5		6	
Kitchen/Nook	5		6	
Ensuite	5	25	3	20
Bathroom #2	5	25	3	21
Kitchen	5	50	3	17
Laundry room	5		5	
Master Bedroom	10		7	
Total Capacity	60		57	
Total Exhaust (Intermittent)		100		57

5.3.3 Smith House Without DCV

Inside temperatures are typically in the 23C to 25C range - with the coolest period usually in the early morning.

Hourly results for three days are shown graphically in the Appendix (section 10.3.2), for the period prior to installation of demand controlled ventilation. Results for one day are also shown in Figure 5.7. Exhaust flows are typically around 30 L/s - this lower flow rate may partially account for the much higher CO_2 values found in this house (peak of over 2,700 ppm during a party on December 25th).

The afternoon/evening of December 29th is interesting because of the approximately six hour decay in CO_2 levels shown during the unoccupied period (section 10.3.2).

Peak CO_2 values lag several hours behind peaks in activity - particularly noticeable during the parties of December 24th and 25th (section 10.3.2).

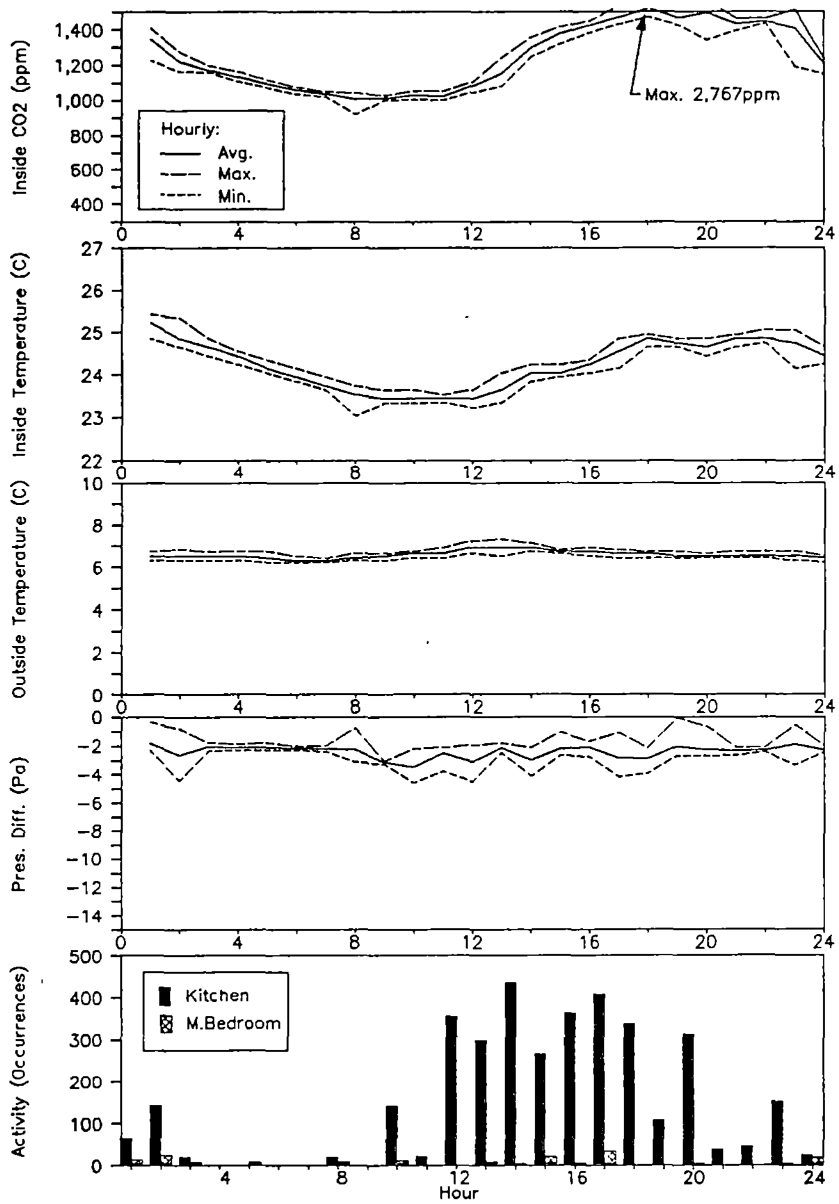

Figure 5.7 Smith house - holiday, Dec 25th

5.3.4 Smith House With DCV

A Massawa integrated controller was installed in early March, 1990 for about two weeks. The occupants were extremely unhappy with its operation due to the fact that it continuously cycled the ventilation on and off. Also, its performance was inconsistent - it would give a totally different picture of the air quality if it was unplugged and then plugged in again. It was removed after about two weeks of operation.

A Campbell Scientific CR21 data logger was then used, for a period of about three weeks in April, to control ventilation based on absolute humidity (Figure 5.8).

Note that, following April 5th, when the DCV controller was turned off and the system was under manual control, peak absolute humidity levels increased sharply and CO_2 levels were generally higher.

The very high pre DCV peaks in CO_2 concentration were eliminated with DCV and average CO_2 concentrations reduced, though with slightly increased exhaust fan flow rates (figure 5.9 and section 10.3.2).

Air quality measurements on the Smith house with DCV recorded formaldehyde in excess of the Health and Welfare Canada target level of 0.05 ppm (Table 5.9). The Smith house had the worst air quality of the three houses based on the Halitec instrument. The fact that the total hydrocarbon and N-decane measurements are below detection limits can be taken as a good finding.

Table 5.9 Indoor Air Quality Test Results - Smith House

Formaldehyde	0.057 ppm
Total Hydrocarbons	<0.4 ppm
N-decane	<0.24 ppm
Halitec Instrument:	
1st Harmonic	6.55
Phase Angle	-60.0

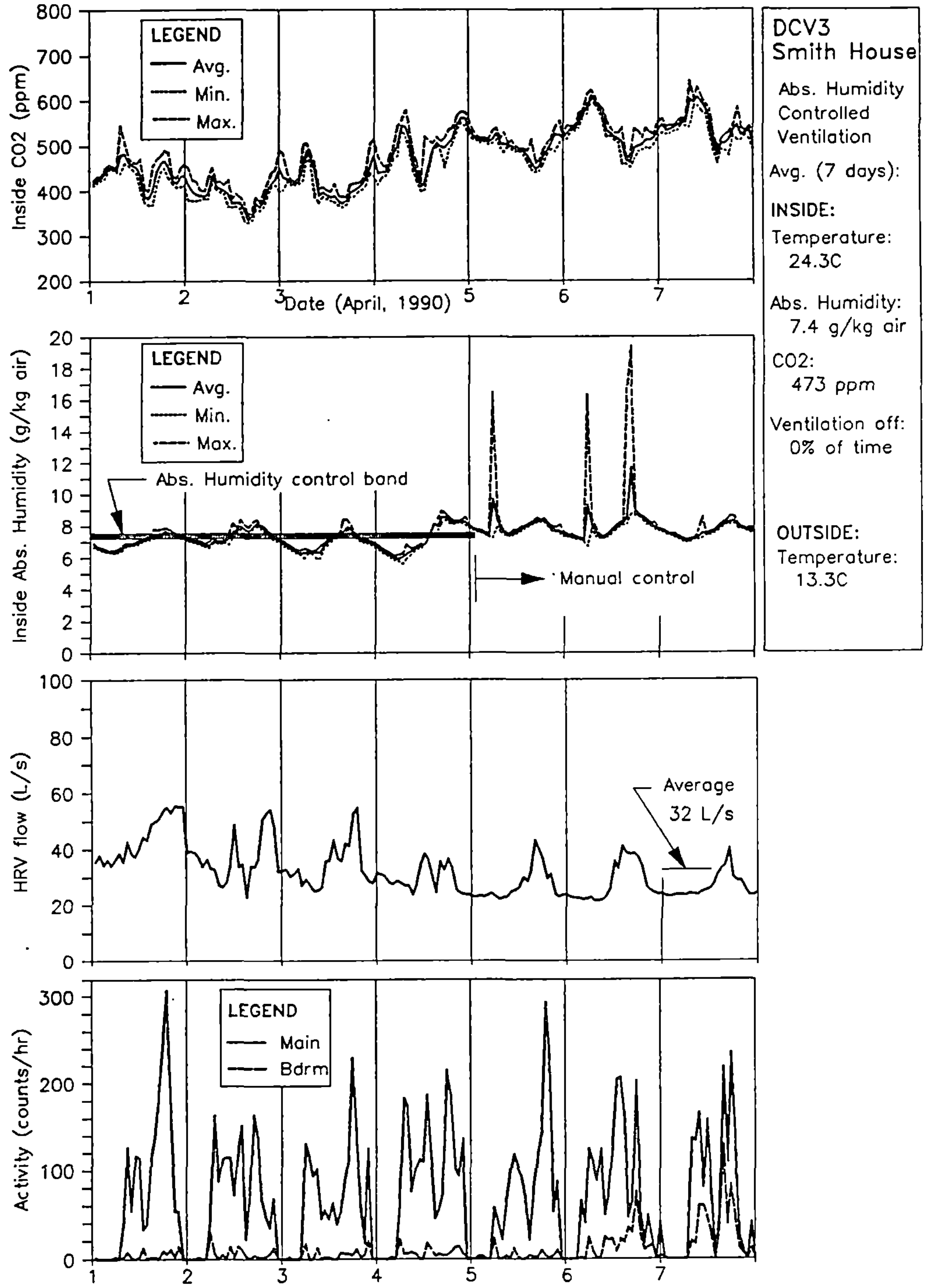

Figure 5.8 Absolute humidity controlled DCV operation

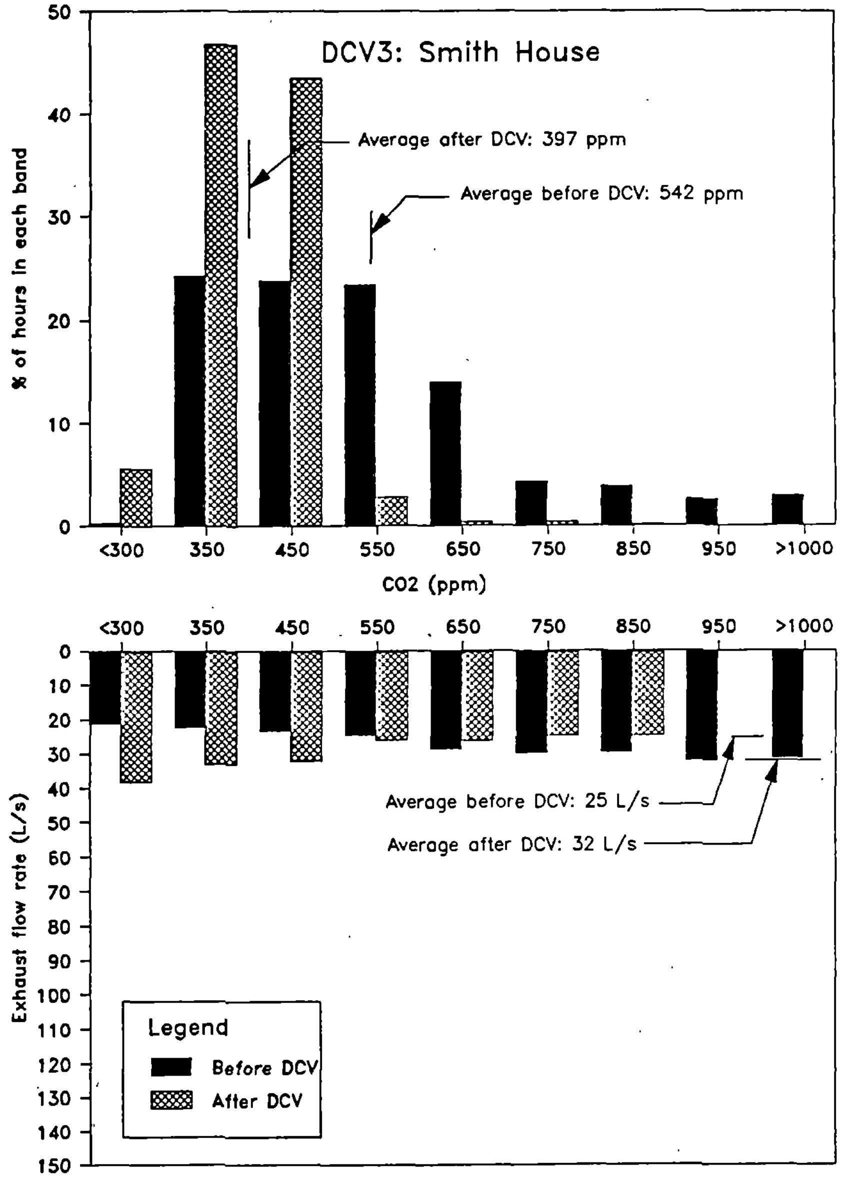

Figure 5.9 Ventilation System Performance with and without DCV (Smith house)

6 INTENSIVE MONITORING METHOD AND RESULTS

6.1 Ventilation Effectiveness Test

6.1.1 Purpose of Test

A ventilation system should control the build-up of building and occupant generated pollutants anywhere in the home. The ventilation systems installed in the research houses were designed to dilute these types of indoor pollutants with outdoor air. The impact of dilution on air quality will depend on how effectively fresh outdoor air is delivered to living spaces in the house. Poor distribution or inadequate supply will cause ventilation dead spots where pollutants can concentrate or linger.

On each of the research houses a tracer gas growth test was performed to measure how effectively fresh air was distributed through the house[12]. The test was performed by injecting the gas at a constant rate into the supply air of the HRV over a one hour period. Oil furnace orifices were calibrated at different pressures in Sheltair's lab and were used to regulate flow rates. Average concentrations of the tracer gas were measured in the exhaust air stream, and at head height in the following locations:

- Living or family room;
- Master bedroom; and
- Basement

Ventilation dead spots were easily identified by probing different locations in the house with a separate hand-held gas analyzer. For example, probing in a kitchen cupboard found extremely low tracer gas concentrations.

A literature search failed to uncover a published formula that could be successfully used to rate the performance of a ventilation system in this manner. An equation was needed that was capable of describing both the effectiveness of distribution and the response time of the system to fresh air demands.

12 There is a great deal of interest in a procedure that could quickly rate the performance of ventilation systems. To this end, we developed an inexpensive multi-point tracer gas system using semi-conductor sensors and refrigerant as a tracer gas. The sensors are on 30 meter cables and are attached to a gas analyzer with data logging capability. We recommend the use of Refrigerant R134A which has a zero ozone depletion potential and a 0.1 global warming effect relative to Refrigerant R12.

After extensive analysis of tracer gas test data from this project, the research team concluded that no existing method for calculating ventilation effectiveness is workable. One common technique looks at differences in equilibrium concentrations of tracer gas in different parts of the house, relative to the concentration in the supply air. However, without natural air change in a house, the equilibrium concentrations are likely to be very similar throughout. The only purpose of such an approach is to determine the impact of natural air change on the air change occurring in different locations within the house - not a big concern for ventilation effectiveness.

Of real importance to ventilation effectiveness is the difference (or variance) between tracer gas time constants from one location to another. These differences can indicate that some locations get too much fresh air, and others too little.

A house with 100% ventilation effectiveness would have identical time constants for all locations (i.e. perfectly distributed fresh air). The greater the differences, the poorer the ventilation effectiveness.

Unfortunately, monitoring data on the research houses was of insufficient duration and detail to permit curve fitting of tracer gas growth rates in multiple locations in each house.

In the view of the research team, further theoretical work and chamber testing is required in order to develop a simple and reliable performance test for evaluating ventilation effectiveness in the field. The development of such a test could greatly facilitate the evolution of ventilation standards and systems, and their incorporation within building codes.

Attempts to measure ventilation effectiveness did provide some useful insights into the factors influencing distribution of fresh air in the research houses. Test results and insights are summarized below.

6.1.2 Method (Sue House)

The tracer gas growth test was performed by injecting freon at 3.44 L/min into the supply air of the HRV over a 1 hour period. Concentrations of freon were kept below the TLV (300 ppm). During this growth test, doors and windows were kept closed and the HRV operated at its normal continuous speed of 62 L/s. The furnace thermostat was turned off and the recirculating blower operated continuously at its low speed of 166 L/s.

6.1.3 Results (Sue House)

Figure 6.1 shows the rise in tracer gas concentrations. Note that the concentrations in the exhaust duct rise more quickly than in other locations in the house. Figure 10.2, located in the Appendix, section 10.1.1, shows the location of sampling points in the Sue house, as well as the location of supply outlets and exhaust inlets. The sensors were located on the 2nd floor in the master bedroom with the door shut, in the centre of the basement, and in the kitchen nook on the main floor. Freon was also sampled in the exhaust duct of the HRV.

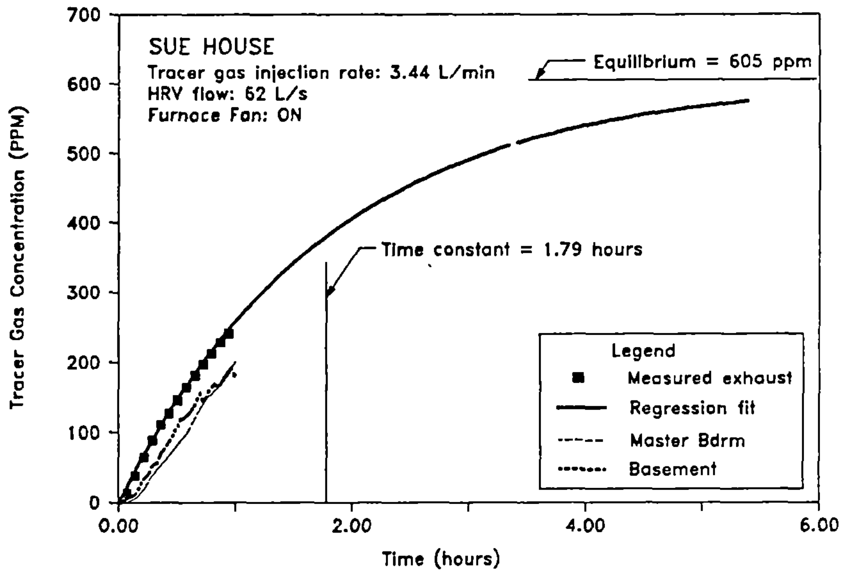

Figure 6.1 Tracer gas growth test: Sue house

During the growth test a portable analyzer was used to sample the tracer gas at different locations in the house and at different heights. Several areas were identified that were not receiving fresh air to any significant degree. Figure 6.2 shows the results of this random sampling on a room by room basis.

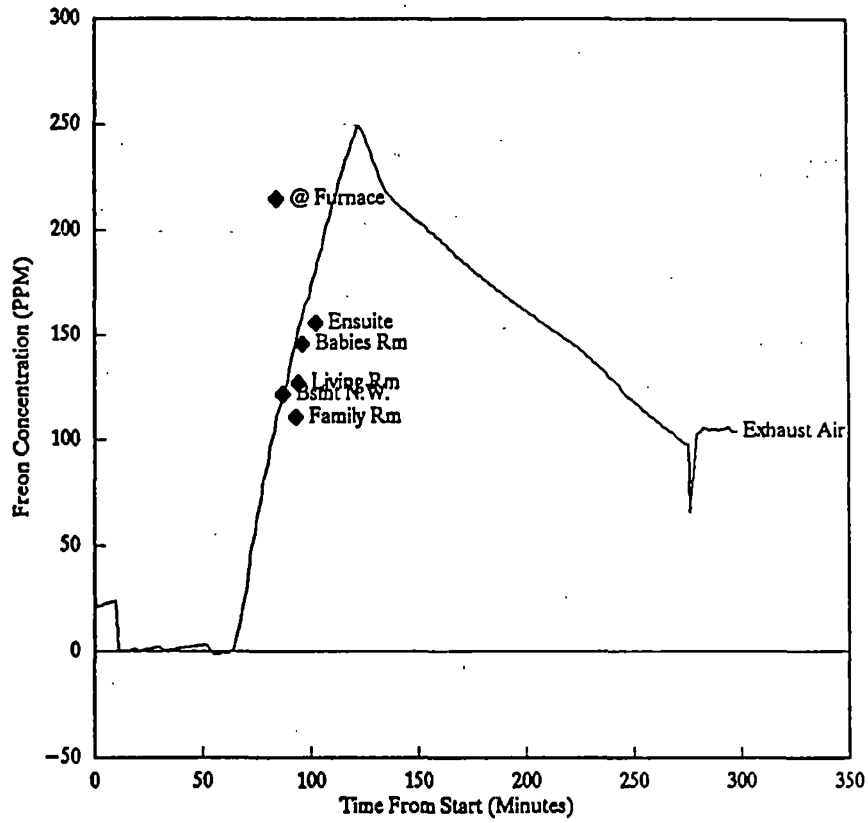

Figure 6.2 Tracer gas Spot Measurements: Sue house

6.1.4 Insights (Sue House)

The growth test proved more difficult than anticipated. The time required to reach an equilibrium state was 8 to 10 hours. (We had wrongly estimated 3 to 4 hours). As a result we had to develop and apply an extrapolation program on the 60 minutes of data collected. The program brackets the predicted equilibrium levels in the exhaust air and other sampling locations.

Major differences in equilibrium concentrations were observed from one locations to another, indicating that natural air change rates varied significantly throughout the house.

In the Sue house, a large percentage of the fresh air was not being delivered to the return air plenum of the furnace, and was instead spilling into the basement. Tracer gas concentrations were especially high in the furnace room, as might be expected. Much of the fresh air was eventually drawn into the return air ductwork, through a multitude of leaks and holes, and was thereby delivered to the master bedroom. However, the circuitous routing had the effect of greatly delaying the response time of the system to sudden increases in fresh air demand. A DCV system would suffer from such poor response time - a factor that may need to be considered in the development of future test procedures for ventilation effectiveness.

6.2 Ventilation Efficiency Test

6.2.1 Purpose of Test

The nominal air exchange rate is the volume of the house divided by the air flow measured at the inlet and outlet of the ventilation system. This nominal rate always over-estimates the actual air exchange rate due to poor mixing, duct leakage, and/or short circuiting in the system. These imperfections all have the effect of lowering the efficiency with which old air is replaced with new. The efficiency may increase under different operating modes, such as when the heating or ventilating systems are operating at high speed.

A tracer gas decay test was performed in each research house to measure the actual air exchange rates. A large portable fan was used to mix the household air to ensure that concentrations were similar in all rooms before decay monitoring began. The ventilation system was operated at a constant rate for an hour while concentrations were monitored in the following locations: living or family room, master bedroom, basement or other portion of house, and the exhaust outlet of ventilation system.

The large number of sensors were combined with an air sampling system (comprised of a pump, sampling chamber, and plastic tubes). This approach allowed researchers to measure efficiency in many different locations throughout the house and to calculate an average performance rating for the entire system.

The efficiency of air exchange was calculated using the following formula:

$$Efficiency = 100 \times \frac{AC_f}{2 \times AC_n} \quad (\%)$$

where

AC_f = Forced air change

= $AC_m - AC_{nat}$

AC_m = Measured total air change, based on the average Freon decay in the house

AC_{nat} = Natural air change rate, based on air change rate with forced ventilation off

AC_n = Nominal air change, based on measurement of HRV supply and exhaust flows

Using this formula, a ventilation system with perfect mixing (or short circuiting) would achieve an efficiency of 50%. A ventilation system displaying characteristics of a piston flow without any mixing, (i.e. a displacement ventilation system), could score as high as 100%. Most Canadian homes, including all the five research homes, experience a combination of partial mixing and short circuiting, and always score below 50% efficiency.

Note the efficiency formula presented above calculates the **forced air change rate** by subtracting the measured natural air change (AC_{nat}) from the measured total air change (AC_m). Although efficiency calculations used by other researchers do not normally make allowances for natural air change, it seems misleading to allow improvements in efficiency rating due to mixing and air changed caused by the uncontrolled and variable influences of weather on a leaky building envelope. Although simply subtracting the natural air change is a crude approach, since some interaction between natural and forced air change rates is likely, this approach is reasonable for a short-term field procedure and is not likely to introduce major errors.

6.2.2 Method (Sue House)

Tracer gas decay tests were performed on the Sue, Jones, and Smith houses to measure ventilation efficiency. Due to limited time and space, only the results from the Sue house are presented. The ventilation system in the Sue house was operated in three different modes during the decay test:

- at a normal ventilation speed of 62 L/s;
- at high speed of 78 L/s with the recirculating blower also at high speed; and
- with both HRV and blower turned off, and intake hoods taped.

With the HRV turned off, we were able to measure the natural infiltration and exfiltration rate caused by stack and wind pressures.

The Sue house was seeded with tracer gas as part of the **growth test** performed for the purpose of measuring ventilation effectiveness.

After the growth test there were large variation in the concentration of freon in different locations in the house. In preparation for the decay test the house air was mixed with a portable 2,000 L/s fan.[13] The normal forced ventilation decay test lasted 1 hour, the high forced ventilation decay test 50 minutes, and the natural ventilation decay test only 30 minutes. During the entire monitoring period, (2 hours and 20 minutes) interior doorways were left open, except for in the master bedroom, where a closed door was intended to simulate worst case conditions for air quality and mixing.

6.2.3 Results (Sue House)

Figure 6.3 shows the air change rate in different locations in the house and includes both natural and forced ventilation rates. Important explanatory details have been written on the graph. Figure 10.2, shows the location of sensors during the tracer gas decay test. The sensors were located on the 2nd floor in the master bedroom with the door shut, the centre of the basement, and in the kitchen nook on the main floor. Freon was also sampled in the exhaust duct of the HRV.

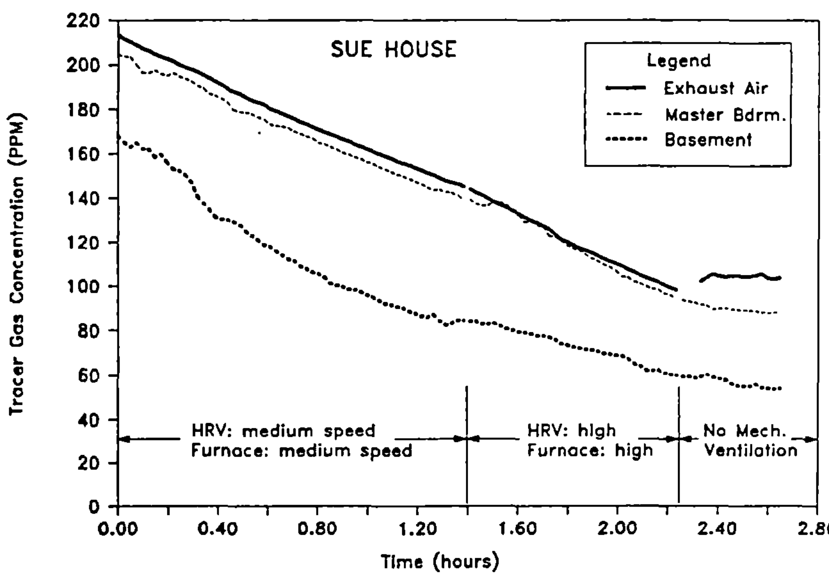

Figure 6.3 Tracer gas decay test - Sue house

13 Unfortunately, the house was not mixed as well as intended. Slight variations remained even after 15 minutes of mixing with the portable fan, and may represent a degree of error in the procedure.

6.2.4 Insights (Sue House)

The Sue house had a ventilation efficiency rating of 42%. An abnormally large amount of infiltration and exfiltration was observed in the Sue house (.22 ACH or 42 L/s). The outdoor temperature during the test was -3 C and the wind speed and direction was 15 km/h from the West.

The ventilation efficiency of the Jones house was 49%, considerably higher than the Sue house. Natural air change was undetectable over the 40 minute monitoring period. The tests on the Jones house were carried out on a day when outdoor temperatures were much warmer (6 C), which may help to explain some of the difference in results.

All three of the research houses measured high ventilation efficiencies, which is probably a by-product of their fully ducted supply and exhaust systems. There were no dead ventilation areas where fresh air did not reach (other than in kitchen cupboards). The Sue house did not perform as well as the Jones and Smith house due to poor distribution and mixing in the basement of the house and poor supply to the master bedroom on the second floor.

The two houses that had redistribution systems (Sue and Smith houses), showed that, even with doors closed, bedrooms are being ventilated as long as the distribution system is operating. Bedrooms in the Jones house were not tested with the doors closed.

There was some evidence of stratification in the Smith house. Spot measurements detected large discrepancies between ceiling locations and floor locations in the living room. Ceiling diffusers will achieve better mixing if the supply air is delivered at a lower temperature than the exhaust air. The supply air in the Smith house is either delivered at the same temperature or, when the house is in a heating mode, delivered at a higher temperature which would exaggerate the stratification. There is obviously a trade off between comfort and performance when delivering air at the ceiling level.

6.3 Inlet Capture Efficiency Test

6.3.1 Purpose of Test

Two capture efficiency tests were completed on the Jones house, one on the kitchen range hood fan and the other on the HRV exhaust inlet in the ensuite bathroom. The method, results and insights are described first for the kitchen range hood and then the bathroom inlet.

The intention was to measure the capture efficiency of a range hood exhaust fan and the HRV inlet when water was boiled on the stove top or a shower was taken in a bathroom. To some degree moisture can be considered a tracer for the smells and other compounds that are produced during cooking. Moisture that did manage to escape the exhaust inlet was monitored as it migrated through the house.

There are many factors that will effect capture efficiency, including total air flow, hood configuration and the velocity of the air stream. This scenario was intended to measure effectiveness of several typical systems, without separating out any of the above factors.

Pots of water were boiled on the stove to simulate the moisture production that would likely occur during meal preparation. Air and moisture flows and temperatures were monitored by a 30 channel data acquisition system. The humidity sensors employed for this test are extremely responsive and are relatively unaffected by changes in temperature, pressure, air velocity, or cigarette smoke. Sensors were placed through the house and in the exhaust ducts. Sensors were calibrated before and after each test.

Poor capture rates will cause moisture to escape into the house. The moisture will diffuse through the house and be absorbed by furnishings. If the house is close to its condensation point, the central ventilation system will need to run for a long time to remove the escaped moisture because of the time constant of moisture desorption. In other words the desorption rate will cause a time delay in removing the moisture. For this reason, a DCV system based partly on humidity control, will greatly benefit from high capture efficiencies.

In the Smith and Morewood house a secondary outcome of this test was to observe the sensitivity of the Aereco extractor bladders to increases in relative humidity. Air flow, humidity, and temperature were measured at the extractors while moisture was produced in the kitchen and bathroom. Air flow, temperature and absolute humidity was also measured at the fresh air inlets on exterior walls in the Morewood house.

6.3.2 Method (Jones House)

Our intention was to simulate the moisture production that would likely occur during meal preparation, while quantifying moisture flows. Two pots of water without lids were boiled on the kitchen range for 53 minutes. The moisture generation rate was approximately 3.4 Kg/hour. The total moisture released was 3 Kg. The range hood exhaust was turned to high speed for the duration of the boil. The range hood was exhausting 91 L/s, (this is considered a high capacity fan for a kitchen). The kitchen exhaust inlet for the HRV is located at a high wall location just inside the dining room. Exhaust flow through the HRV inlet was 11 L/s. Absolute humidity sensors were extensively used for this test. The sensor, as described previously is extremely sensitive to changes in humidity and is relatively unaffected by changes in temperature, pressure, and air velocity.

6.3.3 Results (Kitchen Range - Jones House)

Figure 10.9, in the Appendix, section 10.2.1, shows the layout of absolute humidity sensors. Sensors were located in the range hood exhaust duct, the HRV exhaust duct, and in the kitchen, living room, and dining room. The sensors in the rooms were placed at head height in the approximate centre of the room.

Figure 6.4 shows the change in absolute humidity in the different sensor locations. Note that the humidity scale is different on each graph, although the time scale remains the same.

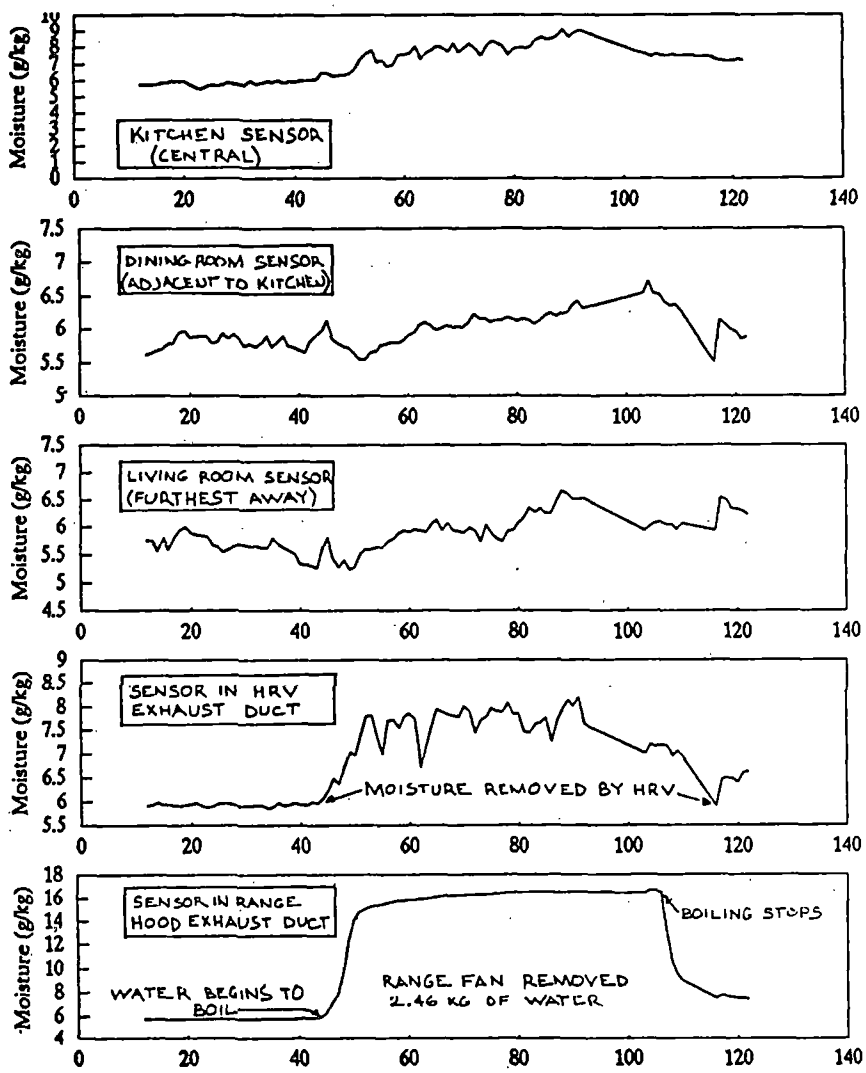

Figure 6.4 Kitchen Range Exhaust: Humidity Dispersion - Jones house

6.3.4 Insights (Jones house)

Calculations showed that of the 3 kg of moisture produced during the test, 2.46 kg exited by the range hood and 0.54 kg escaped into the house. This represents an 82% capture rate.

Average range hood exhaust flow in Canadian houses is approximately 40 L/s[14]. This would suggest that the Jones range hood fan, at 91 L/s, is much larger than average and that the 82% capture rate is probably better than found in the typical new house.

The HRV exhaust removed only 0.059 kg of water during the boiling period. Note that vapour pressure causes a slow but consistent increase in humidity at the furthest sensor location (living room).

A capture efficiency test was conducted on the Smith house which had a similar exhaust hood over an electric range. The results were almost identical and confirmed the measurements in the Jones house. The Sue house had a recirculating range hood fan and could not be tested.

6.3.5 Method (HRV Bathroom Exhaust - Jones House)

The shower in the ensuite bathroom was operated for 16 minutes with both of the bathroom exit doors closed and the shower door closed. No attempt was made to measure the moisture released from the shower. The HRV exhaust inlet was located at a high wall location and was exhausting 17 L/s during the simulation. A through-the-wall grill, located above the bathroom door, allowed air from the balcony area of the kitchen to enter the bathroom. The location of this grill was probably intended to increase the amount of air that the HRV could exhaust from the kitchen. Figure 10.9 in the Appendix, section 10.2.1, shows the layout of absolute humidity sensors. Sensors were located at the ceiling level near shower, in the HRV exhaust duct, in the balcony area of the kitchen on the other side of the bathroom exit door, and finally in the centre of the bathroom, 2 meters from the shower, at head height[15].

6.3.6 Results (HRV Bathroom Exhaust - Jones House)

Figure 6.5 shows four graphs of the absolute humidity sensors in the bathroom. Important explanatory details have been written directly on the graphs.

The HRV exhaust duct removed 0.374 kg of moisture during the showering period. This removal rate was inadequate to control humidity in the bathroom. After the shower, humidity in the duct dropped below the average in the room.

[14] Canada-wide Duct and Chimney Survey, CMHC, 1988-89.

[15] *The sensor on the ceiling fell to the floor during the test when the humidity loosened the tape.*

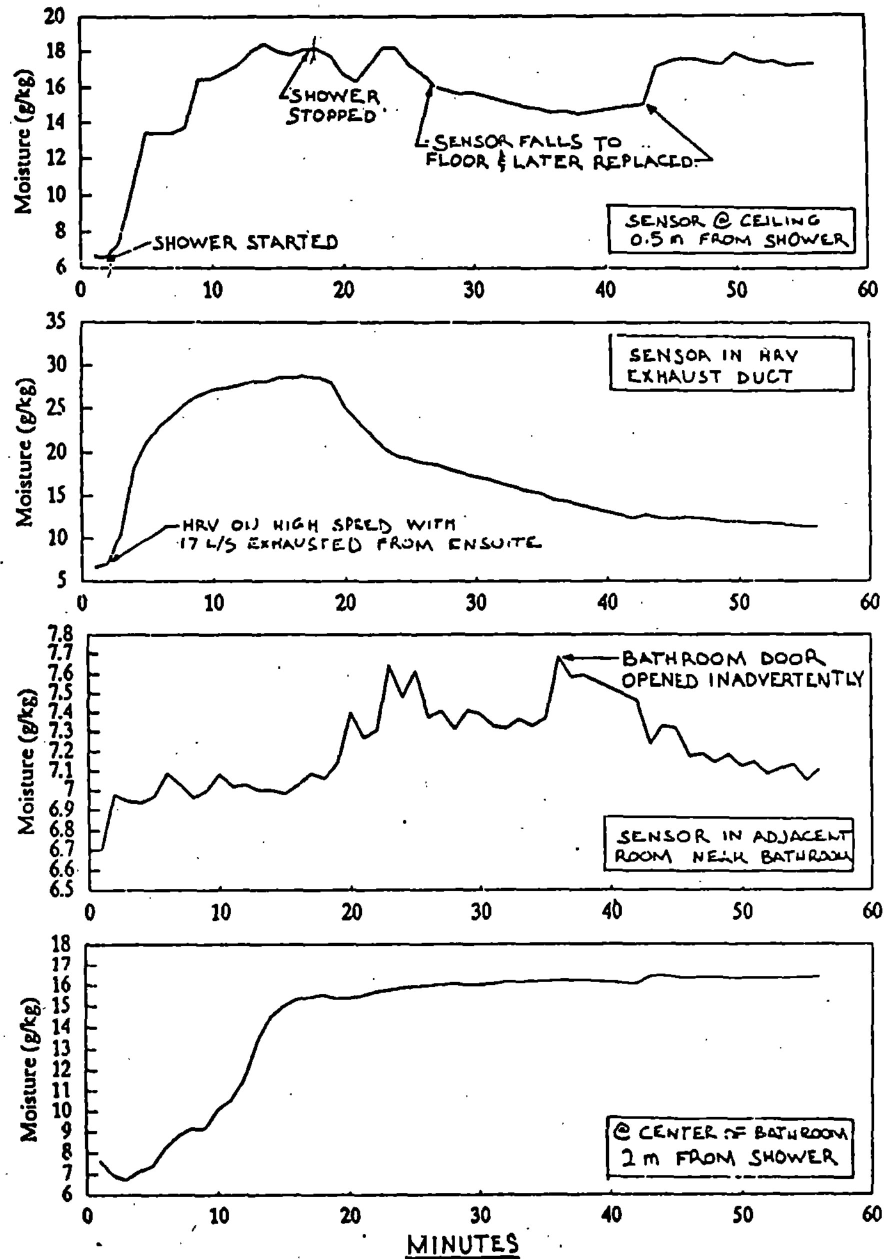

Figure 6.5 HRV Bathroom Exhaust: Humidity Dispersion - Jones house

6.3.7 Insights (HRV Bathroom Exhaust - Jones House)

We suspect that air from the grill above the door is diluting air entering the HRV inlet, thereby reducing the absolute humidity levels in the exhaust duct. The capture rate of the HRV exhaust inlet must be very low because the bathroom becomes saturated with moisture. It is interesting to note that the moisture levels in the bathroom, once elevated, take a long time to decay (i.e. longer than the monitoring time of 1 hour). This is presumably a result of moisture absorption and desorption process which dominate room humidity levels regardless of the air change rate.

The long time constant for moisture removal will likely mean that moisture will escape into the rest of the house when the individual leaves the bathroom. This escaped moisture may elevate moisture levels through the house and prolong high speed operating times for the HRV. This bathroom would benefit from a higher exhaust rate during humidity generation. Higher capture efficiencies in the bathroom would likely mean that the HRV - or any type of humidity controlled central ventilation system - would operate for much shorter periods of time.

An identical test was conducted in the Sue house in the main bathroom. The HRV inlet had extremely low air flows even when all other exhaust inlets in the house were blocked off. With other inlets blocked the HRV was only drawing from one location. The installer had used an unlined stud cavity as a plenum. The leakage from the plenum must have caused the majority of air to be drawn from outside of the bathroom.

The test was aborted and another test was designed on the spot. The 100 L/s exhaust fan from the HRV was removed and directly mounted in the window of the bathroom. The fan was connected to a computerized controller that could turn the fan on when absolute humidity levels exceeded a set point of 7 grams per kg of air. The program would continue to speed up the fan if humidity levels were not controlled. Finally, as humidity levels dropped the computer program would slowly turn the fan to slower speeds until it dropped below a set point.

The performance testing of this mocked-up bathroom DCV system showed that despite air flow in excess of 100 L/s, the fan could not control humidity build-up in the bathroom. The mirror and walls were covered with moisture and one humidity sensor hanging upside down became saturated. Even after the shower was turned off it took more than an hour of continuous exhaust to bring the humidity levels down. At one stage the humidity dropped below the set point and the fan turned off. However, 5 minutes latter, presumably after further desorption, humidity levels again exceeded the set point and the computer turned the fan on.

These results suggest that the typical bathroom HRV exhaust inlet is wholly inadequate for controlling humidity at source, and may also fail to control odours. It leads to the conclusion that, for activity related pollutants, powerful direct exhaust fans are a better approach than low-flow continuous ventilation through a central system.

6.4 Moisture Absorption and Desorption Test

6.4.1 Purpose of Test

The intention of this test was to measure the rate of absorption and desorption in the Smith and Morewood House. The houses are located in very different climatic zones; the Smith house in the coastal area of B.C. and the Morewood house near Ottawa, Ontario. The process of moisture movement in and out of house furnishings and building materials is dynamic and overly complicated for discussion in this report.

The field test was designed to collect 'ball park' measurements of how quickly moisture diffuses through a house, how much moisture is extracted by the ventilation system, and how much was absorbed into the house. A final question of interest was how much time is required for ventilation systems to remove moisture once absorbed by the furnishings and building materials (i.e. the time constant).

The relative humidity in the house and in the outdoor air will have an influence on moisture absorption and desorption rates. The Smith house had indoor absolute humidity levels that were relatively high to begin with (above 7 grams of moisture per kg of air). The Morewood house had extremely low levels of absolute humidity both indoors and outdoors (in the 1 to 2 grams of moisture per kg of air). The two houses probably represent the extremes of conditions in typical Canadian housing.

The effectiveness and efficiency of the ventilation systems is thought to also effect the rate at which moisture will be absorbed and desorbed. High effectiveness rates could counteract high capture rates of range hood fans. High ventilation efficiency rates could reduce both the amount of moisture absorbed and the rate at which moisture was desorbed. It was hoped that the absorption and desorption test might also throw some light on how much impact might be expected from the efficiency and effectiveness already measured.

6.4.2 Method (Morewood House)

Moisture absorption and desorption tests were conducted on the Smith and Morewood house. Both houses had Aereco exhaust extractors which passively regulate air flows depending upon relative humidity. The tests were an excellent analysis of the effect of outdoor climate on indoor conditions. The Morewood data has been presented below the Smith house for purposes of comparison.

Analysis of the Morewood house data that was collected over the Christmas period showed that the dominant influence on air change was wind. For a description of how this house works refer to the Appendix. The house was not particularly tight for a new energy efficient Canadian home (3.0 ACH at 50 Pa). The effect of the leaky building envelope was to exaggerate the influence of wind on air change.

For this simulation the house was partitioned in an attempt to make the tested area tighter and more responsive to changes in relative humidity. The basement was sealed from the rest of the house and the two spare bedrooms were also sealed. Even though the doors and cracks were sealed with 2 inch wide polyethylene tape, this remedial air sealing was only marginally successful.

The tests were carried out on February 6 and 7, 1990. Three portable humidifiers were used to elevate humidity levels in the house from 4 g/kg to 9 g/kg. This required the release of 6.17 litres of water over 1.5 hours. The house was simultaneously seeded with freon and the gases thoroughly mixed. Both the moisture and freon were allowed to decay over a 15 hour period. This was both a good test of the absorption and desorption rate of the house, and a method for measuring the influence of the Aereco ventilators and extractors on total air change in the house.

Figure 10.21 in the Appendix, section 10.4.1, shows the location of sensors in the Morewood house. Sensors were located in the living room, in the kitchen, at the kitchen extractor and at the bathroom extractor. Air flow sensors were located at the kitchen and bathroom extractors and at the living room and master bedroom ventilators.

6.4.3 Results (Morewood House)

Figure 6.6 shows the long decay of moisture in the house during the scenario on February 6. Important comments have been written on the graphs. Figure 6.7, titled "WIND EFFECTS ON WALL VENTILATORS - MOREWOOD HOUSE" shows the continuation of the moisture desorption scenario on February 7, 1990.

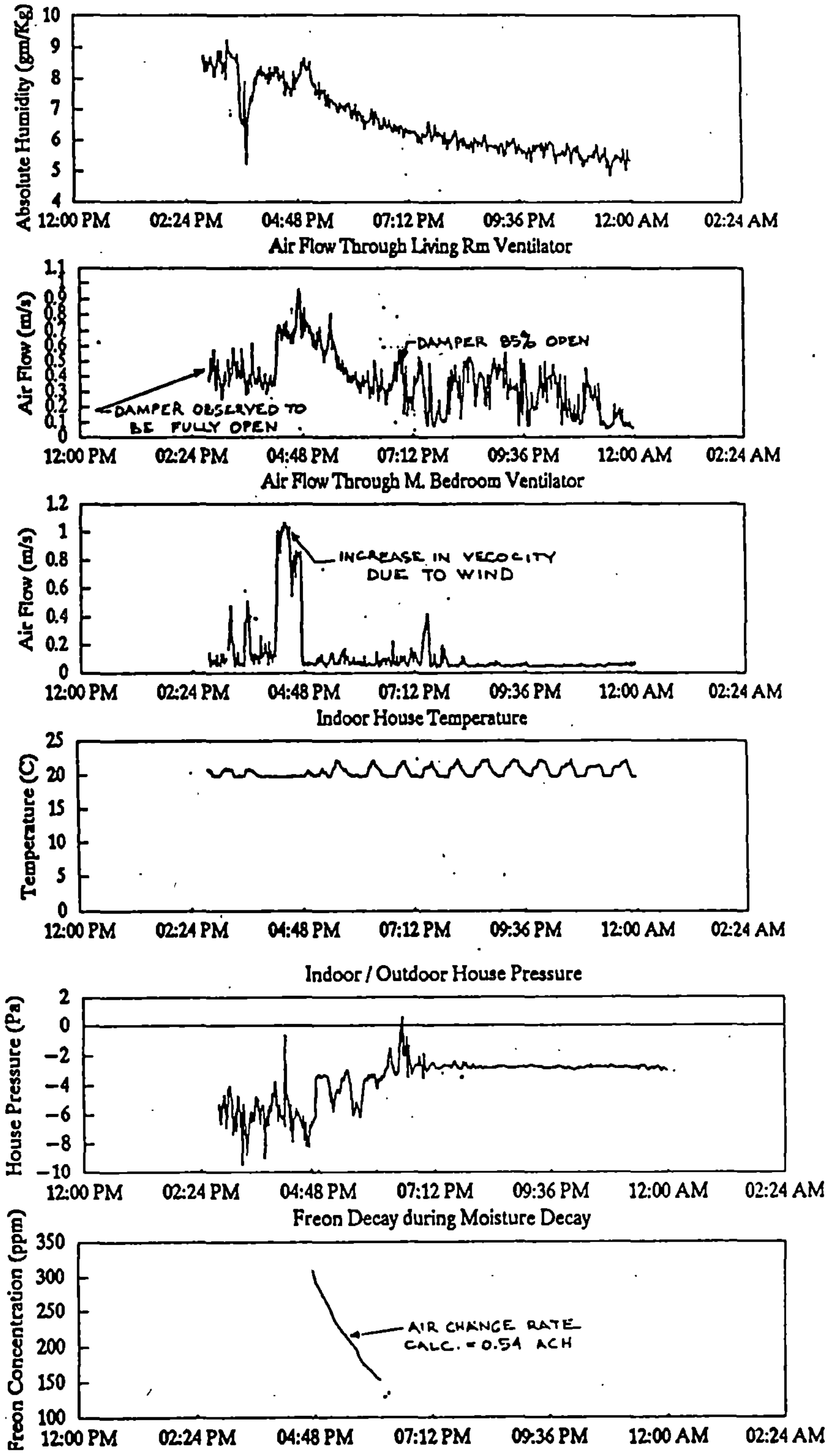

Figure 6.6 Moisture Absorption and Desorption - Morewood house

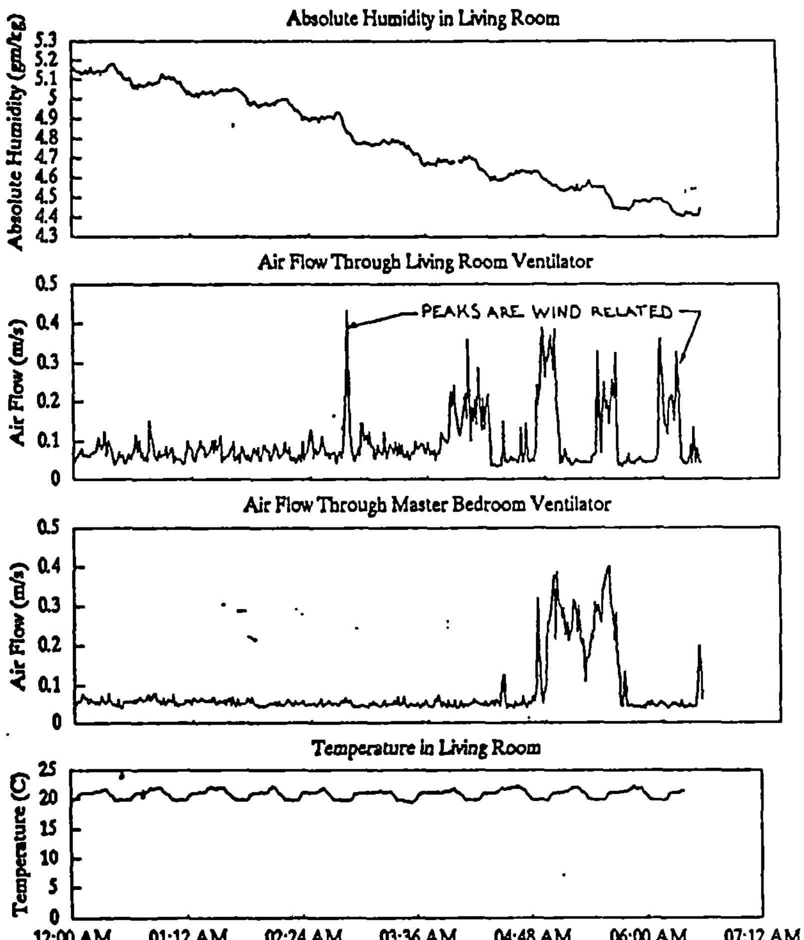

Figure 6.7 Wind Effects on Wall Ventilators - Morewood House

6.4.4 Insights (Morewood House)

Both the Aereco extractors and ventilators responded as expected to increases in moisture level in the Morewood house. However, the combined effect on air change and moisture removal was insignificant.

The tracer gas air change rate remained constant at 0.54 ach which translates into an air flow rate of approximately 20 L/s for the main floor, excluding the volume of the two small bedrooms that were taped off (see Appendix, section .

After 15 hours the humidity had almost returned to the starting point of 4 g/kg. The moisture desorption rate was calculated to be 356 g/hr. This scenario shows that once humidity is released into a house, it takes a large amount of flushing to remove. Of the total 7000 g of moisture released, 5337 g was absorbed into furnishings and building materials. A small amount of moisture may have been retained as condensation on cold surfaces. As will be seen, the moisture desorption rate of the Morewood house is much faster than the moisture desorption rate of the Smith house even though the relative air change rates are very similar (0.54 Morewood house and 0.46 Smith house). Not surprisingly, the dry air in Ontario in mid-winter (measured to be 1.5 g/kg) is far more effective at diluting the moisture than the humid air in the Vancouver area.

6.4.5 Method (Smith House)

Humidity levels were monitored over a 5 hour period in the Smith House. A pot of water was boiled on the range and a shower was operated in the ensuite bathroom. The pot of water was boiled in the kitchen for 45 minutes to elevate the average indoor absolute humidity from 7.0 g/kg to 8.0 g/kg. Approximately 20 minutes later a shower in the ensuite bathroom was operated with the bathroom door closed. At the end of the 16 minute shower the by-pass shutter on the bathroom extractor was opened. The bathroom door was opened 60 minutes after the shower was stopped.

At the start of the scenario the total air exhausted was 33 L/s. Three extractors in the kitchen and bathrooms had bladders partially opened. The effect of the open bladders was to depressurize the house to -2 Pascals (relative to outdoors). This caused 16 L/s of make-up air to enter through natural leaks in the envelope. At all times there is 17 L/s of make-up air entering through a supply duct into the recirculating system. The impact of both the water boiling and the shower was to boost the average absolute humidity in the house from 7 g/kg to 8.5 g/kg. The average indoor temperature was 25 C which gives a calculated relative humidity of 43%.

Figure 10.15 in the Appendix, section 10.3.1, shows the layout of absolute humidity sensors. Sensors were located at the opening of the kitchen extractor and the bathroom extractors. Air flow sensors were located at each extractor, and inside the exhaust duct, one meter up stream of the exhaust fan. A pressure gauge was constantly monitoring indoor/outdoor pressure difference.

6.4.6 Results (Smith House)

Figure 6.8 shows the response of the Aereco extractor bladders to moisture generation in the kitchen and bathroom. Important explanatory details have been noted on the graphs.

The total exhaust flow through the bath extractors increased 3 L/s during the monitoring period, from 33 L/s to 36 L/s. The flow slightly decreased at the kitchen extractor when the bathroom extractor by-pass port was opened. The air velocity at the ensuite extractors changed from 3.9 m/s to 4.0 m/s when absolute humidity was increased from 8 g/kg to 25 g/kg in the ensuite bathroom.

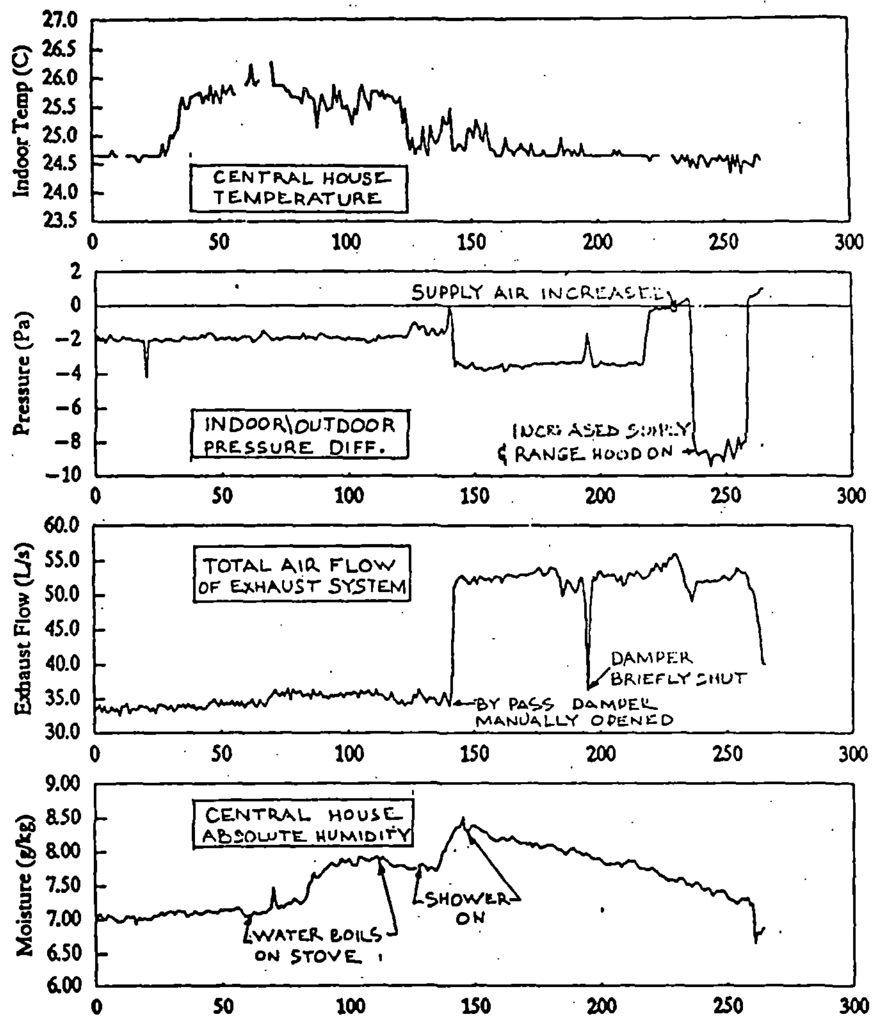

Figure 6.8 Moisture Absorption and Desorption - Smith house

6.4.7 Insights (Smith House)

Aereco literature suggests the bladder in this exhaust extractor has a maximum opening of 9 cm^2, and a flow of 7 L/s, with a pressure drop of 100 Pascals across the opening. A 3 L/s change in flow would equate to a 2.3 cm^2 increase in bladder opening. While this type of response is to be expected, the impact on air change and humidity levels was shown to be marginal.

It should be recognized that temperatures in a bathroom increase rapidly during a shower, especially at the ceiling level where extractors are located. A device that responds to relative humidity will be highly effected by this temperature increase. The overall impact on air flow will be reduced.

The ventilation system in the Smith house was able to remove 225g of moisture per hour. This is considerably less than the Morewood house and is due to the difference in absolute humidity levels between the two climates. It would take the Smith house 9 hours longer, running at its highest ventilation rate, to remove the same amount of moisture as did the Morewood house given the same release of moisture.

7 Helma House Demonstration Project and Further Research

The section describes the design, fabrication, installation and evaluation of a DCV system in the Helma house. Designing a system for a new hose allowed more flexibility in the choice of DCV strategies.

7.1 Description

The Helma house was built during the course of the research by Helma Construction. The house was built on speculation and was difficult to sell due to a down turn in the real estate market. The house construction was complete by September, 1990, and sat empty until it sold in December. Table 7.1 describes the characteristics of the house.

Table 7.1 Helma House Description
2 Storey with full basement 450 m^2 floor area B.C. Hydro Quality Plus Home Air leakage > 0.7 cm^2/m^2 Walls: RSI 3.5 (R20) Ceiling: RSI 7.0 (40) Windows double glazed, 12mm air space Bryant condensing forced air gas furnace State Turbo sealed combustion gas DHW tank 2 Valour side vented sealed gas fireplaces Gas stove with Rangaire 880 L/s exhaust fan VanEE 2000 Variquiet HRV - 3 wire Douglas high/low system - booster fans in bathrooms

7.2 DCV System Design

The Helma house DCV system has five main features that are presented in Table 7.2. The choice of these features is based on the findings from the low level and intensive monitoring of the three research houses.

Table 7.2 Features of the Helma House DCV Systems
1 The system automatically turns on when people are at home. The ventilation rate increases, depending upon the activity level and the number of people at home.
2 An air quality sensor will detect when pollutants are produced and will increase ventilation rates. The detector will sense toxic cleaning chemicals, off-gassing from construction materials and paint.
3 The system automatically monitors moisture levels in the home and will prevent condensation from occurring on window surfaces. The system does this by monitoring the temperatures and moisture levels in the indoor and outdoor air.
4 The information that is being monitored is continuously displayed on a video monitor in the living room. The occupant can always be aware of how the system and house are performing.
5 The occupant can override the system at any time to set minimum and maximum ventilation rates by turning a dial and flicking a switch. The occupant can choose when, and when not to rely on the automatic system.

7.3 Fabrication

A portion of the work on this project was sub-contracted to a pair of electronic engineers, Chris Helston and Bob McKechnie. They were in charge of purchasing equipment, writing software and assembling the controller. Table 7.3 lists the primary equipment that was used for the control system.

Table 7.3 Helma House DCV Controller Equipment List
TTL monitor
MS-DOS computer with 256K memory
3.5 inch, 1.4MB floppy disk drive
Hercules graphics card
RS-232 port
DA/M board with cable, power supply and software
4, P.I.R. sensors, Roconet 3001 miniatures, sharing one channel
Solid state variable speed control
2, AD590 temperature sensors
2, HS7 Shibaura absolute humidity sensors
TGS 800 Figaro semi-conductor sensor and Halitec analyzer
Type F6201-1 Shibaura air flow sensor

7.4 Installation

The equipment was installed in September, 1990. A video monitor was permanently installed in the wall of the living room. The computer was mounted on the wall of furnace room and sensors were located in the supply and exhaust ducts of the HRV. Table 7.4 lists the information that is continuously displayed on the monitor.

Table 7.4 Helma House DCV Video Monitor Display

Indoor Comfort:	
Temperature	.... (C)
Absolute Humidity	.... (g/kg)
Air Quality Indicator	.... (poor, avg., exc.)
Outdoor Conditions	
Temperature	.... (C)
Absolute Humidity	.... (g/kg)
Condensation Protection	
Maximum Allowable Indoor Humidity	.... (g/kg)
Ventilation	
Occupant Activity Level	.... (low, medium, high)
15 minute total	....
1 minute total	....
Fresh Air Supply	....
Average	.... (L/s)
Instantaneous	.... (L/s)
Required	.... (L/s)
Occupant Set Minimum Ventilation Rate	
Recommended Minimum Ventila- tion Rate	.... (L/s)

7.5 Operation

Operation modes were designed into the control software to anticipate the occupant requirements for ventilation. The seven operational modes are described in Table 7.5.

Table 7.5 Helma House DCV Operational Modes

Standby Mode:
If there have been no pulses recorded from the PIR sensors in the last hour (i.e. no activity in the house), turn the HRV off.

Timer Mode:
If the HRV has not operated during the last hour, turn HRV on to high speed for 10 minutes.
Occupant Arrival Mode:
If HRV has been off, a single pulse from a PIR sensor turns the HRV to minimum ventilation rate.
Occupant Generated Pollutant Mode:
For increases in pulses from a PIR sensor over the last hour, increase the speed of the HRV proportionately.
Activity Generated Pollutant Mode:
If the Halitec sensor exceeds its set point because of pollutants detected in the exhaust air, operate the HRV at high speed
Sleep Mode:
At 11:00 PM, run the ventilation system at its minimum rate for the entire night if any pulses have been detected from the PIR sensors since 5:00 PM. A pulse during the night can also activate the ventilation system.

The following formula was derived to give the house condensation protection:

$$W_{max} = 4.1106 \times e^{0.0639 \times T_{si}} \qquad \text{(g/kg)}$$

where,

$$T_{si} = T_{index} \times T_i - T_o(T_{index} - 1) \qquad \text{(C)}$$

W_{max} = Maximum allowable absolute humidity
T_{si} = Indoor window surface temperature
T_i = Indoor temperature
T_o = Outdoor temperature
T_{index} = 0.56 (for double glazed windows with ½ inch air space)[16]

Whenever the maximum allowable indoor humidity is exceeded, the ventilation system is operated at high speed until the humidity drops below the maximum. The objective is to allow the house to have the maximum humidity without causing condensation. (This maximum was assumed to be the optimum comfort level in winter).

[16] Average temperature index from field trials to assess the validity of the Moisture Assessment Prescriptive Procedure (MAPP), prepared for EMR by TROW Ontario Ltd.

The software written to control the system is extremely sophisticated and is able to achieve any ventilation rate by switching between two motor windings and four motor speeds (high, medium, low and off). Moving averages are used to dampen variability and slowly target a given ventilation rate. The result is that changes in flow rates are slow and quiet.

Four PIR sensors, located in the living room, family room, master bedroom and the basement, feed pulses to the computer. The ventilation system increases in air flow by one L/s for every two counts within the last 15 minutes. The large number of sensing locations in this house should give a better correlation between CO_2 levels and pulses than found in the Sue house.

The ventilation system is wired so that switches in the wet rooms can override the control and operate the HRV at high speed. At the same time, small booster fans in bathrooms where the switch is activated will turn on and increase flow from that bathroom. The occupants can also set the minimum ventilation rate by keying in data to the computer.

The Halitec semi-conductor gas analyzer measures air quality in the exhaust air. This equipment operates the sensor in an AC mode and does Fourier analysis of the waveform generated by the resistance through the semi-conductor. A set-point based on an equation that uses the first harmonic and the phase angle will activate the high speed of the HRV. Many household contaminants will be detected by this sensor, including paint, nail polish, hair spray and cleaning solutions.

7.6 Evaluation

The following insights from the Helma house DCV project:

- The Halitec sensor responds to both a cigar being smoked in the house and the opening of a container of lacquer thinner.
- No condensation has occurred on window surfaces from September to December.
- Pulses from the PIR sensors slowly increase ventilation rates. A proper evaluation of the system will have to wait for the new owners to move into the house.

- We would not have installed an HRV in this house if we had been in complete control of the heating and ventilating design[17].
- The trial DCV system worked extremely well and the video monitor displaying environmental conditions became a special feature in this new house.
- We believe this was a successful demonstration of how a DCV system might be integrated into a new house.
- It is technically feasible to reduce the equipment to a small, wall-mounted, device.

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17 Instead, high capacity, activity related fans would have been installed in bathrooms; the mixing system in the house would have been upgraded, and mixing would only occur if pulses had been received from the PIR sensors. Finally, exhaust only ventilation would have been installed.

8 SIMULATIONS & ECONOMICS

8.1 General

A series of hourly simulations were performed using the Enerpass/Contam87 combined program. A number of problems were experienced with early versions of the program. Of several hundred runs performed, over half had to be scrapped, along with the input files, due to changes in the program to remove inconsistencies and "bugs". After about six months of "debugging", the program is reasonably reliable and easy to use, but is still extremely slow - typically about 7 to 10 minutes per simulated day on an IBM AT with a math co-processor. For this reason most of the results rely on extrapolations of results from runs of one to three months in duration.

The houses simulated were assumed to be heated with a forced air system and were therefore divided into only two zones - main floor and basement. Inter-zonal air flows[18] had to be estimated and could be critical if pollutant emissions are strongly zone dependant.

The base house is a bungalow with full basement, 123 m^2 per floor (see Appendix, section 10.5, for more detail). Simulations with continuous fan operation (base cases) and demand controlled ventilation (based on CO_2 levels) were carried out for Vancouver, Toronto and Winnipeg. The tables that follow describe the changes to occupancy, fan rates and heat recovery that were incorporated.

8.2 Simulation Results

The results of the simulations are shown in the tables that follow, listed under Vancouver, Toronto and Winnipeg. The procedure used was as follows:

- Perform a full year simulation using Enerpass
- Perform several short runs of the base (continuous ventilation) and demand controlled ventilation (DCV) cases in order to find a CO_2 set-point, for the latter, that would result in the same average CO_2 levels as the base case.

  Selected runs were also carried out for a DCV system that matched the base case peak values of carbon dioxide concentration.

[18] The program inputs were based on standard values (ASHRAE), modified to match simulations to measured results in the low level monitoring of the three research houses.

- Perform an Enerpass/Contam87 run of the DCV case for the period from January to March, inclusive (50% of the space heating was found to occur during this period). The reason for limiting the duration of these runs was to keep simulation time to a reasonable length - about 8 hours per run on a 386 computer.
- The monthly space heating results from the DCV run were compared to that for the base case; the average reduction calculated and applied to the base case for the rest of the year.
- Fan energy savings were assumed to be 25% (low level monitoring showed non-optimized savings of from 23% with activity sensors to 24% with a CO_2 sensor were possible - greater reductions may be possible)

Carbon dioxide levels are shown in Figure 8.1, for continuous fan (base case), versus match average and match peak DCV control scenarios. The results are for two days - a weekday, followed by a weekend with 20% higher occupancy. The simulation was for Winnipeg, but the shape of the curves will be similar for the other two locations.

Figure 8.1 CO_2 Comparison - 3 Simulation Scenarios

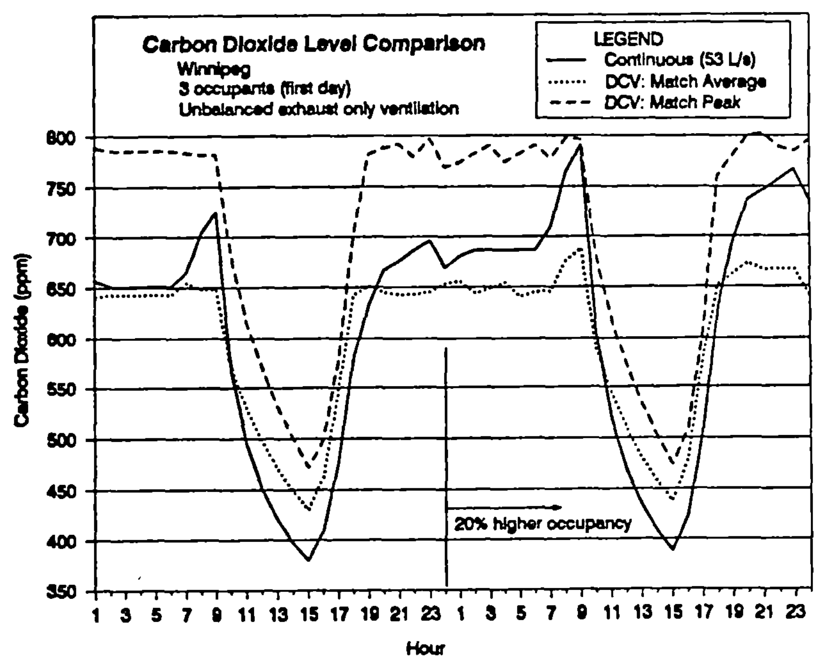
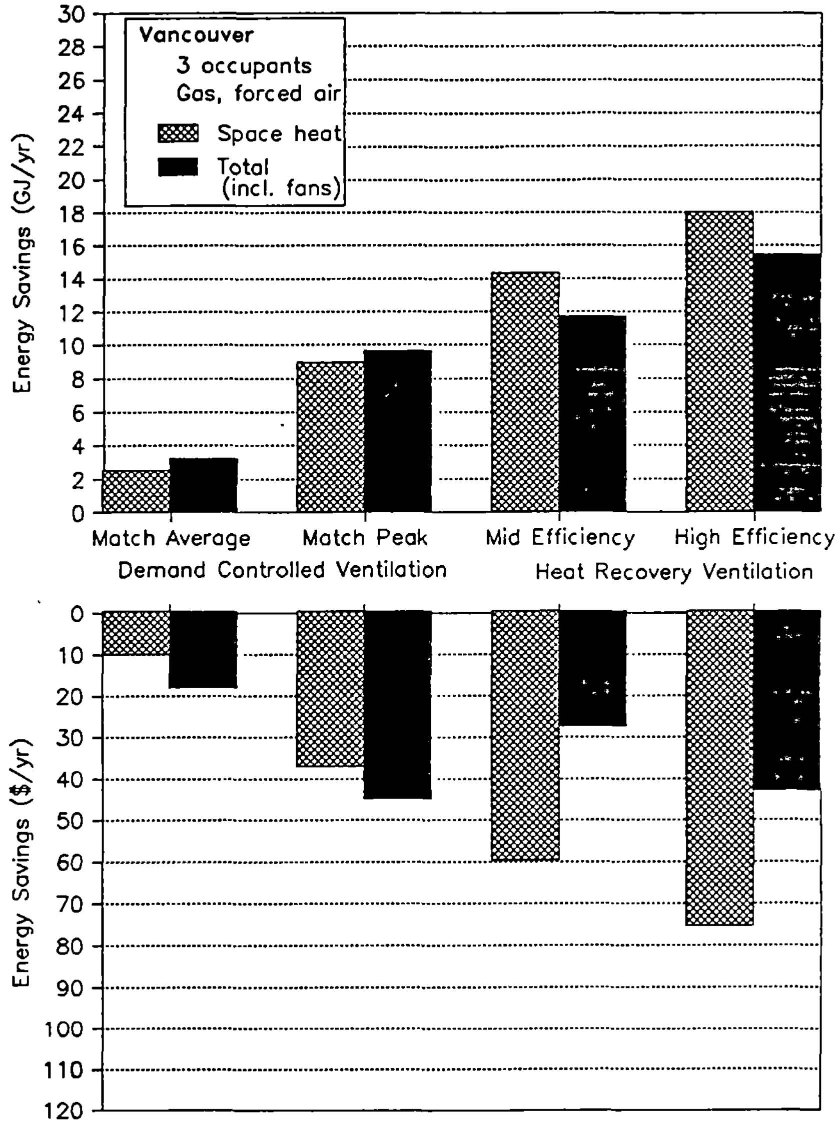
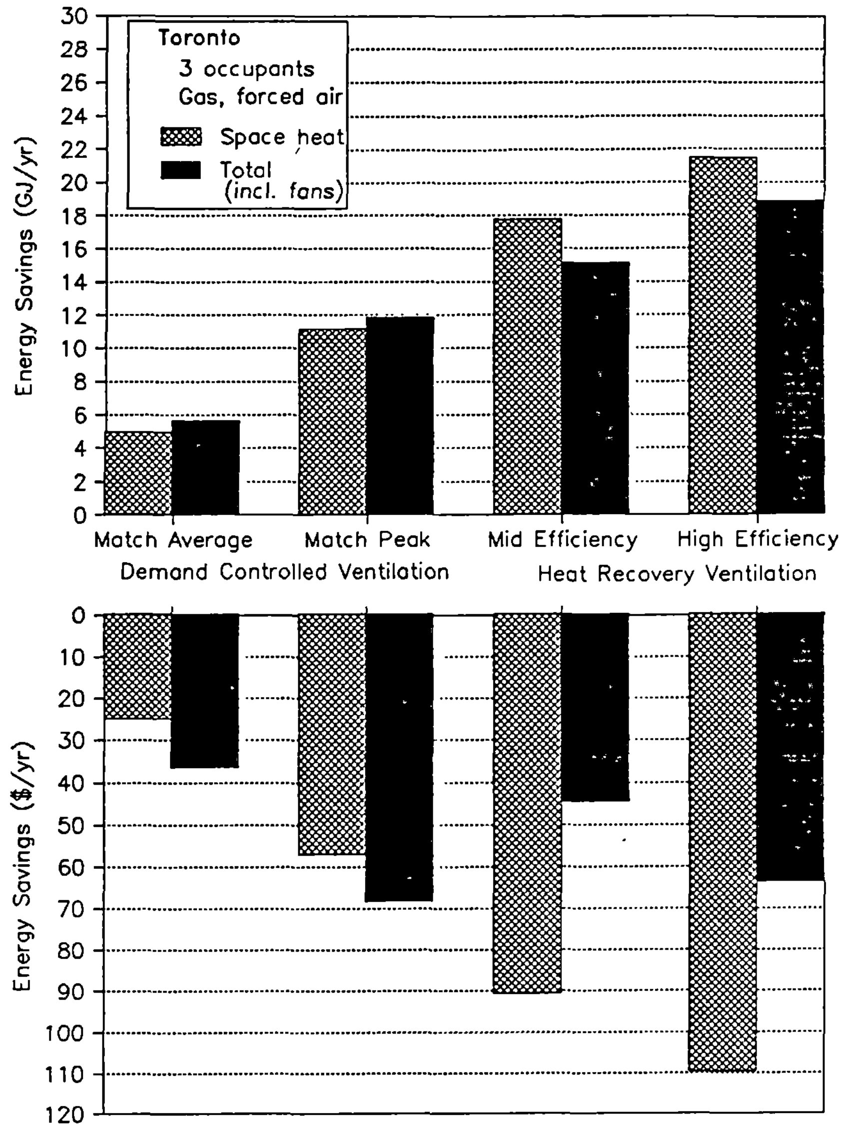


Figure 8.2 Comparison of DCV and HRV for Vancouver



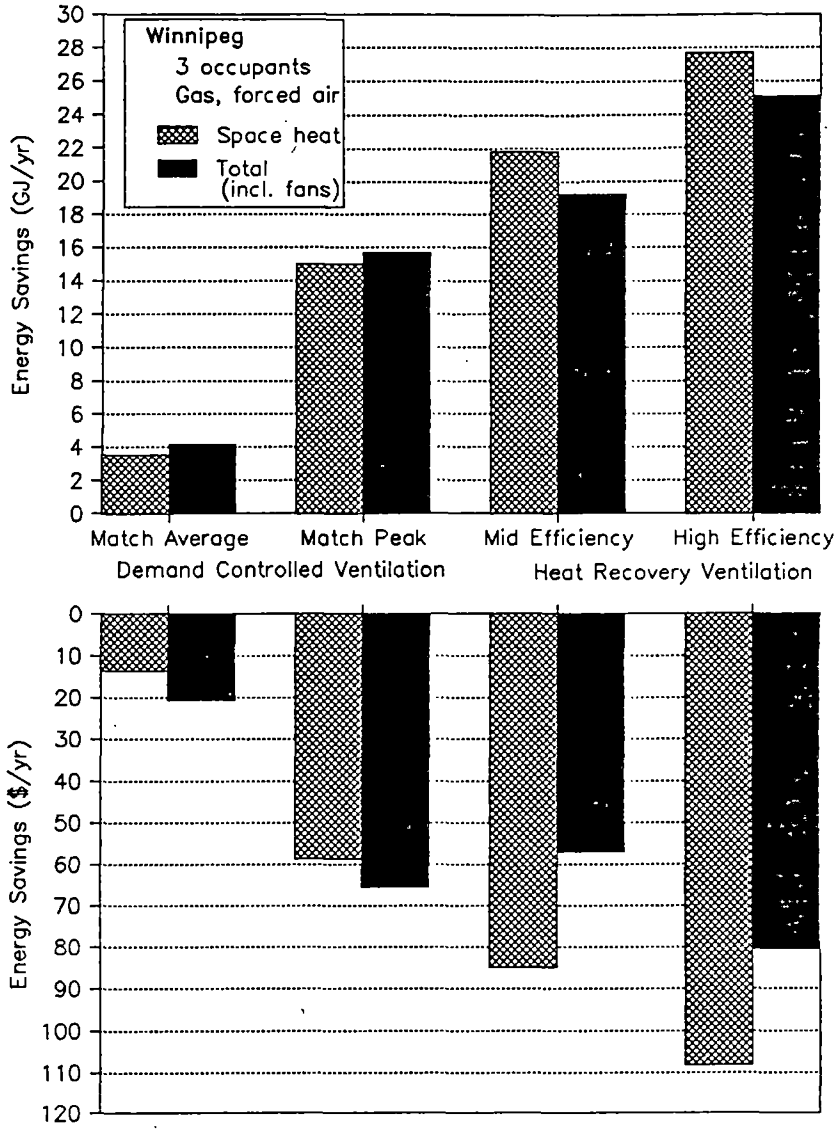
VANCOUVER:	DCV Match Average	DCV Match Peak	HRV Low Efficiency	HRV High Efficiency
Space Heat savings (GJ/yr)	2.5	8.9	14.3	18.0
Vent. Fan savings (GJ/yr)	0.7	0.7	-2.6	-2.6
TOTAL SAVINGS (GJ/yr)	3.2	9.6	11.7	15.4
Space Heat savings ($/yr)	$11	$37	$60	$76
Vent. Fan savings ($/yr)	$8	$8	($32)	($32)
TOTAL SAVINGS ($/yr)	$19	$46	$28	$44

Figure 8.3 Comparison of DCV and HRV for Toronto



TORONTO:	DCV Match Average	DCV Match Peak	HRV Low Efficiency	HRV High Efficiency
Space Heat savings (GJ/yr)	4.9	11.1	17.7	21.4
Vent. Fan savings (GJ/yr)	0.7	0.7	-2.6	-2.6
TOTAL SAVINGS (GJ/yr)	5.6	11.8	15.1	18.8
Space Heat savings ($/yr)	$25	$57	$91	$110
Vent. Fan savings ($/yr)	$12	$12	($46)	($46)
TOTAL SAVINGS ($/yr)	$37	$69	$45	$64

Figure 8.4 Comparison of DCV and HRV for Winnipeg



WINNIPEG:	DCV Match Average	DCV Match Peak	HRV Low Efficiency	HRV High Efficiency
Space Heat savings (GJ/yr)	3.5	15.0	21.8	27.7
Vent. Fan savings (GJ/yr)	0.7	0.7	-2.6	-2.6
TOTAL SAVINGS (GJ/yr)	4.2	15.7	19.2	25.1
Space Heat savings ($/yr)	$14	$59	$85	$108
Vent. Fan savings ($/yr)	$7	$7	($28)	($28)
TOTAL SAVINGS ($/yr)	$21	$66	$57	$81

DCV ventilation rates were reduced by about 10% (match average) to 25% (match peak), from a base level of 0.32 air changes per hour.

Savings ranged from about $19 per year (Vancouver) to $37 per year (Toronto) for runs matching DCV **average** CO_2 levels to non-DCV levels. With a 10 year system life, these savings would translate into an allowable economic investment of about $190 to $370.

Runs with set points matching base case **peak** CO_2 levels showed savings of from $37 (Vancouver) to $69 per year (Toronto) - translating into an allowable economic 10 year investment of from $370 to $690.

The DCV system envisaged here was basically a quiet exhaust fan with a 'smart' controller, and minimal ductwork for non forced-air systems. With the lower ventilation rates used by DCV systems (particularly match peak DCV), **building pollutants**, such as formaldehyde, would have to be controlled by sealing particle board and other sources of building related pollutants.

Another factor that became apparent during the economic analysis is the importance of efficient fans. While the amount of energy used was not a large amount, the dollar value of the fan energy became significant due to the disparity between natural gas and electrical energies.

For comparison purposes, a number of simulation runs were performed with heat recovery ventilation systems, with and without DCV. Two ranges of efficiencies were used to represent a likely upper and lower limits of performance.[2]

Demand control produced significantly less space heating savings with HRVs. Most of the savings was due to electrical energy saved due to turning the fans off during periods of low CO_2.

In general, the range of savings for DCV (match average to match peak carbon dioxide concentration) are comparable to the range for heat recovery ventilators (see figures 8.2, 8.3, 8.4), and capital costs for DCV should be considerably less. Also, the HRV systems have a history of problems with defrost controllers, damper motors, etc.- indicating significant maintenance costs that have not been quantified in this analysis.

Since the limits of DCV technology have not been fully explored, it seems likely that it represents an economically viable alternative to current HRV systems. In addition, air quality can be controlled in a consistent manner according to the individual needs of each family.

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19 "High efficiency" runs used values of 65% to 74% (depending on outside temperature), while the "low efficiency" runs used a value of 50%.

9 CONCLUSIONS

DCV offers benefits only when occupant generated pollutants exceed building related pollutants and when occupant generated pollutants vary with time. For this reason, DCV is best considered as part of a complete house system.

Source control of building generated pollutants at the construction stage is essential for applying DCV control strategies in new Canadian homes. The average new Canadian house may be too toxic to take full advantage of DCV. The rewards for improved source control include lower heating and cooling costs, less complicated ventilation hardware, and better air quality indoor and out.

CO_2 is an excellent indicator of occupancy and ventilation requirements in residential buildings. A small, moderately priced passive CO_2 gas analyzer performed well in three research houses.

Activity related pollutants are best controlled by high capacity, directly vented exhaust fans with high capture efficiencies.

Relative humidity is a poor indicator of occupancy. Response times are slow. Often there is no discernable change in RH despite major changes in occupancy and CO_2 concentrations. Moreover, the dehumidistats commonly employed for RH control were found to be grossly inaccurate, subject to drift over time, and lacking any convenient means for re-calibration. Absolute humidity is a better indicator of occupancy, but still displays a lag time due to the absorption and desorption characteristics of the house. Ventilation control based on absolute humidity is limited to the heating season, and is best combined with a window inside surface temperature to provide condensation control.

Passive Infra Red (PIR) activity sensors proved low cost and reliable during the field trials. As a secondary sensor technology they have a poor short term correlation with CO_2 but excellent long term correlation. The poor short term correlation is to be expected, since activity is sensed instantly whereas pollutant concentrations rise over time. Short term correlations could be improved with more sampling points, and a software program that is able to gauge the level of activity over time.

High mixing rates in residential houses are preferable to zoning and can greatly reduce the ventilation requirements on a room by room basis. By means of air mixing, the whole house volume can be made to dilute occupant generated pollutants, without additional heating or cooling cost. Operating times for recirculation systems can be part of a DCV strategy. A whole house air mixing system is a very useful feature for a DCV system. In an energy efficient home, the ventilation requirements - not the heating load - should dominate the design specifications for the air distribution system.

Economic analysis of DCV systems showed small savings in operating costs given current energy prices. The savings are partly due to reductions in electricity use achieved by turning off ventilations fans.

Large savings in the capital cost of equipment can be obtained by substituting exhaust only DCV ventilation and forced air distribution for a conventional HRV.

DCV systems are particularly effective at **reducing peak pollutant** concentrations. This offers improved health and comfort, even if the mean level of pollutants are similar for systems without DCV.

Semi-conductor sensors (e.g. Figaro TG5800) appear to have potential as an overall IAQ indicator if used in alternating operation with a breather that periodically flushes the sampling chamber to automatically zero the sensor.

Further research, including theoretical work and chamber testing, is needed to develop a simple and reliable performance test capable of describing the effectiveness of fresh air distribution, and the response time of systems to fresh air demands. The development of these tests could greatly facilitate the evolution of ventilation systems, and the incorporation of minimum standards within the building codes.

Low cost multi-point tracer gas equipment now makes evaluating the performance of ventilation systems feasible for all groups in the housing industry. In their present state tracer gas growth and decay tests were found to be useful for evaluating DCV strategies.

A DCV controller was permanently installed in a new house and preliminary results show the system is performing to expectations.

Inlets equipped with humidity controlled bladders were found to be particularly **ineffective** for DCV applications, both in a coastal climate and in central Canada. The bladders are influenced by temperature changes - indoors and out - which confuses their performance and slows their response time. They provide too little air flow to have a significant impact on humidity levels. Their design seems to ignore the very significant impact of accidental air leakage - especially in houses subject to constant depressurization. Their capture efficiencies are very poor; as humidity is generated by occupants it is absorbed by the house and desorbed over many hours. The result is unnecessarily long periods of high ventilation rates, and ventilation rates that are not synchronized with periods of high occupant activity. Application of this technology in Canadian houses is not recommended as a part of any DCV strategy.

DCV system design can be simplified by defining the most common operating modes for the house, and configuring the air mixing and air change rates accordingly. Typical operating modes could be: standby (with timer activated intervals of operation); occupant arrival; high activity; odour control; and sleep.

A potential exists for lowering the capital costs of sophisticated DCV systems by using a multipurpose home computer. A computer capable of interpreting sensor data and controlling ventilation, should also be capable of monitoring maintenance requirements and home security.

Occupants should not be relied upon to optimize the operation of ventilation systems. Fully automatic systems, with computer control, appear to operate more effectively over the short and long term.

Installation of a DCV system in a new house has demonstrated the viability of DCV in terms of practicality and performance. The affordability of such DCV systems is still a barrier, primarily due to the absence of mass produced computer controllers.

DCV systems have the potential to become highly visible **sales features**, especially if occupants are provided with continuous feedback on indoor and outdoor environments.

Spot measurements for formaldehyde and Total Volatile Organic Compounds, carried out under varying conditions, did not reveal any major air quality concerns in the three test houses. This was to be expected, since the houses had been designed to minimize building pollutant loads.

An evaluation of the Halitec sensor is required where the sensor would be exposed to different quantities and mixtures of gases commonly found in houses. Such an evaluation would provide a better bench mark for assessing the ability of this sensor to control odours and to detect excessive levels of various organic compounds.

Commissioning of three energy efficient houses has revealed significant problems with current ventilation systems:

- Leaky ductwork can lose 30% to 40% of the air flows and lead to depressurization of furnace room
- Spilling gas furnaces and boilers;
- Inadequate balancing of air distribution systems, partly due to improperly placed flow measurement stations;
- Recycling of combustion air into houses through supply air inlets;
- Grossly inadequate dehumidistats;
- Inefficient fans.

10 APPENDIX

10.1 Sue House

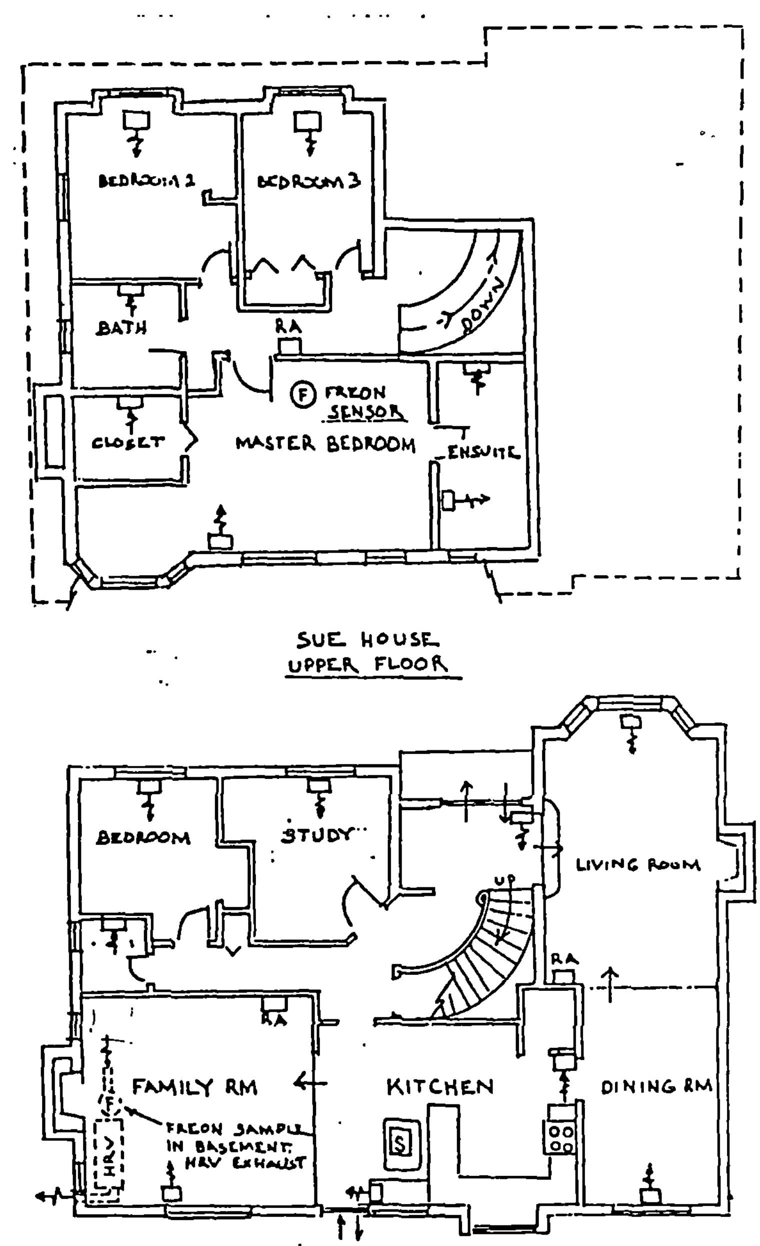
10.1.1 Sue House Detailed Description

This two storey plus basement house is located in west-central Burnaby, near the boundary with Vancouver. There are two working adults and one baby living in this house

The fireplace, the DHW tank, and the mid-efficiency furnace are all side vented and share the same exterior wall as the HRV and combustion air intake.

Forced air distribution system

Figure 10.1 Sue House



Legend
Supply Air
Exhaust
RA Return Air
S Sampling Station

Figure 10.2 Sue House Floor Plan

10.1.2 Sue House Detailed Results

Table 10.1 Sue House: Low-level Data Completeness			
House	Period	Complete Data (hours)	Remarks
DCV1: Sue house Gas forced-air furnace HRV	November, 1989 to March, 1990	856	Absolute humidity and furnace flow sensors late in arriving; CO_2 data from 20 January, 1990
	March-April, 1990	580	Activity controlled DCV

Hourly data for the Sue house, prior to installation of the DCV controller, is shown for three days in the graphs following:

Table 10.2 Sue house: Hourly Performance Without DCV	
Date	Remarks
Monday, 18 December, 1989	Typical working day
Saturday, 24 December, 1989	Holiday; party
Friday, 29 December, 1989	Typical working day

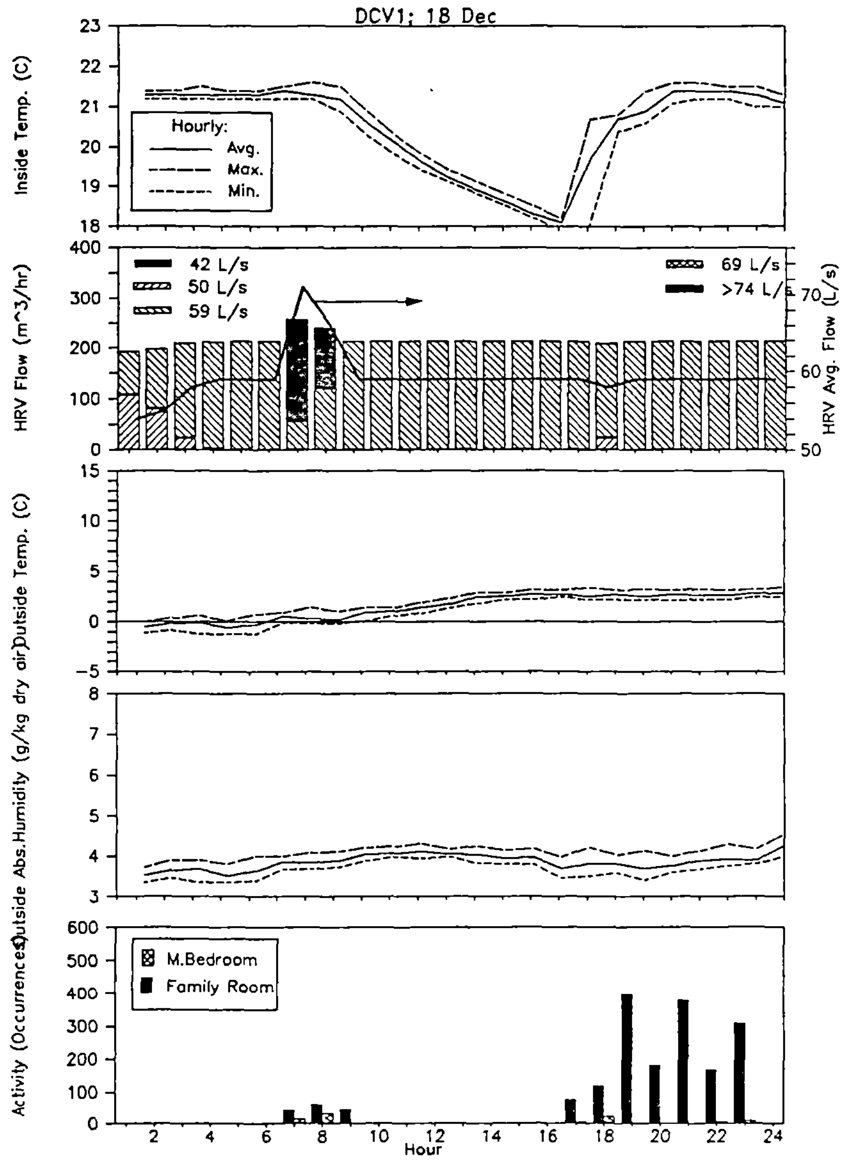


Figure 10.3 Sue house - working day (18 Dec 89)

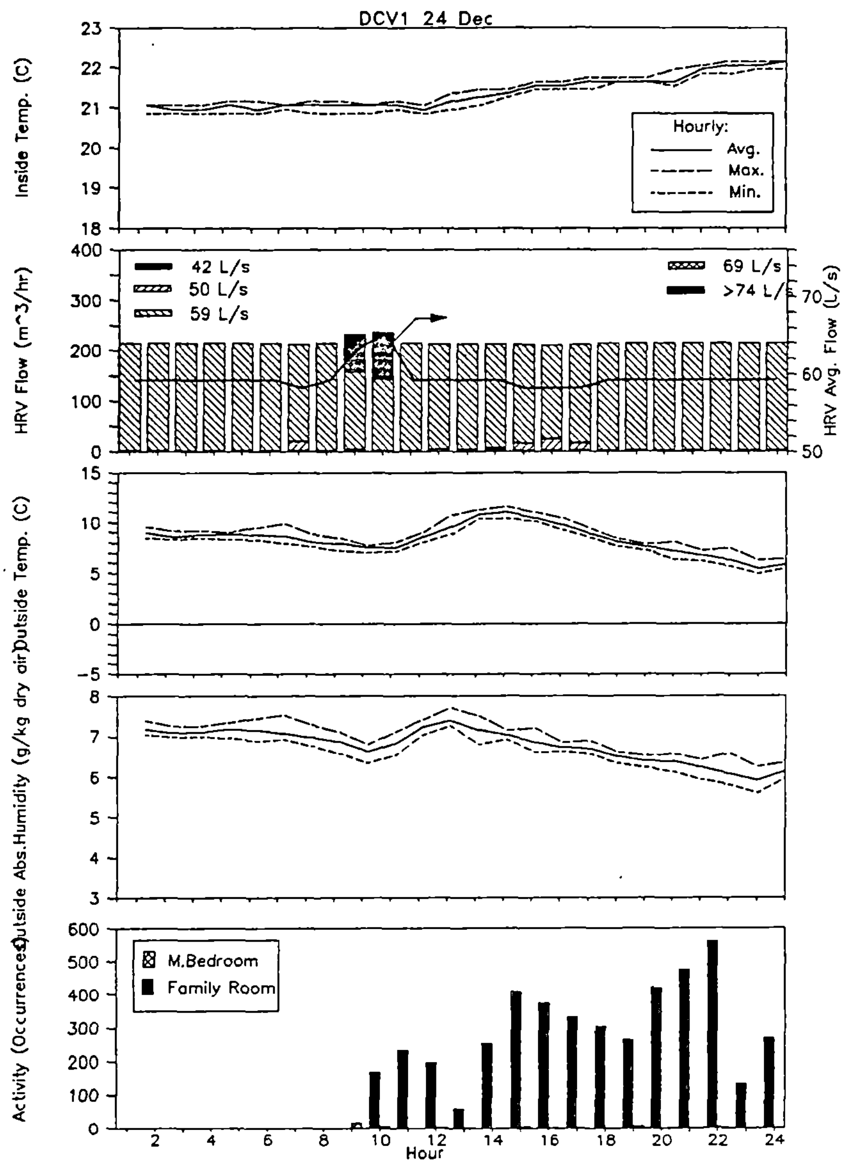


Figure 10.4 Sue house - holiday (24 Dec 89)

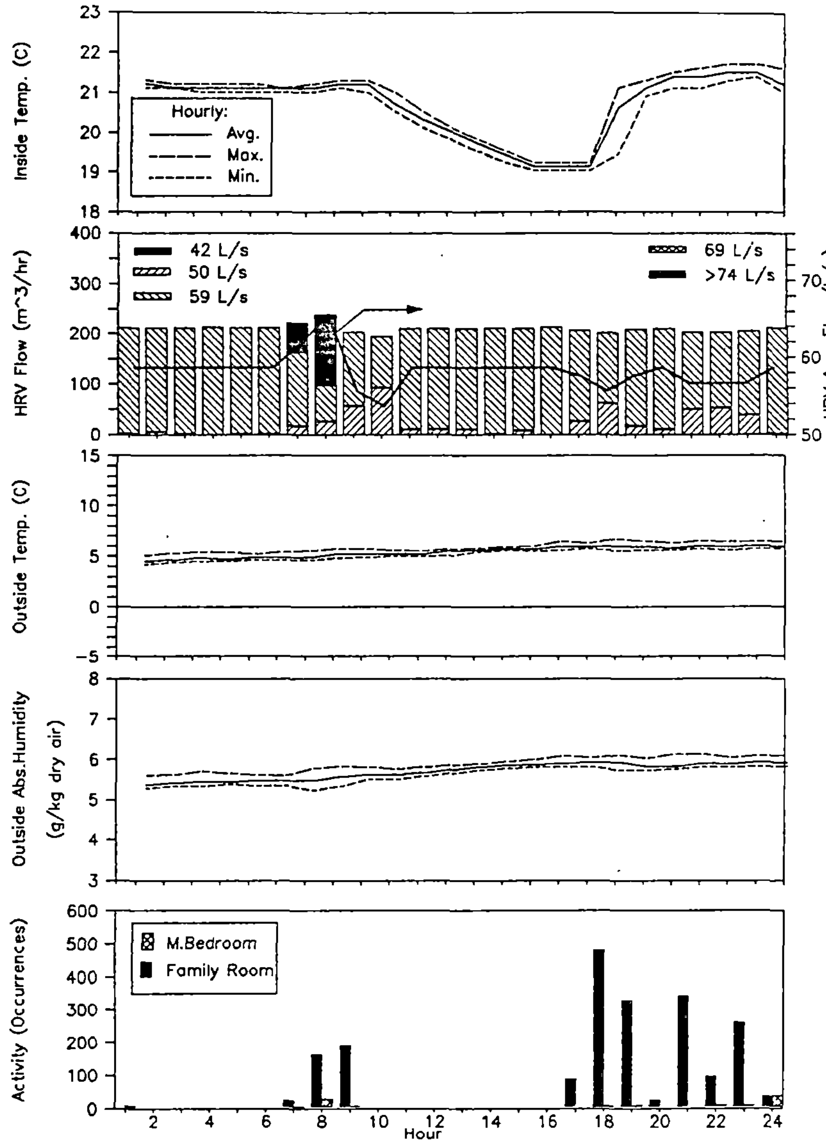


Figure 10.5 Sue house - working day (29 Dec 89)

Table 10.3

Sue House Without DCV

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts	Furn.On (min)	Dryr.On (min)	HRV<38	HRV42	HRV50	HRV58 (m^3/hr)	HRV69	HRV>74	HRVavg (L/s)	Furnace (L/s)	AbHavg (g/kg)
>1000		0	0.0%																			
>900	<=1000	0	0.0%																			
>800	<=900	21	2.5%	2.9	21.4	41	838	801	945	131	8	38	30	3		0	200	1	9	59	155	5.9
>700	<=800	167	19.5%	1.7	21.4	39	743	701	1,000	91	6	34	30	75		2	195	3	15	81	155	4.9
>600	<=700	203	23.7%	3.8	21.3	40	652	601	2,250	87	4	27	36	108	0	5	197	2	9	89	155	5.5
>500	<=600	141	16.5%	4.4	21.0	40	550	500	920	89	3	23	28	113		19	182	0	4	88	157	5.1
>400	<=500	250	29.2%	4.8	20.6	41	452	401	570	58	4	18	18	68		50	144	0	12	76	159	4.8
>300	<=400	58	6.8%	4.1	19.8	42	341	301	445	23	2	8		13	0	128	61		1	56	163	4.2
<300		16	1.9%	5.0	18.8	43	286	269	305	13	1	0				129	60			53	164	4.3
	AVG.			3.8	20.9	40	571	524	1,106	75	4									80	157	5
	TOTAL	856								492	27	149	141	381	0	334	1,039	6	50			

Sue House With DCV

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts	Furn.On (min)	Dryr.On (min)	HRV<38	HRV42	HRV50	HRV59 (m^3/hr)	HRV69	HRV>74	HRVavg (L/s)	Furnace (L/s)	AbHavg (g/kg)
>1000		0	0.0%																			
>900	<=1000	6	1.0%	13.6	22.1	44	922	885	948	36	1			130						36		7.3
>800	<=900	25	4.3%	10.4	21.6	44	849	763	908	72	3	5		114		4	2	13	10	40		7.2
>700	<=800	34	5.9%	10.7	21.6	43	753	684	865	84	6	4	42	98		21	1	14	16	42		7.1
>600	<=700	51	8.8%	9.1	21.6	43	642	562	756	54	3	7	43	52	2	57	9	47	43	58		6.1
>500	<=600	226	39.0%	8.5	21.4	42	546	397	649	52	4	10	23	82	2	32	80	41	45	78		5.6
>400	<=500	215	37.1%	12.4	21.3	42	456	385	547	84	3	3	24	107	1	56	52	71	26	87		5.7
>300	<=400	23	4.0%	15.1	21.0	41	389	366	428	59	3		21	0		133	56			52		5.5
<300		0	0.0%																			
	AVG.			10.5	21.4	42	544	443	639	67	4									75		6
	TOTAL	580								442	24	29	153	583	5	304	200	186	140			

There was generally a reasonable correlation between CO_2 and activity counts (without DCV), on a long term, statistical basis (see Figure 10.6[20]), but a poorer correlation with hourly data (Figure 10.7). The hourly data correlates the **change in CO_2 source strength** against the **activity** - correlations of hourly values of CO_2 vs activity showed virtually no correlation. The poorer correlation on an hourly basis is likely due to a lag in CO_2 levels relative to activity (see section 10.3.2)

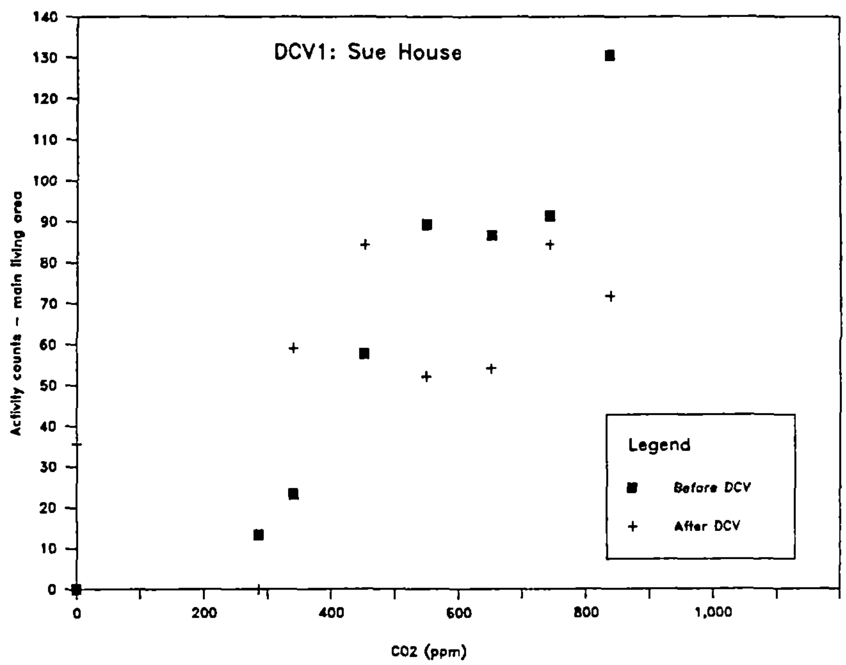


Figure 10.6 Correlation of Averaged CO_2 and Activity (Sue house)

[20] This graph used averaged CO_2 and Activity from the bands of data shown in the statistical result table 10.3. Therefore, the values shown represent activity in each of the CO_2 bins.

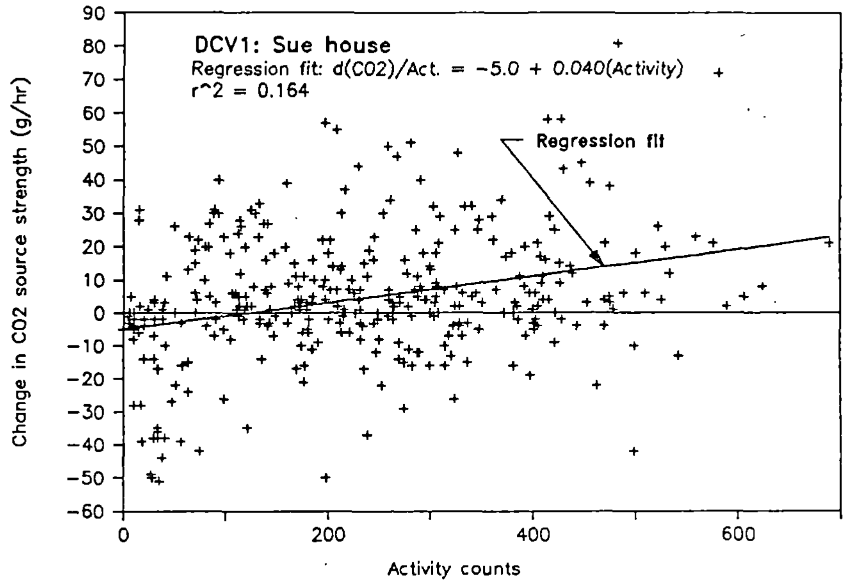


Figure 10.7 Correlation of Hourly CO_2 and Activity (Sue house)

10.2 Jones House

10.2.1 Jones House Detailed Description

This two storey plus basement house is located near the top of the Capital Hill district of north Burnaby. There are two working adults and four children living in this house.

Figure 10.8 Jones house

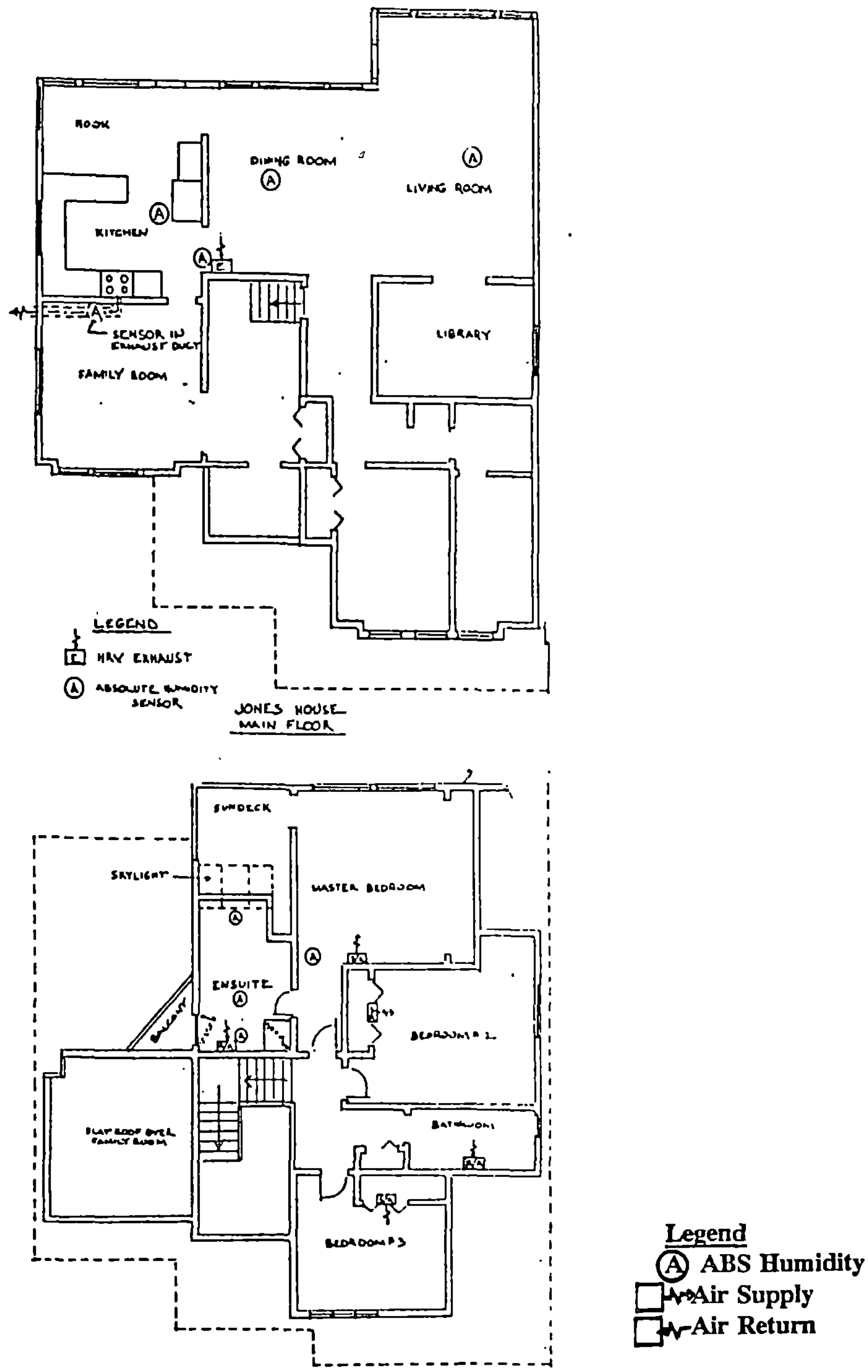


Figure 10.9 Jones House Floor Plan

10.2.2 Jones House Detailed Results

Table 10.4 Jones House: Low-level Data Completeness

House	Period	Complete Data (hours)	Remarks
DCV2: Jones house Gas boiler (radiant slab)/HRV	November, 1989 to February, 1990	1,168	CO_2 sensor late in arriving
	February to April, 1990	1,115	189 hours with complete flow data; CO_2 controlled DCV

Hourly data for the Jones house, prior to installation of the DCV controller, is shown for three days in the graphs following:

Table 10.5 Jones house: Hourly Performance Without DCV

Date	Remarks
Thursday, 28 December, 1989	Left on holidays about 0930
Monday, 1 January, 1990	Arrived back from holidays about 1430
Wednesday, 10 January, 1990	Typical working day

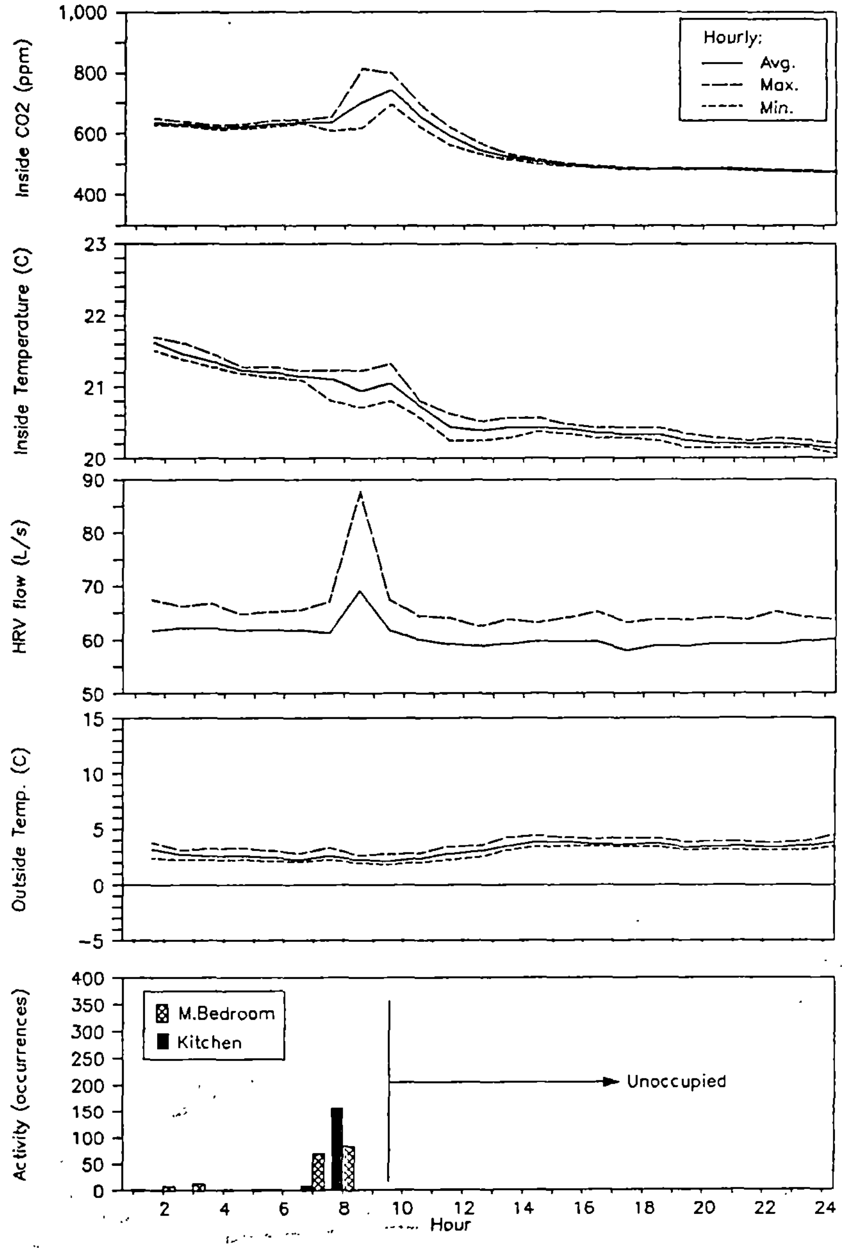


Figure 10.10 Jones house - Leaving on holidays (28 Dec 89)

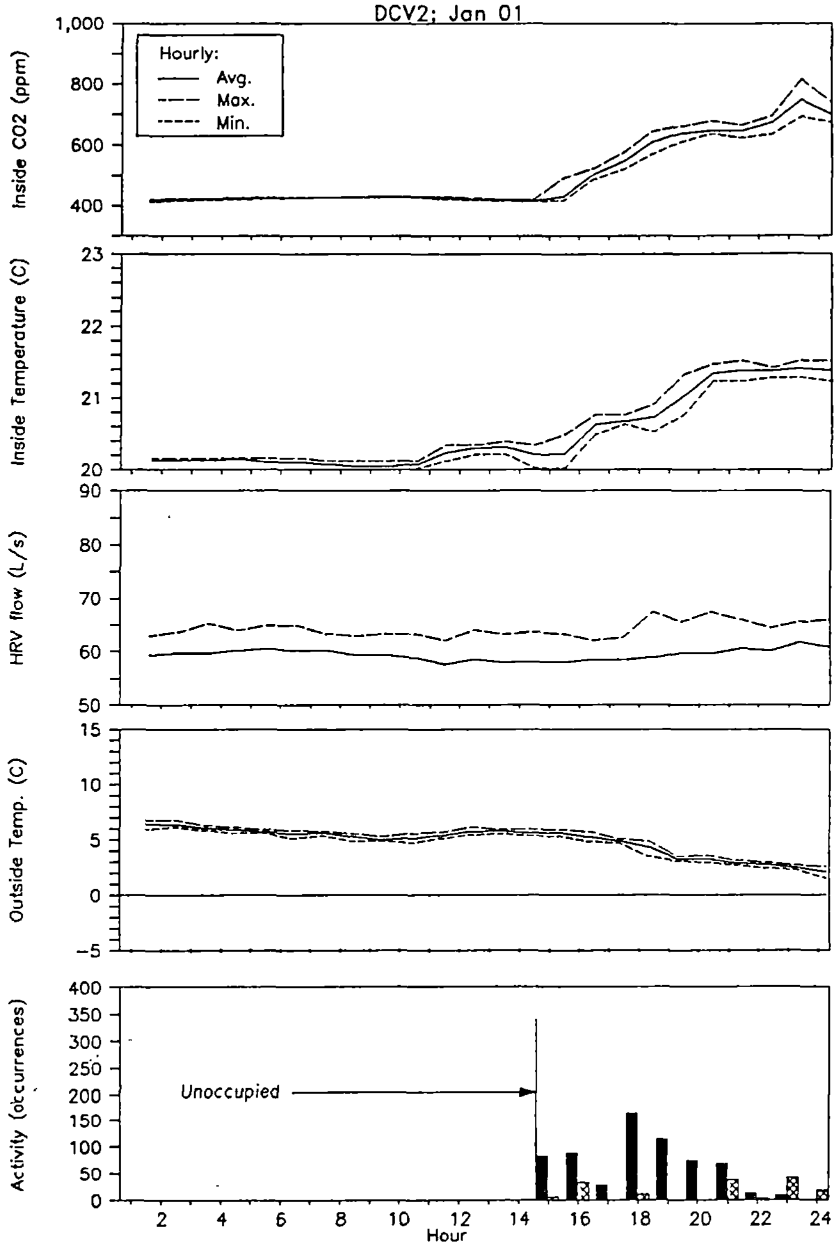


Figure 10.11 Jones house - Arriving back from holidays (01 Jan 90)

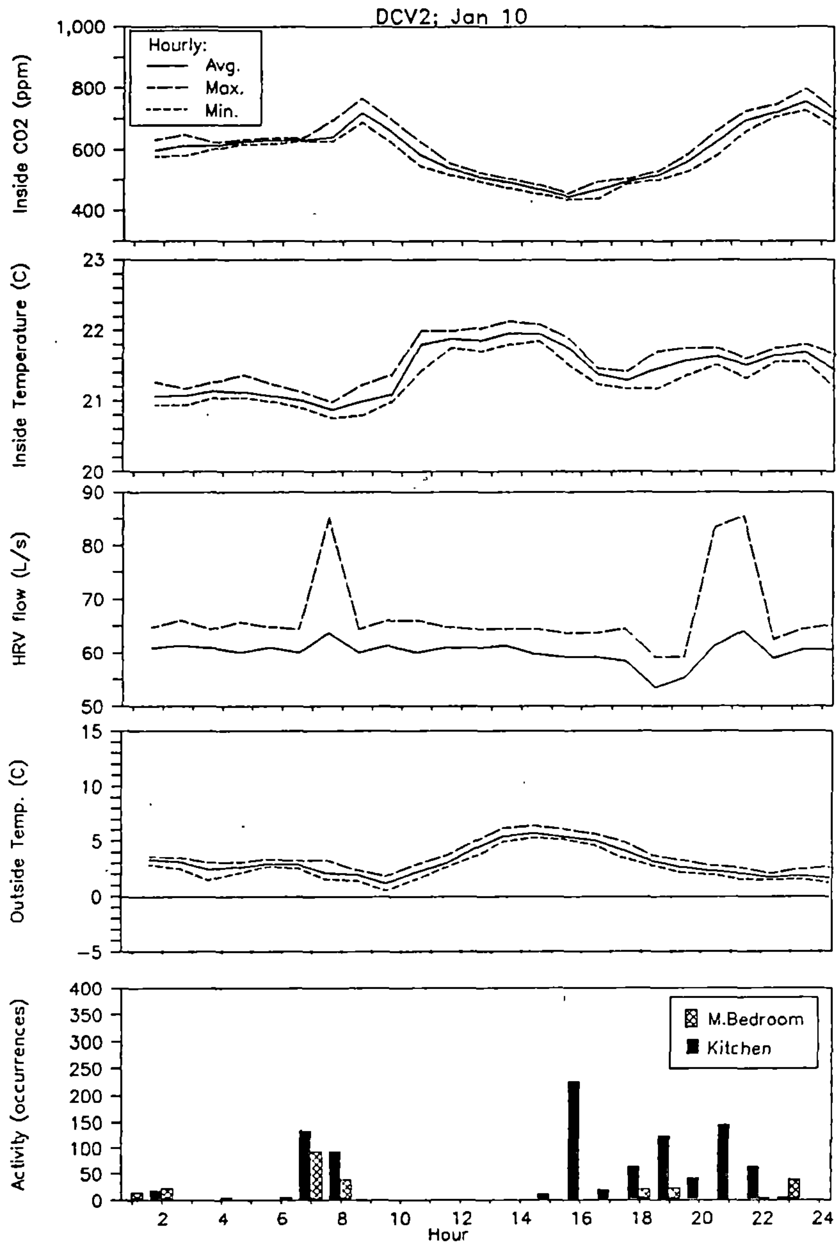


Figure 10.12 Jones house - Typical working day (10 Jan 90)

Table 10.6

Jones House Without DCV

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts)	HRVavg (L/s)	HRVmax (L/s)
>1000		0	0.0%										
>900	<=1000	4	0.3%	2.6	21.4	41	918	824	996	102	24	58.5	62.5
>800	<=900	23	2.0%	4.3	21.7	40	844	748	980	69	12	62.4	67.7
>700	<=800	105	9.0%	2.5	21.4	38	739	646	888	59	24	63.1	68.1
>600	<=700	397	34.0%	1.8	21.3	37	643	470	848	50	17	63.1	69.1
>500	<=600	381	32.6%	2.6	21.3	37	560	446	780	36	13	61.9	67.0
>400	<=500	225	19.3%	4.2	21.0	39	448	390	592	15	10	60.8	65.8
>300	<=400	33	2.8%	6.1	20.4	41	386	370	452	4	0	59.2	63.7
<300		0	0.0%										
	AVG.			2.7	21.2	38	584	466	772	39	15	62	
	TOTAL	1,168								335	100		

Jones House With DCV

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts	HRVoff (min)	HRVF2	HRVF3	HRVF4	HRVF5 (m^3/hr)	HRVF6	HRVF7	HRVavg (L/s)	HRVmax (L/s)	HRV%off (L/s)
>1000		0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
>900	<=1000	0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
>800	<=900	2	0.2%	8.0	21.6	37	818	732	870	117	48	0	0	0	0	0	0	0	141	144	0.0%
>700	<=800	70	6.3%	2.2	21.6	30	723	626	844	60	31	0	0	1	94	8	0	189	92	104	0.0%
>600	<=700	498	44.7%	1.9	21.6	30	645	536	800	38	15	0	0	1	154	25	0	80	81	102	0.0%
>500	<=600	313	28.1%	4.2	22.0	30	552	410	804	31	9	24	0	2	91	6	0	61	61	104	11.4%
>400	<=500	174	15.6%		22.2		458	358	602	19	7	45	0	0	19	0	0	56	21	0	11.7%
>300	<=400	58	5.2%		23.0		369	286	528	26	3	50	0	0	0	0	0	55	15	0	4.3%
<300		0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
	AVG.			2.2	21.9	24	581	466	759	34	13								63		
	TOTAL	1,115								291	113		0	3	358	39	0	441			27.4%

Jones house (flow histogram known)

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts	HRVoff (min)	HRVF2	HRVF3	HRVF4	HRVF5 (m^3/hr)	HRVF6	HRVF7	HRVavg (L/s)	HRVmax (L/s)	HRV%off (L/s)
>1000		0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
>900	<=1000	0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
>800	<=900	0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
>700	<=800	8	4.2%		21.7		713	650	780	82	59	0	0	1	94	8	0	189	81	0	0.0%
>600	<=700	67	35.4%		21.7		637	536	760	44	16	0	0	1	154	25	0	80	72	0	0.0%
>500	<=600	60	31.7%		22.3		548	478	804	33	9	24	0	2	91	6	0	61	44	0	12.9%
>400	<=500	51	27.0%		22.5		454	366	602	20	7	45	0	0	19	0	0	56	21	0	20.2%
>300	<=400	3	1.6%		23.1		389	360	400	33	1	50	0	0	0	0	0	55	15	0	1.3%
<300		0	0.0%									0	0	0	0	0	0	0	0	0	0.0%
	AVG.				22.1		558	474	726	35	13								49		
	TOTAL	189								212	92	119	0	3	358	39	0	441			34.4%

There was generally a reasonable correlation between CO_2 and activity counts, for all three houses, on a long term, statistical basis - though less so with DCV (Figure 10.13[21])

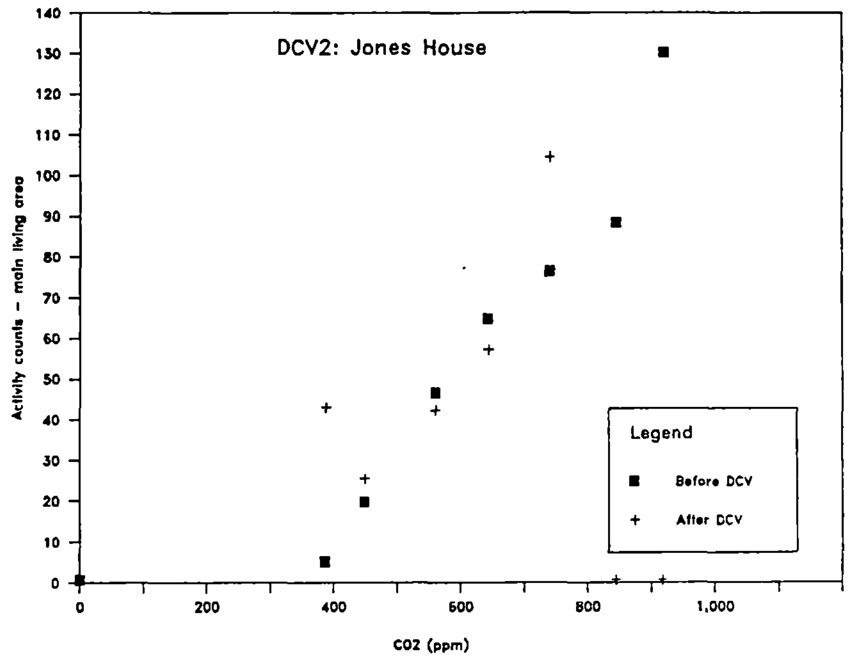


Figure 10.13 Jones house: Correlation of Averaged CO_2 and Activity

[21] This graph used averaged CO_2 and Activity from the bands of data shown in the statistical result table 10.6. Therefore, the values shown represent activity in each of the CO_2 bins.

10.3 Smith House

10.3.1 Smith House Detailed Description

This one storey house is located on the Fraser River delta, in Ladner, south of Richmond. There are two adults (one working away from home) living in this house - both are smokers.

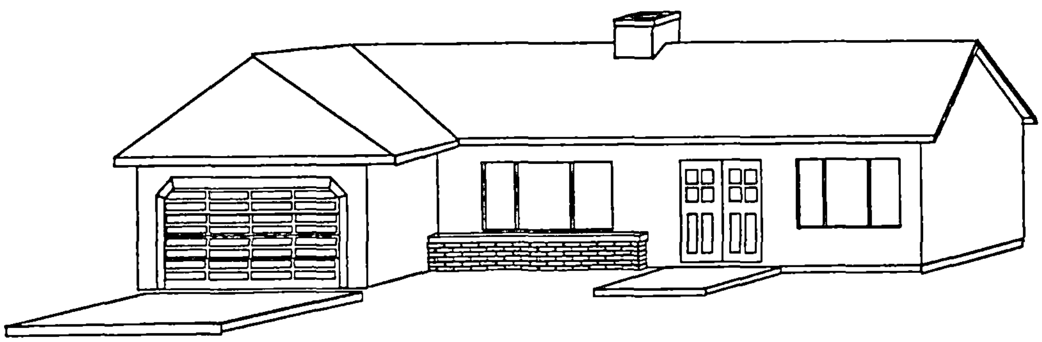


Figure 10.14 Smith house

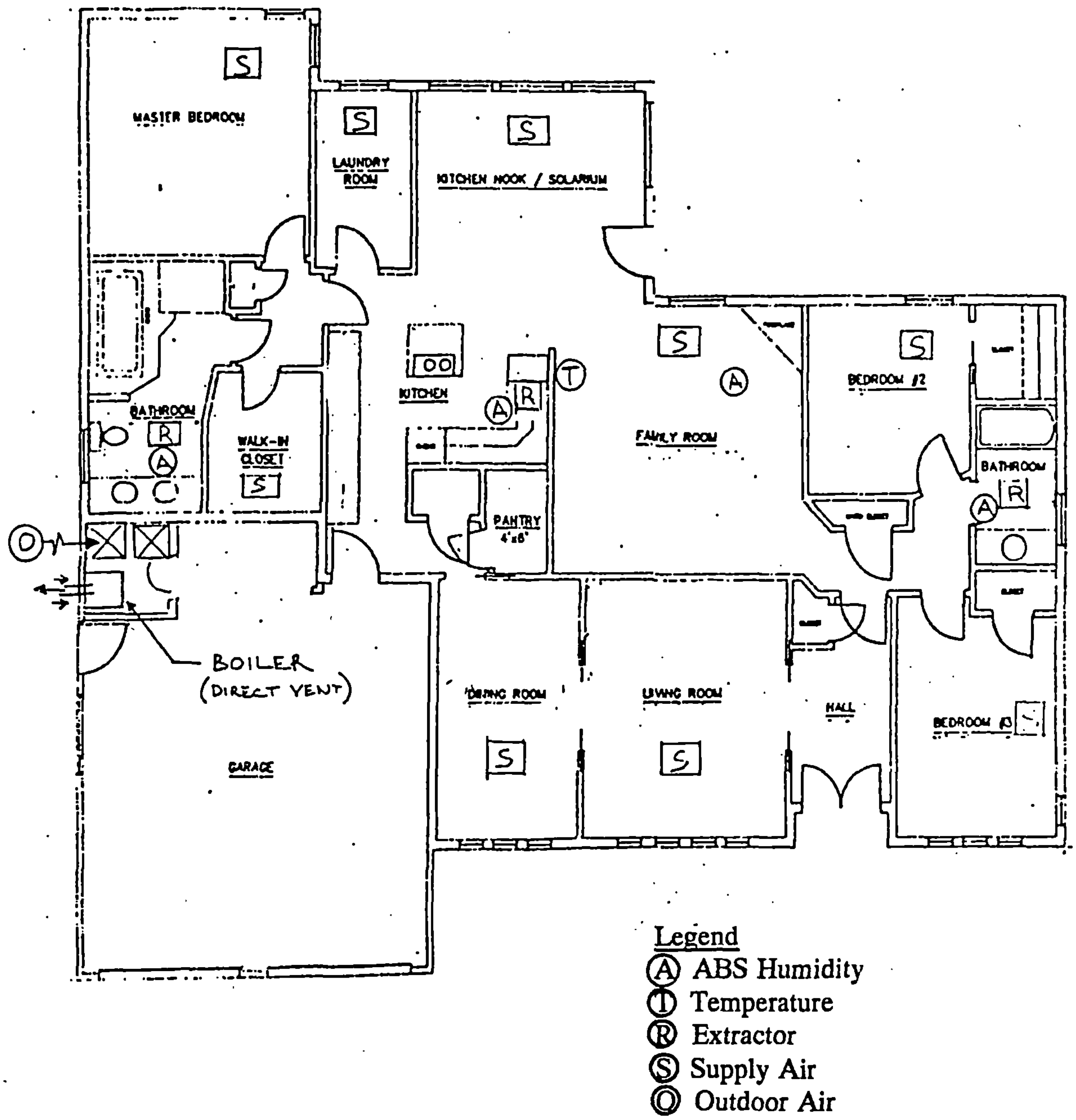


Figure 10.15 Smith House Floor Plan

10.3.2 Smith House Detailed Results

Table 10.7 Smith house: Low-level Data Completeness

House	Period	Complete Data (hours)	Remarks
DCV3: Smith house Gas boiler (radiant slab and forced air)/Aereco	November, 1989 to February, 1990	1,385	CO_2 sensor late in arriving
	Massawa: March, 1990 Abs.Humidity: March-April, 1990	846	DCV: Massawa Integrated controller DCV: Absolute humidity controlled

Inside temperatures were typically in the 23C to 25C range - with the coolest period usually in the early morning.

Hourly data for the Smith house, prior to installation of the DCV controller, is shown for three days in the graphs following:

Table 10.8 Smith house: Hourly Performance Without DCV

Date	Remarks
Saturday, 24 December, 1989	Holiday; party
Sunday, 25 December, 1989	Holiday; party
Friday, 29 December, 1989	Working day; House unoccupied from about 1400 to 2200

Exhaust flows are typically around 30 L/s - this lower flow rate probably in part accounts for the much higher CO_2 values found in this house (peak of over 2,700 ppm during a party on December 25th).

The afternoon/evening of December 29th is interesting because of the approximately six hour decay in CO_2 levels shown during the unoccupied period.

Peak CO_2 values lag several hours behind peaks in activity - particularly noticeable during the parties of December 24th and 25th.

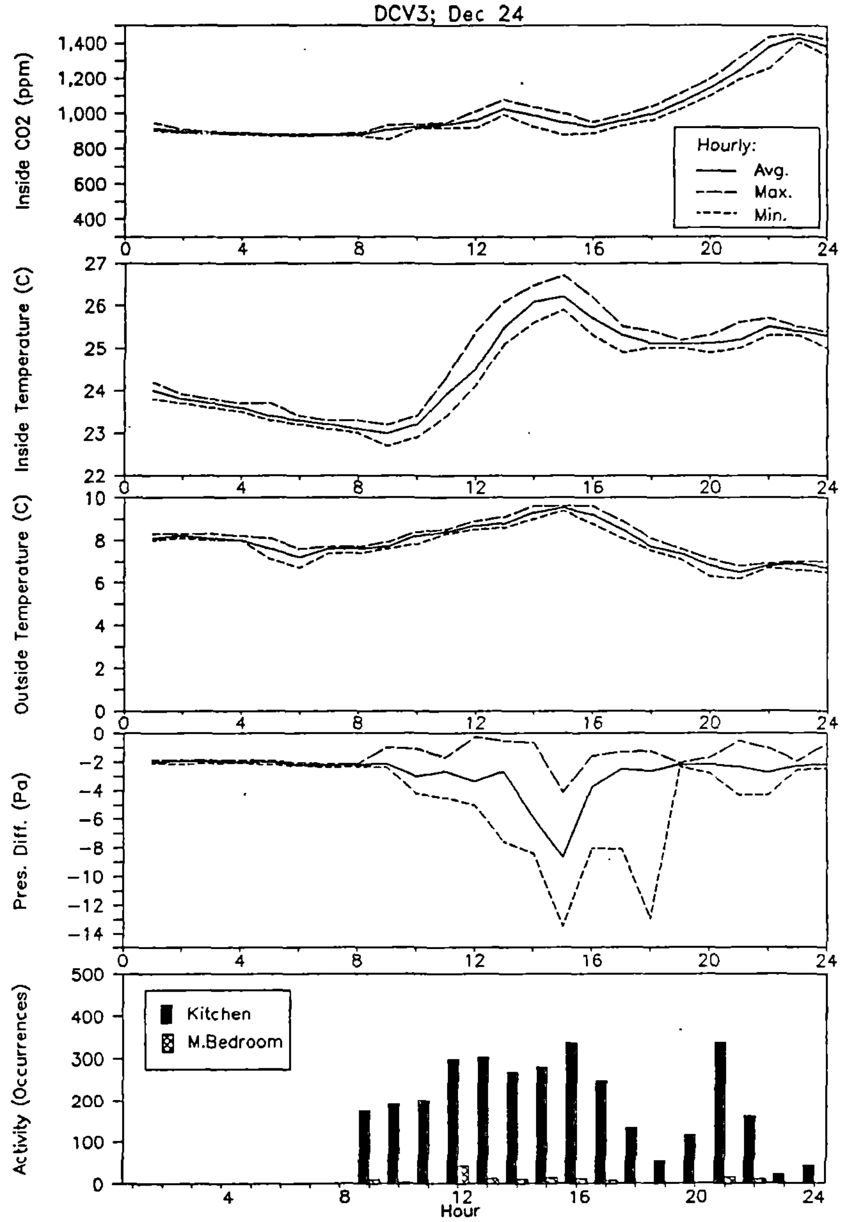


Figure 10.16 Smith house - holiday: December 24th

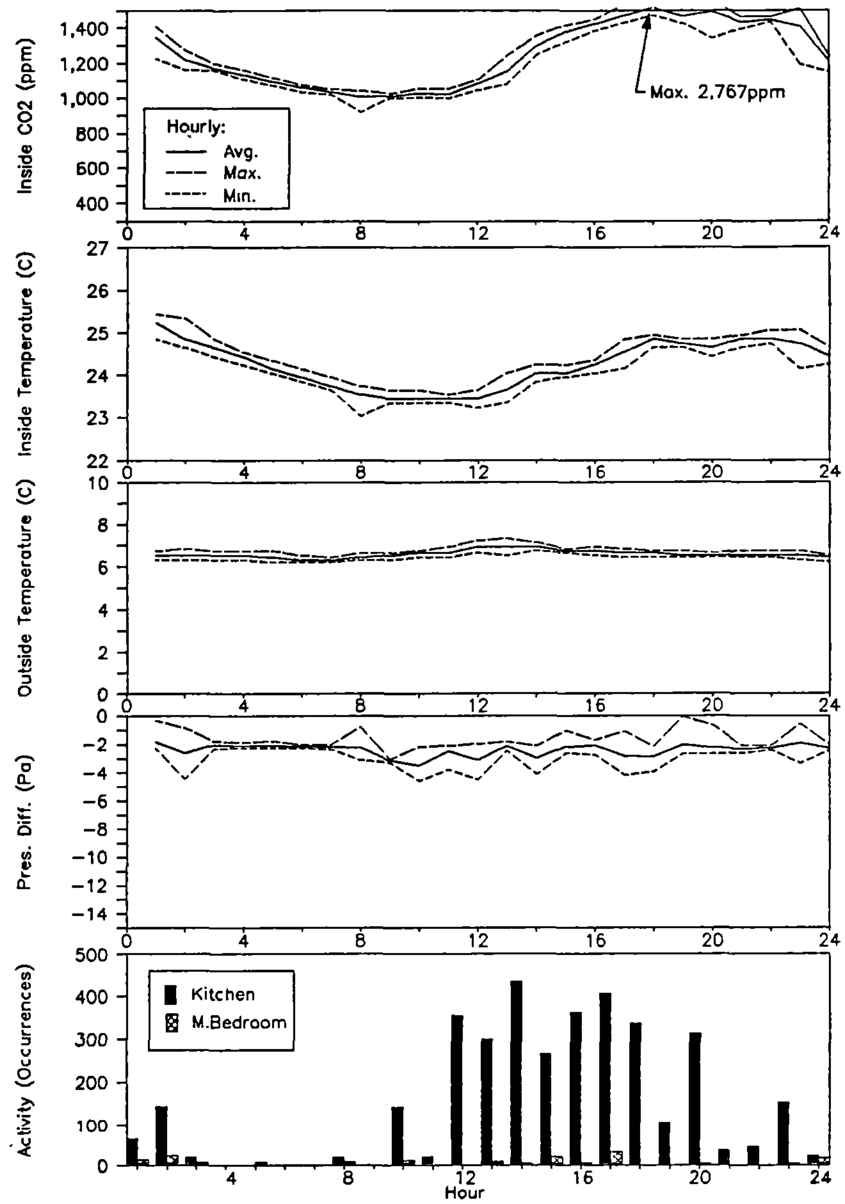


Figure 10.17 Smith house - holiday: December 25th

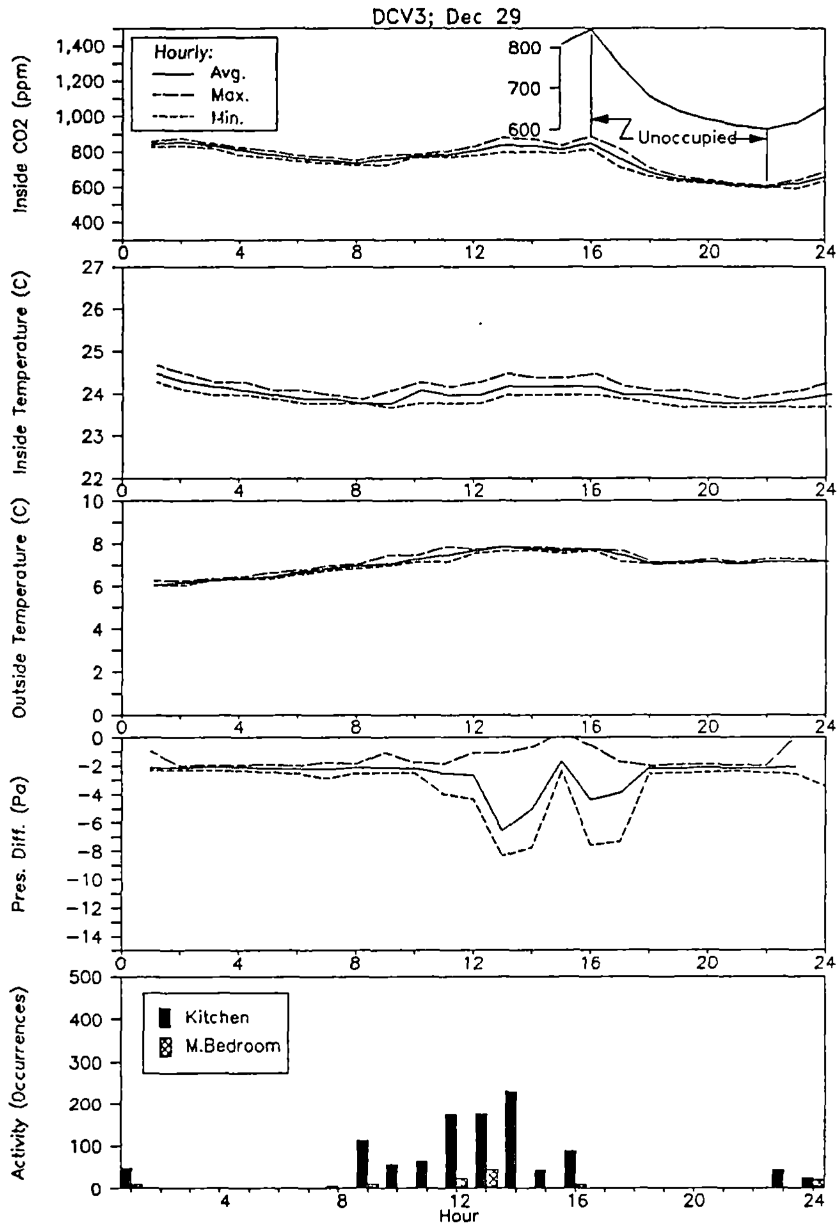


Figure 10.18 Smith house - working day: December 29th

Table 10.9
Smith House Without DCV

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts	Furnace (min)	Flo<22	Flo24	Flo27	Flo30	Flo33 (m^3/hr)	Flo36	Flo40	Flo43	Flo47	Flo51
>1000		41	3.0%	6.7	24.4	41	1,187	975	2,767	170	5	36.8	75.6			85.8	7.4	2.2	3.3	3.4	2.2	3.5
>900	<=1000	37	2.7%	7.0	24.0	40	951	825	1,073	146	8	34.7	75.6			76.0	13.8	1.6	1.3	2.2	1.7	4.7
>800	<=900	55	4.0%	7.3	24.2	38	844	729	955	114	5	30.0	75.6			74.0	6.3	1.2	0.8	2.2	2.0	1.7
>700	<=800	61	4.4%	7.5	23.9	37	749	653	915	105	5	34.5	75.6			62.9	2.3	2.1	1.0	1.5	4.2	3.5
>600	<=700	195	14.1%	8.5	24.2	37	633	487	821	75	3	31.5	75.6			71.9	1.0	0.8	1.0	1.9	2.1	0.5
>500	<=600	325	23.5%	7.7	24.5	34	552	345	685	74	4	27.1	75.6			15.5	0.5	0.8	2.1	2.5	1.8	0.3
>400	<=500	330	23.8%	6.5	24.5	29	446	357	577	69	5	20.1	75.6				0.5	1.3	2.7	1.9	0.6	0.3
>300	<=400	336	24.3%	6.3	24.7	24	366	263	481	66	3	20.1	75.6				0.2	0.9	1.4	1.1	0.3	0.1
<300		5	0.4%	9.2	26.2	24	289	273	333	70	0	27.0	75.6									
	AVG.			7.1	24.4	31	542	408	721	79	4											
	TOTAL	1,385								889	38		680.4	0.0	0.0	386.1	32.0	10.9	13.8	16.7	14.9	14.5

Smith House With DCV

Average CO2		Hours	%Total	Toavg (C)	Tiavg (C)	RHiavg (%)	CO2avg (ppm)	CO2min (ppm)	CO2max (ppm)	Act_dwn (counts	Act_up (counts	AHavg	Flo<22	Flo24	Flo27	Flo30	Flo33 (m^3/hr)	Flo36	Flo40	Flo43	Flo47	Flo51
>1000		0	0.0%																			
>900	<=1000	0	0.0%																			
>800	<=900	2	0.2%	12.7	23.8		856	802	1,028	242	10	8.2	11.9	57.0	0.8	17.8	0.9					
>700	<=800	4	0.5%	13.6	23.8		750	586	836	261	8	8.2	13.5	52.3	0.4	21.8	0.5					
>600	<=700	4	0.5%	13.1	23.3		659	560	726	103	7	7.7	12.6	46.6	3.1	27.1	3.9					
>500	<=600	24	2.8%	12.8	23.5		518	368	632	106	12	7.5	24.9	34.9	4.3	14.0	0.8			1.9	6.8	5.2
>400	<=500	368	43.5%	13.5	23.8		438	292	564	69	5	7.4	14.4	23.3	8.6	16.3	3.3	0.5	0.7	5.2	23.9	15.0
>300	<=400	396	46.8%	13.0	24.2		358	250	829	59	4	6.1	6.9	13.0	20.7	27.5	9.6	1.3	1.1	3.6	11.4	9.0
<300		48	5.7%	16.2	25.0		274	213	355	93	3	6.3	0.1	1.4	18.4	28.0	21.1	5.2	0.7	1.8	4.4	12.2
	AVG.			13.4	24.0		397	274	681	68	5	6.8										
	TOTAL	846								933	48		84.3	228.5	56.3	152.5	40.1	7.0	2.5	12.5	46.5	41.4

Table 10.9

Smith House Without DCV

Average CO2		Flo54	Flo>56	FloAvg (L/s)	dPavg (Pa)	dPmin (Pa)	dPmax (Pa)
>1000		0.8		31.2	-2.5	-3.3	-1.8
>900	<=1000	5.0	4.0	31.8	-2.9	-4.3	-1.9
>800	<=900			29.5	-3.0	-4.1	-1.6
>700	<=800	0.3		29.5	-5.0	-6.2	-3.8
>600	<=700	0.2		28.4	-2.9	-4.3	-1.7
>500	<=600	0.0		24.4	-3.4	-4.5	-2.4
>400	<=500	0.3	0.1	23.2	-4.6	-6.7	-2.8
>300	<=400	0.2	0.1	22.2	-3.6	-5.3	-2.3
<300				21.0	-3.3	-5.8	-2.1
	AVG.			24.9	-3.7	-5.2	-2.4
	TOTAL	6.8	4.2				

Smith House With DCV

Average CO2		Flo54	Flo>56	FloAvg (L/s)	dPavg (Pa)	dPmin (Pa)	dPmax (Pa)
>1000							
>900	<=1000						
>800	<=900			24.6	0.8	-1.2	1.1
>700	<=800			24.6	1.8	-0.1	3.6
>600	<=700			25.9	2.0	0.4	2.6
>500	<=600	0.4		25.9	1.1	0.2	2.1
>400	<=500	3.3	0.1	31.8	1.7	0.6	3.3
>300	<=400	9.4	4.5	32.8	0.2	-1.2	1.9
<300		14.2	28.6	37.8	0.1	-1.7	2.1
	AVG.			32.4	0.9	-0.4	2.5
	TOTAL	27.4	33.2				

There was generally a reasonable correlation between CO_2 and activity counts, on a long term, **statistical basis** - though less so with DCV (see Figure 10.19[22]).

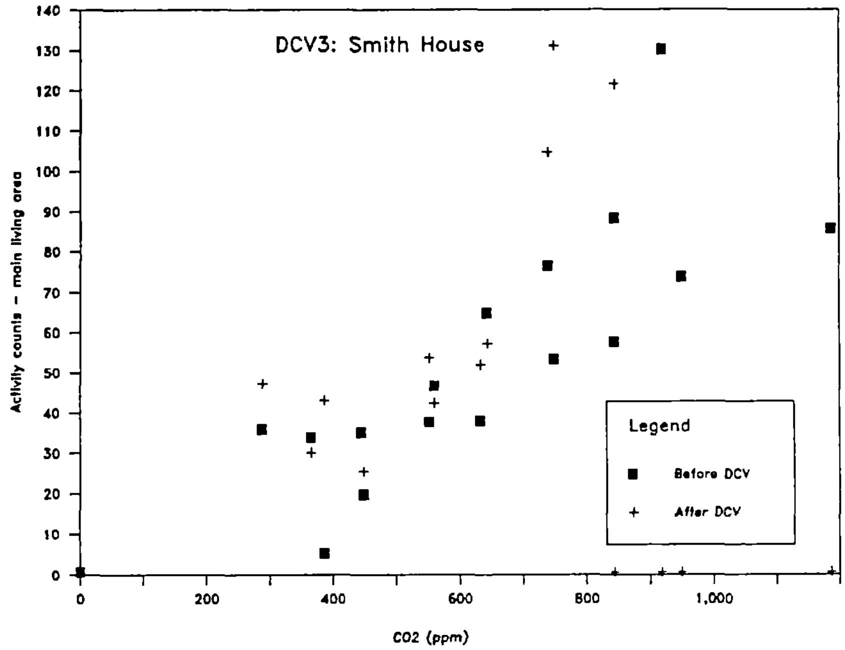
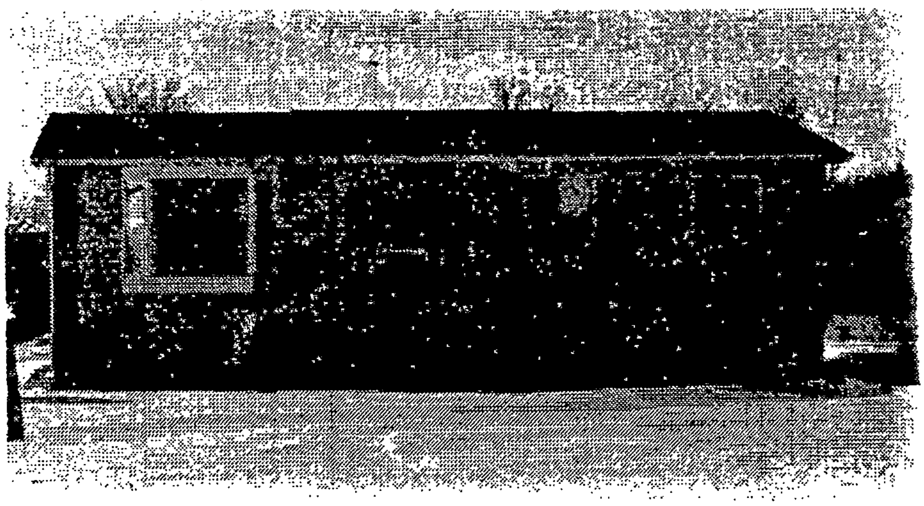


Figure 10.19 Correlation of Averaged CO_2 and Activity Smith house

22 This graph used averaged CO_2 and Activity from the bands of data shown in the statistical result table 10.9. Therefore, the values shown represent activity in each of the CO_2 bins.

10.4 Morewood House

10.4.1 Morewood House Detailed Description



Legend
Ⓐ ABS Humidity
Ⓕ Air Flow Sensor
Ⓣ Temperature
[R] Extractor
Ⓢ Supply Damper

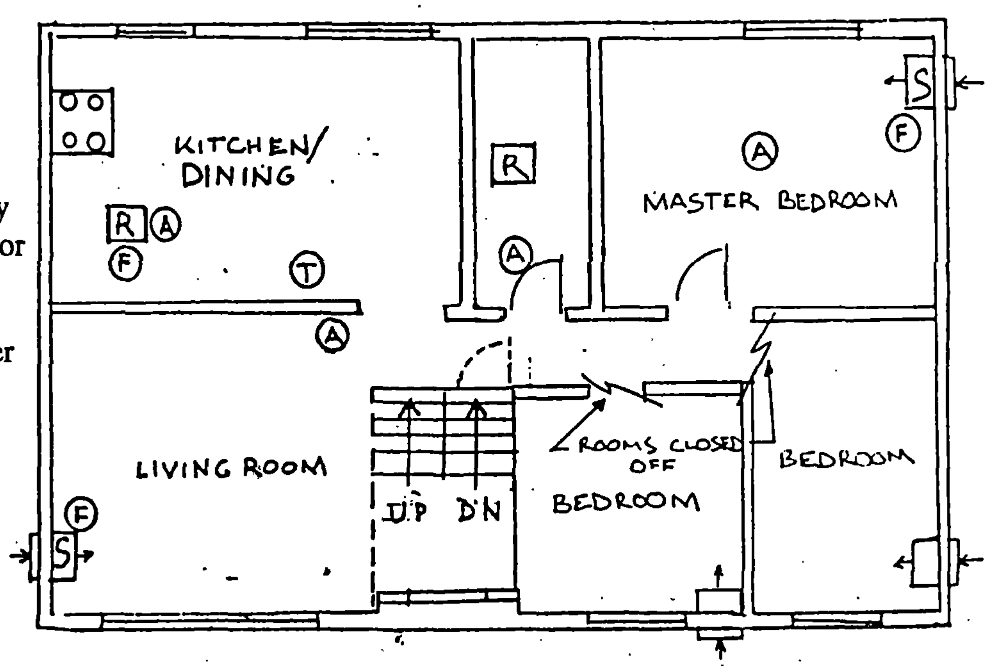


Figure 10.20 Morewood house floor plans

10.4.2 Morewood House Detailed Results

Prior to visiting the Morewood House, four days of low level monitoring results were analyzed[23]. The results for December 25th are presented in Figure 10.22.

The data for the house was complicated to analyze, mostly because the ventilation system did not respond to increases in humidity as it was designed. The dominant influence on ventilation appears to be wind direction and speed. This is partially because of a fairly high equivalent leakage area (ELA) in the house and its exposed location. Even though the house seems to be over-ventilated (extremely dry), the CO_2 levels reached close to 2,000 ppm on Christmas day.

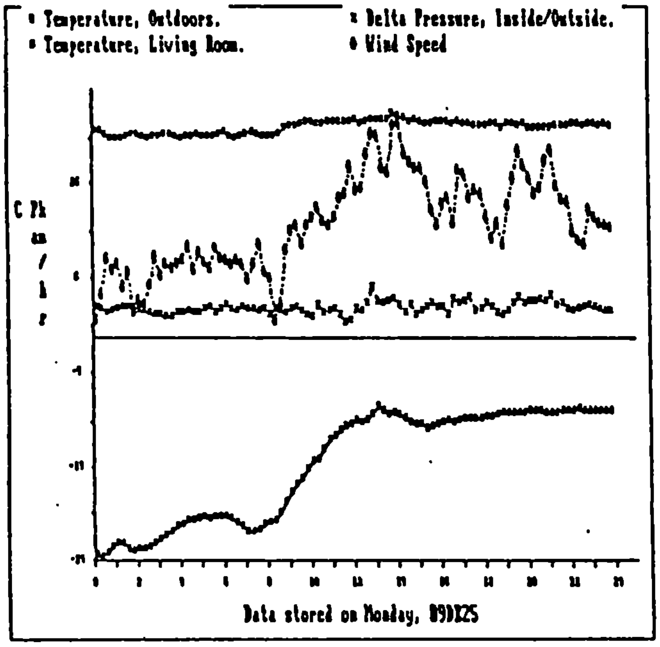
The majority of the house leakage is not in the wall ventilators, but in the natural leakage through the envelope. Visual observation by our technologist indicated that the majority of the leaks are in the unfinished basement. The large natural leakage area causes the house to operate at a low level of house depressurization (average -3 Pascals)[24]. Changes in damper positions in response to increases in humidity are not translated into increases in air flow through the wall ventilators. The direction and speed of wind is a much larger factor in whether ventilation increases through the ventilators.

The location of the neutral pressure plane in the Morewood house will have an extremely large effect on the direction of air flow through the high wall main floor ventilators. If the exhaust flow and wind effects are not able to lift the neutral pressure plane above the main floor ceiling, the ventilators will exhaust air.

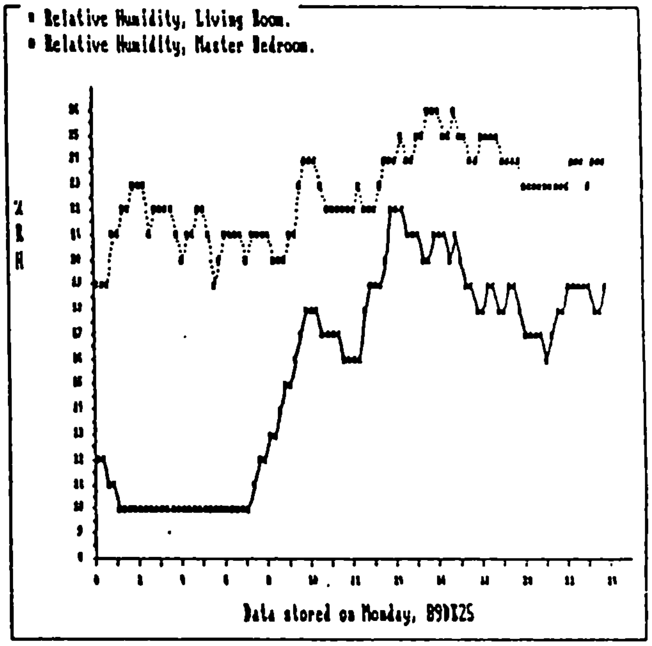
---

23 Data supplied by Scanada Consultants for December 24th to 27th

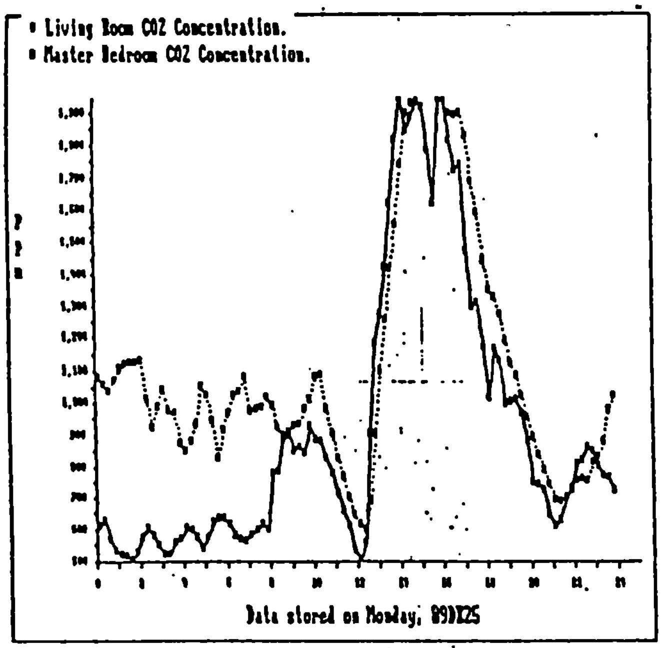
24 Aereco recommends that houses be depressurized to at least -10 Pa under normal operating conditions.



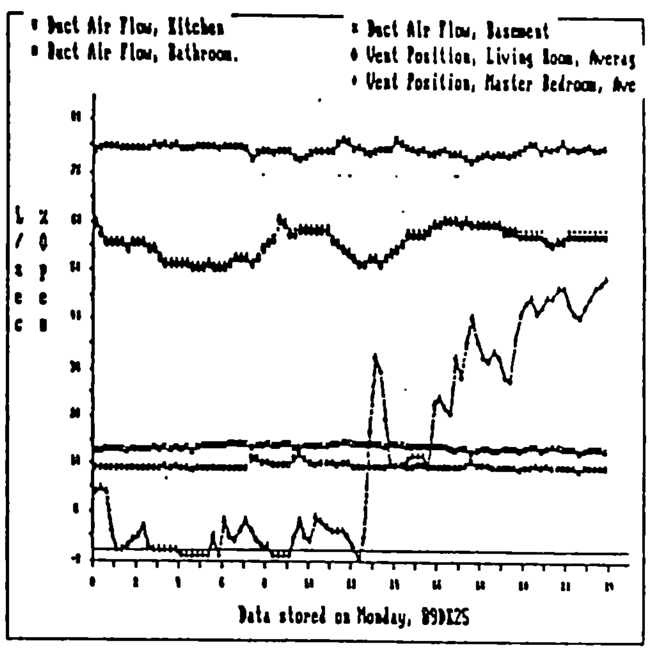
Weather Conditions - Influence on Ventilaiton



Occupant, Activity, and Building Generated Moisture



Occupant Generated Pollutant - CO2



Ventilation Air Flow - Extractors and Ventilators and House ELA

Figure 10.21 Low Level Monitoring - Morewood house

If the house were tightened, and the level of depressurization increased to -10 Pa, the effect would not be to increase ventilation, but only to cause a zoning effect. If the humidity increased in one room, a proportion of the fresh air supplied to the house would be diverted to that room by the opening of dampers. The small response of the extractor bladders to increases in humidity (which was also measured in the Smith house), seems to be the major reason why ventilation rates do not increase substantially with humidity. Figure 10.23 shows that over time the kitchen extractor bladder is responsive, but the total impact on house ventilation seems marginal.

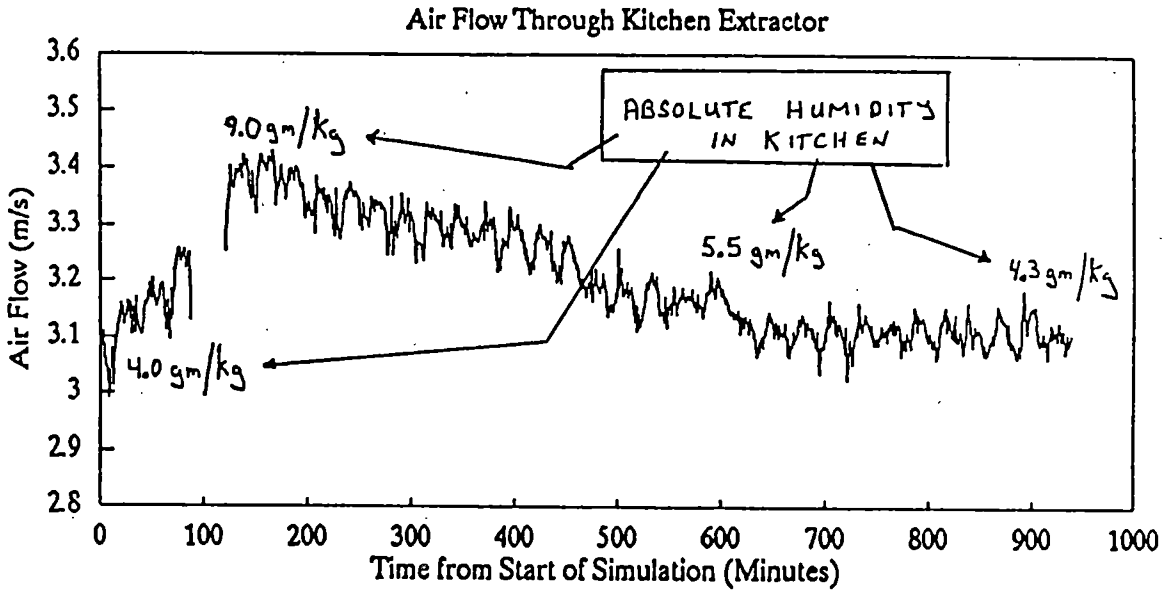


Figure 10.22 Bladder Closing on Kitchen Extractor - Morewood house

Although the system is presented by the manufacturer as an automatic system, it appears that it would only be effective if the manually operated by-pass dampers were used by occupants when cooking, showering and visiting[25].

A more detailed analysis of the Morewood house is presented in a memo to our technologist that follows:

Comments on the Morewood House:

The house has three air extractors that are constantly exhausting air from the house (similar to the Smith house). The house is constantly depressurized to 3 Pa. Pressure changes seem to mostly occur because of wind, and not because of changes in T_o, T_i, or operation of by-pass dampers or the air extractors. The by-pass dampers were not operated manually during the four days from December 24th to 27th (they probably never get used if they were not used over the Christmas period).

The ELA of the house was measured to be 422 cm^2 with the supply dampers in the closed position, and 512 cm^2 in the open position. The supply inlets are responsible for a maximum of 90 cm^2. The data from the living room inlet suggests that the dampers are usually between 55% and 75% open. The 75% open occurs with high amounts of indoor humidity (i.e. 25% RH - quite low for comfort). This means that the house normally operates with an ELA of about:
$ELA = 422 + (90 \times 0.55) = 471$ cm^2.

If we use an average flow equation for the house of:
$Q = C \times P^n$
where $C = 21.13$, $P = 3$ Pa, and $n = 0.74$, the flow under normal operation is about 47 L/s. The exhaust flow is divided between the three extractors in about the following proportions:

Bathroom	12 L/s
Basement	12 L/s
Kitchen	23 L/s

(I am doing the breakdown because I do not trust the flows measured by the flow calibration stations)

I calculated air changes per hour rates[26] based on the decay of CO_2 on three of the four days. The results were as follows:

Dec 25, 10:30 to 12:00	72 L/s or 0.56 ach
Dec 26, 08:00 to 10:30	68 L/s or 0.53 ach
Dec 27, 12:00 to 14:15	65 L/s or 0.51 ach

[25] The builder of the Smith house explained to the householders from the onset that the Aereco system, in his opinion, is semi-automatic and requires their input for proper operation.

[26] Based on a volume of 460 m^3

There was no noticeable difference in relative humidity in the living room (average 17%) or the bedroom (25%)[27] on these three days. The only difference between these days appears to be higher winds at those times. Tentatively, we can say that the ventilation rate in the Morewood house is influenced more by wind than relative humidity.

From the point of view of main floor pollutants, the air flow rates are over-estimated due to using the whole house volume. If we used the main floor volumes, the calculated flow rates would be 35 L/s (Dec 25), 34 L/s (Dec 26), and 33 L/s (Dec 27).

The fresh air supply area is divided between six supply inlets and the leakage area in the rest of the house, in about the following proportions:

Supply inlets	= (49/471) x (47/6)
	= 0.81 L/s each
Remaining ELA	= (422/471) x 47
	= 42.1 L/s

Slight changes in damper position will insignificantly increase air flow (i.e. forget about it in the current configuration). This means that the system does not have control over where fresh air is supplied. Hence, the fresh air will most likely be supplied to the basement, where the majority of the leaks are located.

As we witnessed in the Smith house, large increases in both absolute and relative humidity had insignificant effects (2 - 3 L/s) on total household exhaust, although exhaust from any one location could increase more than this, while flows decreased in other locations (the pressure in the total exhaust system is supposed to stay constant, which should mean that flow would not drop in the other locations). With changes so minute in both the air extractors and the supply ventilators, interest in them seems to be academic.

Rather than investigate the operation of the Aereco system, we'll concentrate on the effects of using dry outdoor air to control indoor humidity. The Morewood house is not tight enough to be zone controlled by relative humidity and hence is not the best test of the Aereco system. If the inlet supply ventilators made up more than 50% of the total ELA of the house, then we might see some major changes in ventilation, within a zone, due to local increases in relative humidity.

[27] I believe the difference between the two locations is a calibration error in the sensors

10.5 Simulation Results

10.5.1 Simulation Details

The detailed descriptions of the house and mechanical system used in the simulations are included in the input section of the Enerpass/Contam file in section 10.5.2.

The runs assumed that the houses were sufficiently air-tight to benefit from DCV. To eliminate infiltration as a variable, all the houses were run assuming 0.1 ach natural infiltration. This corresponds to houses with ELAs of 200 cm² in Vancouver, 170 cm² in Toronto, and 150 cm² in Winnipeg.

The occupancy schedule used for both base and DCV runs varied from hour to hour (Figure 10.23).

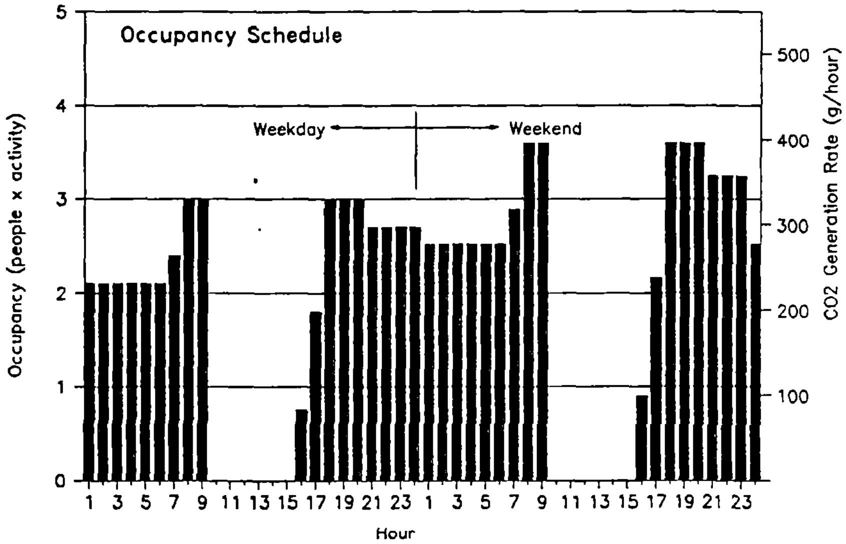


Figure 10.23 Occupancy Schedule

Table 10.10 provides more detail on the simulation runs portrayed in section 8. The ventilation fan capacities are the average low (including time off) and high speed respectively.

The BASE case average and maximum CO_2 levels were used as targets for the match average and match peak scenarios, respectively.

Additional runs for six occupants were also carried out with savings similar to those for three occupants but with higher average and maximum CO_2 levels (Table 10.11).

Table 10.11 also shows the results for HRV systems with DCV. Most of the savings for demand control of HRV systems WAS due to turning the fans off during periods of low CO_2.

Table 10.10 Simulation Results

Gas forced air heating, 3 occupants

VANCOUVER:

		BASE (continuous exhaust fan)
Fan Capacity	(L/s)	53
Ventilation + Infiltration	(ach)	0.32
CO2 - average	(ppm)	571
- maximum	(ppm)	802
Space Heat Energy	(GJ/yr)	59.5
Ventilation Fan Energy	(GJ/yr)	2.6

		DCV:		Continuous HRV:	
		Match avg.	Match peak	low effic.	high effic.
Fan Capacity	(L/s)	25/75	25/75	19/57	19/57
Ventilation + Infiltration	(ach)	0.30	0.23	0.31	0.31
CO2 set-point	(ppm)	655	790		
CO2 - average	(ppm)	574	659	589	589
- maximum	(ppm)	694	804	835	835
Space Heat savings	(GJ/yr)	2.5	8.9	14.3	18
Fan savings*	(GJ/yr)	0.7	0.7	-2.6	-2.6
TOTAL DCV SAVINGS	(GJ/yr)	3.2	9.6	11.7	15.4
	($/yr)	$18.60	$45.55	$27.89	$43.47

TORONTO:

		BASE (continuous exhaust fan)
Fan Capacity	(L/s)	53
Ventilation + Infiltration	(ach)	0.32
CO2 - average	(ppm)	571
- maximum	(ppm)	802
Space Heat Energy	(GJ/yr)	82.0
Ventilation Fan Energy	(GJ/yr)	2.6

		DCV:		Continuous HRV:	
		Match avg.	Match peak	low effic.	high effic.
Fan Capacity	(L/s)	25/75	25/75	19/57	19/57
Ventilation + Infiltration	(ach)	0.29	0.24	0.31	0.31
CO2 set-point	(ppm)	645	770		
CO2 - average	(ppm)	560	695	589	589
- maximum	(ppm)	658	801	835	835
Space Heat savings	(GJ/yr)	4.9	11.1	17.7	21.4
Fan savings*	(GJ/yr)	0.7	0.7	-2.6	-2.6
TOTAL DCV SAVINGS	(GJ/yr)	5.6	11.8	15.1	18.8
	($/yr)	$36.66	$68.66	$44.94	$63.94

WINNIPEG:

		BASE (continuous exhaust fan)
Fan Capacity	(L/s)	53
Ventilation + Infiltration	(ach)	0.32
CO2 - average	(ppm)	571
- maximum	(ppm)	802
Space Heat Energy	(GJ/yr)	112.6
Ventilation Fan Energy	(GJ/yr)	2.6

		DCV:		Continuous HRV:	
		Match avg.	Match peak	low effic.	high effic.
Fan Capacity	(L/s)	25/75	25/75	19/57	19/57
Ventilation + Infiltration	(ach)	0.29	0.23	0.31	0.31
CO2 set-point	(ppm)	645	790		
CO2 - average	(ppm)	562	707	589	589
- maximum	(ppm)	655	823	835	835
Space Heat savings	(GJ/yr)	3.5	15.0	21.8	27.7
Fan savings*	(GJ/yr)	0.7	0.7	-2.6	-2.6
TOTAL DCV SAVINGS	(GJ/yr)	4.2	15.7	19.2	25.1
	($/yr)	$20.69	$65.58	$57.16	$80.52

*based on 25% off-time

Table 10.11 DCV Simulation Results

Gas forced air heating

VANCOUVER:			Exhaust Fan		HRV	
	Occupants:		3	6	3	6
Continuous	Fan Capacity	(L/s)	53	53	39	
(base case)	Ventilation + Infiltration	(ach)	0.32	0.32	0.31	
	CO2 - average	(ppm)	571	816	589	
	- maximum	(ppm)	802	1276	835	
	Space Heat Energy	(GJ/yr)	59.5	49.7	41.5	
	Ventilation Fan Energy	(GJ/yr)	2.6	2.6	5.2	
Demand						
Controlled:	Fan Capacity	(L/s)	25/75	25/75	19/57	
(match avg.)	Ventilation + Infiltration	(ach)	0.30	0.29	0.31	
	CO2 set-point	(ppm)	655	995	675	
	CO2 - average	(ppm)	574	823	581	
	- maximum	(ppm)	694	1066	726	
	Space Heat savings	(GJ/yr)	2.5	2.6	0.3	
	Fan savings*	(GJ/yr)	0.7	0.7	1.3	
	TOTAL DCV SAVINGS	(GJ/yr)	3.2	3.3	1.6	
		($/yr)	$18.60	$19.19	$17.35	

TORONTO:			Exhaust Fan		HRV	
	Occupants:		3	6	3	6
Continuous	Fan Capacity	(L/s)	53	53	39	39
(base case)	Ventilation + Infiltration	(ach)	0.32	0.32	0.31	0.31
	CO2 - average	(ppm)	571	816	589	851
	- maximum	(ppm)	802	1276	835	1339
	Space Heat Energy	(GJ/yr)	82.0	73.3	60.6	52.2
	Ventilation Fan Energy	(GJ/yr)	2.6	2.6	5.2	5.2
Demand						
Controlled:	Fan Capacity	(L/s)	25/75	25/75	19/57	19/57
(match avg.)	Ventilation + Infiltration	(ach)	0.29	0.28	0.29	0.3
	CO2 set-point	(ppm)	645	995	675	1025
	CO2 - average	(ppm)	560	818	581	837
	- maximum	(ppm)	658	1025	726	1127
	Space Heat savings	(GJ/yr)	4.9	5.8	-0.1	0.3
	Fan savings*	(GJ/yr)	0.7	0.7	1.3	1.3
	TOTAL DCV SAVINGS	(GJ/yr)	5.6	6.5	1.2	1.6
		($/yr)	$36.66	$41.37	$22.67	$24.64
Demand						
Controlled:	Fan Capacity	(L/s)			25/75	
	Ventilation + Infiltration	(ach)			0.20	
	CO2 set-point	(ppm)			1000	
	CO2 - average	(ppm)			797	
	- maximum	(ppm)			1005	
	Space Heat savings	(GJ/yr)			5.1	
	Fan savings*	(GJ/yr)			1.4	
	TOTAL DCV SAVINGS	(GJ/yr)			6.5	
		($/yr)			$50.59	

*based on 25% off-time

Table 10.11 DCV Simulation Results

	Gas forced air heating				
WINNIPEG:			Exhaust Fan		HRV
	Occupants:		3	6	3
Continuous	Fan Capacity	(L/s)	53	53	39
(base case)	Ventilation + Infiltration	(ach)	0.32	0.32	0.31
	CO2 - average	(ppm)	571	816	589
	- maximum	(ppm)	802	1276	835
	Space Heat Energy	(GJ/yr)	112.6	103.7	86.1
	Ventilation Fan Energy	(GJ/yr)	2.6	2.6	5.2
Demand					
Controlled:	Fan Capacity	(L/s)	25/75	25/75	19/57
(match avg.)	Ventilation + Infiltration	(ach)	0.30	0.29	0.31
	CO2 set-point	(ppm)	645	995	675
	CO2 - average	(ppm)	562	823	593
	- maximum	(ppm)	655	1066	735
	Space Heat savings	(GJ/yr)	3.5	4.8	1.4
	Fan savings*	(GJ/yr)	0.7	0.7	1.3
	TOTAL DCV SAVINGS	(GJ/yr)	4.2	5.4	2.7
		($/yr)	$20.69	$25.55	$12.78
Demand					
Controlled:	Fan Capacity	(L/s)	25/75		
	Ventilation + Infiltration	(ach)	0.28		
	CO2 set-point	(ppm)	675		
	CO2 - average	(ppm)	585		
	- maximum	(ppm)	700		
	Space Heat savings	(GJ/yr)	6.6		
	Fan savings*	(GJ/yr)	0.7		
	TOTAL DCV SAVINGS	(GJ/yr)	7.2		
		($/yr)	$32.53		
Demand					
Controlled:	Fan Capacity	(L/s)	25/75		
	Ventilation + Infiltration	(ach)	0.18		
	CO2 set-point	(ppm)	1000		
	CO2 - average	(ppm)	830		
	- maximum	(ppm)	1004		
	Space Heat savings	(GJ/yr)	20.5		
	Fan savings*	(GJ/yr)	0.7		
	TOTAL DCV SAVINGS	(GJ/yr)	21.2		
		($/yr)	$87.06		

*based on 25% off-time

10.5.2 Sample Run

Enerpass/Contam87 run

Sample, January to March run of WDCFANG3 file for
- Winnipeg
- Demand Controlled ventilation air flow
- FAN exhaust system (unbalanced)
- Gas heat (forced air)
- 3 occupants

WDCFANG3
File Name: WDCFANG3
System Type: Single-zone forced air
Options: None

Building Description Data

Zone #1
Living & bedrooms

Wall				Window			Door	
link to (zone)	area (m^2)	wall code	dir	area (m^2)	frame code	glazing code	area (m^2)	R value
0	24.5	-1	E	1.9	7	3	0.	1.
0	29.7	-1	S	4.6	7	3	1.9	1.4
0	24.5	-1	W	1.9	7	3	0.	0.
0	29.7	-1	N	4.6	7	3	1.8	1.4

Floor

link to	area (m^2)	construction code	average zone height (m)
1	122.7	10	2.45

Ceiling		Skylight		
area (m^2)	const code	area (m^2)	frame code	glaz code
122.7	-1	0.	1	1

Below Grade Walls				Below-Grade/Slab-on-Grade Floors			
area (m^2)	const code	avg depth (m)	insul depth(m)	insul area(m^2)	uninsul area(m^2)	const code	height to ceil (m)
0.	1	0.	0.	0.	0.	17	2.4

Building Description Data

Zone #2
Basement

Wall				Window			Door	
link to (zone)	area (m^2)	wall code	dir	area (m^2)	frame code	glazing code	area (m^2)	R value
0	9.2	-1	E	1.1	7	3	0.	1.
0	11.1	-1	S	1.1	7	3	0.	1.
0	9.2	-1	W	1.1	7	3	0.	1.
0	11.1	-1	N	1.1	7	3	0.	1.

Floor

link to	area (m^2)	construction code	average zone height (m)
0	0.	13	2.8

Ceiling		Skylight		
area (m^2)	const code	area (m^2)	frame code	glaz code
0.	-1	0.	1	1

Below Grade Walls				Below-Grade/Slab-on-Grade Floors			
area (m^2)	const code	avg depth (m)	insul depth(m)	insul area(m^2)	uninsul area(m^2)	const code	height to ceil (m)
81.4	6	1.8	1.8	0.	122.7	1	2.75

Environment Data

Soil type: dry clay
Orientation of the Building is 0.0 Degrees from South (Positive East)
Slope of Skylight Glazing from Horizontal 0.0
Infiltration type: Air Changes

Zone	1	2
Nominal	0.10	0.10
Maximum	0.30	0.30

HVAC and Equipment Data

: C System: Single-zone forced air

Heating Data
Central Heating Source Heat Pump

Equipment Code (1 - 5)	1
Location of Central Thermostat (zone)	1

Cooling Data
Central Cooling Source No Cooling System

HVAC System Air Handling Data

HVAC System: Single-zone forced air

AIR FLOW (l/s)

Zone	1	2
Supply	140	30
Return	140	30
Outdoor	0	0
Makeup	--	--
Exhaust	25	0
Transfer	30	20
from zone	2	1
Transfer	0	0
from zone	0	0

SCHEDULES (code)

Zone	1	2	
Supply			2
Outdoor			2
Makeup	--	--	
Exhaust	2	2	
Transfer	2	2	
Transfer	2	2	

FAN POWER (W)

Zone	1	2	
Supply			100
Return			100
Makeup	--	--	
Exhaust	50.0	15.0	

Operating Schedules

edule number	Title	Operating Days	Schedule Ratio	Hourly Values					
1	internal heat gai	5	1.20	15	15	15	15	15	15
				50	100	100	11	15	15
				15	15	15	50	100	100
				68	63	63	56	56	19
2	supply air	7	1.00	100	100	100	100	100	100
				100	100	100	100	100	100
				100	100	100	100	100	100
				100	100	100	100	100	100
3	dhw profile	5	1.00	0	0	0	0	0	0
				4	11	2	20	2	5
				2	0	0	4	11	20
				11	4	2	0	2	0
4	Occ. Living/bdrms	5	1.20	69	70	70	70	70	70
				80	100	100	0	0	0
				0	0	0	25	60	100
				100	100	90	90	90	70
5	OCC BEDROOMS	5	1.00	100	100	100	100	100	100
				50	0	0	0	0	0
				0	0	0	0	0	0
				0	0	0	25	40	50
7	Bathing	5	1.00	0	0	0	0	0	0
				40	0	0	0	0	0
				0	0	0	0	0	0
				0	20	0	0	40	0
8	Heating Th.stat	7	1.00	0	0	0	0	0	0
				100	100	100	100	100	100
				100	100	100	100	100	100
				100	100	100	100	100	0
9	schedule 9	7	0.25	0	16	29	35	37	44
				49	51	56	65	55	41
				47	57	67	58	44	26
				18	13	2	1	1	1

Operating Data

Zone #1
Living & bedrooms

Maximum Occupancy		3
Activity Level (0 - 9)		2
Occupancy Schedule (1 - 9)		4
Process Loads	Heat (W)	1200.0
	Moisture (kg/hr)	0.6
Process Schedule (1 - 9)		1
Heating Setpoint		21.0
Degrees of Setback		0.0
Heating Schedule (1 - 9)		8
Cooling Setpoint		28.0
Cooling Setup		0.0
Cooling Schedule (1 - 9)		8

Zone #2
Basement

Maximum Occupancy		1
Activity Level (0 - 9)		3
Occupancy Schedule (1 - 9)		7
Process Loads	Heat (W)	120.0
	Moisture (kg/hr)	0.1
Process Schedule (1 - 9)		1
Heating Setpoint		0.0
Degrees of Setback		0.0
Heating Schedule (1 - 9)		1
Cooling Setpoint		0.0
Cooling Setup		0.0
Cooling Schedule (1 - 9)		1

Water Heating Data

Daily Hot Water Load (L/day)	250.0
Hourly Hot Water Demand Schedule (1 - 9)	3
Heat Source:	Boiler
Desired Hot Water Temperature (C)	55.0
Volume of Auxiliary Tank (L)	272.0
Height of Auxiliary Tank (m)	1.2
R-Value of Auxiliary Tank (m^2 C/W)	1.8
Zone Location of Tank and DWH Heat Pump	2
Boiler Equipment Code (1 - 5)	1

Economic Data

Off-Peak Electricity Schedule 2
Ratio of Peak to Off-Peak Cost 0.0

Electric Peak Rate Structure :

First 175.0 kWhr at	5.3
Next 0.0 kWhr at	0.0
Next 0.0 kWhr at	0.0
Remainder at	3.8
Minimum Charge ($) .	4.68
Demand Rate ($/kW) .	0.0
Demand Threshold ...	2

Fossil Fuel #1 - Natural Gas
Fossil Fuel Rate Structure :

First 5652.0 at	14.5
Next 0.0 at	0.0
Next 0.0 at	0.0
Remainder at	11.9
Minimum Charge ($) .	6.25

Fossil Fuel #2 - Natural Gas
Fossil Fuel Rate Structure :

First 1.0 at	9.0
Next 1.0 at	8.0
Next 1.0 at	7.0
Remainder at	6.0
Minimum Charge ($) .	5.00

Lighting and Electrical Data

Zone	1	2
Indoor Receptacles		
Load (W/m^2)	0.0	0.0
Schedule	1	1

Lighting Control: Off

Zone	1	2
Indoor Lighting		
Load (W/m^2)	0.0	0.0
Schedule	1	1
Lum Eff(lm/W)	45.0	45.0
Illum (lux)	12.0	12.0
Coefficient of Utilization		
Lighting	0.5	0.5
Daylight	0.5	0.5

Outdoor Receptacle Load (W)	0.0
Outdoor Receptacle Schedule Code	1
Outdoor Lighting Load (W)	0.0
Outdoor Lighting Schedule Code	1

Contaminant Species and Kinetic Element Data

Contaminant # 1	CO2	Conc. Units (per g air) :	ug-CO2
Contaminant # 2	NO2	Conc. Units (per g air) :	g-NO2

Kinetic Element # 1

	CO2	NO2
CO2	0.0	-0.0
NO2	0.0	-0.0

Kinetic Element # 2

	CO2	NO2
CO2	0.0	-0.0
NO2	0.0	-0.0

Zone Contaminant Generation

Zone Zone	1	2AIR FLOW (l/s)
Contaminant # 1		
Gen. Rate	100.0	10.0
Max. Conc	320.0	999.0
Gen. Sched	4	4
Kinetic ID	0	0
Contaminant # 2		
Gen. Rate	0.0	0.0
Max. Conc	99.9	99.9
Gen. Sched	4	4
Kinetic ID	0	0

HVAC System: Single-zone forced air

AIR FLOW (l/s)

Zone	1	2
Supply	140	30
Return	140	30
Outdoor	0	0
Makeup	---	---
Exhaust	75	0
Transfer	30	20
from zone	2	1
Transfer	0	0
from zone	0	0

SCHEDULES (code)

Zone	1	2	
Supply			2
Outdoor			2
Makeup	---	---	
Exhaust	2	2	
Transfer	2	2	
Transfer	2	2	

FAN POWER (W)

Zone	1	2	
Supply			100.000000
Return			100.000000
Makeup	---	---	
Exhaust	70.0	25.0	

****
* ENERPASS 3.0 RESULTS *
****

INPUT DATA FILE : WDCFANG3.V30
DATE : 1990 9 7 TIME : 0:31

SIMULATION WEATHER DATA FOR CITY : WINNIPEG
AND YEAR : 1971

HVAC SYSTEM TYPE: SINGLE ZONE FORCED AIR

****
* DESIGN DAY HEAT LOAD PERCENTAGES *
****

COMPONENT	ZONE 1 [%]	ZONE 2 [%]	ZONE 3 [%]	ZONE 4 [%]	ZONE 5 [%]	ZONE 6 [%]	ZONE 7 [%]	TOTAL [%]
WALLS	17.7	7.0	.0	.0	.0	.0	.0	24.8
WINDOWS	23.6	8.0	.0	.0	.0	.0	.0	31.5
DOORS	1.5	.0	.0	.0	.0	.0	.0	1.5
ROOF	11.0	.0	.0	.0	.0	.0	.0	11.0
INFILT.	12.0	9.5	.0	.0	.0	.0	.0	21.5
VENTIL.	.0	.0	.0	.0	.0	.0	.0	.0
B/G WALLS	.0	4.3	.0	.0	.0	.0	.0	4.3
B/G FLOOR	.0	5.5	.0	.0	.0	.0	.0	5.5
TOTAL [%]	65.8	34.2	.0	.0	.0	.0	.0	100.0
LOAD IN KW	6.3	3.3	.0	.0	.0	.0	.0	9.5

99% OUTDOOR DESIGN TEMPERATURE (C) -34.4
GROUND DESIGN TEMPERATURE (C) 5.8

****
* FUEL CONSUMPTION OVER SIMULATION PERIOD *
****

	ELEC (kWh)	N GAS (m^3)	N GAS (m^3)	COST
SPACE HEAT	.0	1441.4	.0	208.86
HOT WATER	.0	267.4	.0	38.75
PROC. ENERGY	1257.9	-	-	18.63
LIGHTING	.0	-	-	.00
AIR COND	.0	-	-	.00
FAN ENERGY	603.2	-	-	8.93
DEMAND/MIN. CHG				.00
TOTAL	1861.1	1708.8	.0	275.17

****
* DEGREE-DAY TOTALS *
****

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
HEATING	1243.	879.	750.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2872.
COOLING	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

****
* MONTHLY PEAK ELECTRICITY DEMAND *
****

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
KW	1.9	1.9	1.9	.0	.0	.0	.0	.0	.0	.0	.0	.0
DAY	5	33	61	0	0	0	0	0	0	0	0	0
HOUR	8	8	8	0	0	0	0	0	0	0	0	0

****
* FLOOR AREA BY ZONE IN M^2 *
****

TOTAL	1	2	3	4	5	6	7
245.	123.	123.					

```
                       ********************************
                       *  ENERGY SUMMARY - BAR GRAPH  *
                       ********************************

 (GJ)          0.       10.       20.       30.       40.       50.
               +---+----+----+----+----+----+----+----+----+----+----

SPACE HEAT     ======================================================

HOT WATER      ==========

PROC. ENERGY   ]]]]]

LIGHTING

AIR COND

FAN ENERGY     ]]
               +---+----+----+----+----+----+----+----+----+----+----

 ELEC: ]]] N GAS: ===

     ENERGY CONSUMPTION PER UNIT FLOOR AREA   79.6 equiv. kWh/m^2

                     **********************************
                     *  ECONOMIC SUMMARY - BAR GRAPH  *
                     **********************************

$ dollars      0.       50.      100.      150.      200.      250.
               +---+----+----+----+----+----+----+----+----+----+----

SPACE HEAT     ==========================================

HOT WATER      ========

PROC. ENERGY   ]]]]

LIGHTING

AIR COND

FAN ENERGY     ]]

DEMAND CHARGE
               +---+----+----+----+----+----+----+----+----+----+----

 ELEC: ]]] N GAS: ===

      ENERGY COST PER UNIT FLOOR AREA  $ 1.12 /m^2
```

****

* ENERGY ANALYSIS SUMMARY *

****

	|<---- HEAT GAINS			---->|	<---- SPACE HEATING				---->|
MON	SOLAR TRANS. (GJ)	OCCUPANT HT GAIN (GJ)	PROC. HT GAIN (GJ)	LIGHTING HT GAIN (GJ)	HEAT LOAD (GJ)	% LOAD SENSIBLE	PREHEAT ENERGY (GJ)	CENTRL HT SUP (GJ)	REHEAT ENERGY (GJ)
JAN	2.40	.33	1.55	.00	17.88	100.00	.00	23.20	.00
FEB	2.56	.30	1.41	.00	12.39	100.00	.00	16.47	.00
MAR	3.24	.34	1.57	.00	10.23	100.00	.00	13.98	.00
YR	8.2	1.0	4.5	.0	40.5	100.0	.0	53.7	.0

*** PEAK HEATING SUPPLY ***

	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6	ZONE 7	TOTAL
kW	9.6	2.1	.0	.0	.0	.0	.0	11.7
DAY/HOUR	15/ 3	15/ 3	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	15/ 3

** AVERAGE HEAT CONVERSION EFFICIENCY (%): 75.50

** MAXIMUM HUMIDIFICATION RATE (KG/HR): .00

```
*****************************
*  ENERGY ANALYSIS SUMMARY  *
*****************************
```

|<--- SPACE COOLING --->|<--- FAN --->|<--- HOT WATER --->|

MON	COOLING LD SENS (GJ)	COOLING LD LAT (GJ)	AIR CON ENERGY (GJ)	FAN ENERGY (GJ)	VENTIL RATE (AC/HR)	HEATING LOAD (GJ)	ENERGY SUPPLY (GJ)	H/PUMP INPUT (GJ)	TOTAL ENERGY (GJ)
JAN	.00	.00	.00	.75	.30	1.81	3.41	.00	28.91
FEB	.00	.00	.00	.68	.30	1.65	3.11	.00	21.66
MAR	.00	.00	.00	.75	.31	1.82	3.43	.00	19.73
YR	.0	.0	.0	2.2	.30	5.3	10.0	.0	70.3

*** PEAK COOLING SUPPLY (kW) ***

	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6	ZONE 7	TOTAL
	.0	.0	.0	.0	.0	.0	.0	.0
DAY/HOUR	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0

** AVERAGE COOLING C.O.P. : .00

****
*   ECONOMIC SUMMARY IN $ *
****

MON	SRCE	SPACE HEAT	HOT WATER	PROC. ENERGY	LIGHTING	AIR CON	FAN ENERGY	DEMAND CHARGE	TOTAL
JAN	ELEC	.00	.00	6.20	.00	.00	2.98	.00	9.19
	N GAS	90.31	13.29	---	---	---	---	---	103.60
FEB	ELEC	.00	.00	6.21	.00	.00	2.98	.00	9.19
	N GAS	64.12	12.10	---	---	---	---	---	76.22
MAR	ELEC	.00	.00	6.22	.00	.00	2.97	.00	9.19
	N GAS	54.42	13.36	---	---	---	---	---	67.79
TOT	ELEC	.00	.00	18.63	.00	.00	8.93	.00	27.56
TOT	N GAS	208.86	38.75	---	---	---	---	---	247.61
	TOTAL	208.86	38.75	18.63	.00	.00	8.93	.00	275.17

****
* MONTHLY TEMPERATURE RANGE *
****

MON	ZONE	MIN. TEMP (C)	NUMBER OF HOURS BUILDING ZONE AIR TEMP WAS under 16C	16C	18C	20C	22C	24C	26C	28C	30C	over 32C	MAX. TEMP (C)	AVG. TEMP (C)
JAN	1.	21.0	0.	0.	0.	744.	0.	0.	0.	0.	0.	0.	21.0	21.0
	2.	12.5	687.	32.	19.	6.	0.	0.	0.	0.	0.	0.	20.7	13.8
FEB	1.	21.0	0.	0.	0.	672.	0.	0.	0.	0.	0.	0.	21.2	21.0
	2.	12.5	672.	0.	0.	0.	0.	0.	0.	0.	0.	0.	15.4	14.2
MAR	1.	21.0	0.	0.	0.	744.	0.	0.	0.	0.	0.	0.	21.3	21.0
	2.	14.1	744.	0.	0.	0.	0.	0.	0.	0.	0.	0.	15.9	15.2

****
* MONTHLY HUMIDITY RANGE *
****

MON	ZONE	MIN. HUM. (%)	NUMBER OF HOURS ZONE RELATIVE HUMIDITY WAS under 10%	10%	20%	30%	40%	50%	60%	70%	80%	over 90%	MAX. HUM. (%)	AVG. HUM. (%)
JAN	1.	14.1	0.	729.	15.	0.	0.	0.	0.	0.	0.	0.	21.1	16.8
	2.	15.5	0.	66.	678.	0.	0.	0.	0.	0.	0.	0.	26.6	22.9
FEB	1.	14.4	0.	290.	382.	0.	0.	0.	0.	0.	0.	0.	29.4	21.2
	2.	22.5	0.	0.	356.	316.	0.	0.	0.	0.	0.	0.	36.1	28.6
MAR	1.	20.3	0.	0.	644.	100.	0.	0.	0.	0.	0.	0.	33.6	26.2
	2.	30.4	0.	0.	0.	707.	37.	0.	0.	0.	0.	0.	41.4	34.7

****
* MONTHLY CONTAMINANT SUMMARY *
****

		CONTAMINANT #1 (ug-CO2/Mg-air)			CONTAMINANT #2 (g-NO2/Mg-air)		
MON	ZONE	MIN	MAX	AVG	MIN	MAX	AVG
JAN	1.	105.465	364.893	279.467			
	2.	41.591	308.339	234.673			
FEB	1.	101.620	370.097	279.162			
	2.	104.792	314.133	236.976			
MAR	1.	101.495	370.964	278.962			
	2.	103.902	315.099	238.254			

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+ ambient CO_2