Final Report

FIELD INVESTIGATIONS OF INDOOR ENVIRONMENT AND ENERGY USAGE IN MID-RISE RESIDENTIAL BUILDINGS

Report prepared for

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EXECUTIVE SUMMARY

Over the last three decades, the growth in multi-unit residential building stock is phenomenal. There are about 3.2 million residential units provided by multi-unit residential buildings accounting for about 31% of the total housing dwellings in Canada. Despite the size and importance of this segment of the housing stock, little information is available with regard to general performance, occupant responses with regard to indoor air quality and, above all, energy efficiency.

The focus of the present study was to evaluate the thermal and indoor environment performance of mid-rise buildings, more specifically three to five storey apartments. Pertinent questions which were evaluated during the course of work include the following:

- What is the airtightness of mid-rise apartment buildings which have the air-barrier system installed as per the 1990 Code requirements?
- What is the status of the installed capacity of ventilation systems and how are these systems performing?
- How do occupants perceive indoor air quality in mid-rise apartment buildings and what are the trends in common indoor environment parameters?
- How is the building performing based on the thermal and energy efficiency criteria?
- How does the mid-rise residential segment compare to high-rise and single family housing?

The research plan included the development of test and evaluation protocols for indoor environment parameters, energy consumption patterns and ventilation system performance parameters for mid-rise buildings. As part of the field work, a total of eight buildings were chosen for detailed evaluation; four buildings in Vancouver, two in Ottawa and two in Toronto. All the buildings were built in the last five years (1990 or later) to reflect current design and construction practices. The detailed evaluation of eight mid-rise residential buildings showed the following trends:

Air Leakage and Ventilation Performance:

- The airtightness of the building shell ranged from 2.23 L/s.m^2 to 3.60 L/s.m^2 at 75 Pa pressure difference. The measured values of airtightness for various buildings are significantly higher than what can be expected in buildings with carefully installed and commissioned air barrier systems. The airtightness from current practice should range from as low as 0.3 to 1.7 L/s.m^2 at 75 Pa pressure difference as per opinions of some participants of Building Science Insight seminars conducted by National Research Council of Canada.
- The air change rate tests using the passive sampling devices showed that the mechanical ventilation accounted for 0.1 to 0.67 air changes per hour in occupied suites. In several buildings, the estimated mechanical ventilation rate was substantially lower than the required rate of 0.30 air changes per hour as per CSA Standard F-326.
- All except one Ottawa building have a corridor make-up air ventilation system. The installed capacity of these systems met or exceeded the ventilation requirements set by ASHRAE Standard 62-1989 which was about 20 to 80 L/s per suite. Measured air flow rates for the corridor ventilation system ranged from 55% to 99% of the rated installed ventilation capacity in the building.
- The corridor ventilation air entering the suite through the door was negligible in five of the eight buildings due to weatherstripping of the suite/corridor entry door. Ventilation air entering the suite through the corridor in the other three buildings ranged from 13 to 27 L/s. The supply of ventilation air in suites falls short off the requirements set by CSA F-326 which ranged from 20 to 35 L/s per suite.

- All suites had bathroom exhaust and kitchen exhaust fans. In all buildings, the installed capacity of bathroom and kitchen exhaust fans met the requirements set by CSA F-326. However, the measured air flow rates of kitchen and bathroom exhaust fans showed that most bathroom fans exhausted 30% to 85% of their rated capacity. The performance of kitchen fans was slightly better than bathroom fans but not acceptable. Kitchen fans exhausted 50% to 90% of their rated capacity.
- Occupant surveys showed that about 82% occupants regularly used kitchen exhaust fans while 41% of occupants regularly used bathroom exhaust fans.
- From the above observations, we found that mid-rise residential buildings had the necessary ventilation and exhaust equipment installed to meet the code requirements. However, the performance evaluation showed that these exhaust and ventilation systems did not function to the required level and generated significantly low air movement in the building. Make-up air system provided the fresh air in corridors which eventually dumped to outside due to a lack of proper transfer mechanism between the corridor and the suites. The under-performance of ventilation systems also seem to cause high levels of relative humidity, high levels of carbon dioxide, window condensation and mold growth in several buildings.

Indoor Environment:

- Occupant surveys reported that about 16% of tenants feel that they suffer from health problems due to poor indoor air quality in some buildings. About 39% of tenants complained about window condensation; 14% of occupants complained about mold growth in their suites; and only 57% of occupants felt that the quality of indoor air was acceptable in their buildings.
- In several buildings, relative humidity and carbon dioxide levels exceeded the normal acceptable limits set by Health Canada Guidelines. These buildings also had insufficient ventilation and air movement in the suites. Occupant complaints are also high. The occupant complaints in these building seem to be due to improper and/or lack of adequate ventilation and air distribution.
- The emissions of formaldehyde and VOCs from building materials were substantially below acceptable limits in all buildings.
- The field survey also showed that the electromagnetic fields were much lower than 8 milligauss in all test units. Ontario Hydro recommends a level up to 20 milligauss near the equipment and about 8 milligauss at 0.3 m away from the source.
- Lighting levels in common areas of mid-rise apartment buildings generally met or exceeded the requirements set by good practices and Code requirements.

Energy Use in Buildings:

- The purchased energy in mid-rise buildings ranged from 146 to 263 kWh/m^2 of floor area per year. The annual energy cost ranged from \$6.76/m^2 to \$20.05/m^2 with an average of about \$10/m^2. The utility bill for each suite ranged from \$461 to \$1,683 per year. The average utility bill per suite was about \$746 per year based on costing data available for the year 1994.
- The analysis of heat gains during the heating season showed that solar gains contributed about 10% (11.5 ± 3.1 kWh/m^2) of space heating requirements while the internal gains accounted for 19% (21.4 ± 4.7 kWh/m^2) of the space heating needs. The average purchased space heating energy requirements was about 112.8 ± 23.6 kWh/m^2.
- The heat loss components during the heating season were as follows: walls accounted for 16%; roof at 7%; below grade losses at 8%; windows and doors at 30%; air leakage at 23% and the mechanical ventilation at 16% of total heat losses.

- Energy balance analysis showed that for the eight test buildings the energy use was as follows:
  - purchased energy ranged from 146 to 263 kWh/m^2 and average of 184.6 ± 40.7 kWh/m^2.
  - space heating accounted for 43.5% ± 8.8%;
  - domestic hot water use accounted for 25.3% ± 2.6%;
  - lighting accounted for 14.8% ± 4.8%; and
  - miscellaneous energy use (suite appliances, air-conditioning and other equipment) accounted for 15.8% ± 5.1%.
- Comparison showed that the mean value of the energy consumption for a high-rise and mid-rise building is almost the same. Compared to a single family housing, the mid-rise residential units had about 10% less energy consumption per unit area despite the fact that mid-rise units had significantly less exposed surface area than single-family houses.

Overall, the field survey and energy analyses provided significant new insights into the mid-rise apartment buildings. These findings should help in future design, construction and commissioning of apartment buildings. Further work is needed to develop design criteria, construction details, effective ventilation systems, quality control and commissioning procedures and, above all, a comprehensive guidelines for interweaving occupant comfort and energy efficiency in mid-rise residential buildings.

RÉSUMÉ

Au cours des trente dernières années, le parc des logements collectifs a connu une croissance phénoménale. Les immeubles résidentiels procurent aux Canadiens quelque 3,2 millions de logements, soit 31 % de l'ensemble des logements au pays. En dépit de la taille et de l'importance de ce segment du parc de logements, on en sait peu sur la performance générale de ces habitations, sur les opinions de leurs occupants au sujet de la qualité de l'air intérieur et, surtout, sur leur efficacité énergétique.

La présente étude avait pour but d'évaluer la performance de bâtiments de hauteur moyenne comptant de trois à cinq étages en regard du chauffage et du milieu intérieur. L'évaluation a été faite à partir des questions énoncées ci-dessous :

- Dans quelle mesure les immeubles d'appartements de moyenne hauteur sont-ils étanches à l'air lorsque leurs pare-air ont été mis en oeuvre conformément aux exigences du Code de 1990?
- Quelle est la tenue en service des installations de ventilation et comment ces systèmes se comportent-ils?
- Comment les occupants perçoivent-ils la qualité de l'air intérieur dans les immeubles d'appartements de moyenne hauteur et quelles sont les tendances relatives aux paramètres communs du milieu intérieur?
- Quelle est la performance de l'immeuble par rapport aux critères d'efficacité thermique et énergétique?
- À quel niveau se situe le segment des immeubles de moyenne hauteur comparativement aux tours d'habitation et aux maisons individuelles?

Le plan de recherche prévoyait l'élaboration de protocoles d'essai et d'évaluation pour le milieu intérieur, les habitudes de consommation d'énergie et la performance des installations de ventilation des immeubles de moyenne hauteur. Sur le terrain, huit bâtiments ont été sélectionnés pour subir une évaluation détaillée, soit quatre bâtiments à Vancouver, deux à Ottawa et deux autres à Toronto. Tous les bâtiments ont été construits au cours des cinq dernières années (à partir de 1990), donc selon les méthodes actuelles de conception et de construction. L'évaluation détaillée de ces huit immeubles résidentiels de moyenne hauteur a fait ressortir les tendances suivantes :

Fuites d'air et performance de la ventilation

- L'étanchéité à l'air de l'enveloppe des bâtiments varie de 2,23 L/s.m² à 3,60 L/s.m² à une différence de pression de 75 Pa. Les valeurs mesurées de l'étanchéité à l'air de divers immeubles sont de beaucoup supérieures à ce qu'elles devraient être pour des bâtiments dont les pare-air ont été mis en oeuvre et mis en service avec le plus grand soin. Les méthodes actuelles devraient permettre d'atteindre une étanchéité à l'air dans un éventail compris entre 0,3 et 1,7 L/s.m² à une différence de pression de 75 Pa. C'est du moins l'avis de certains participants aux séminaires *Regard sur la science du bâtiment* présentés par le Conseil national de recherches du Canada.
- Les essais visant à déterminer le taux de renouvellement d'air, effectués au moyen d'appareils d'échantillonnage passifs, ont montré que la ventilation mécanique permettait d'obtenir des taux de 0,1 à 0,67 renouvellement d'air par heure dans des appartements occupés. Dans plusieurs

bâtiments, le taux de ventilation mécanique estimé était sensiblement inférieur au taux requis de 0,30 renouvellement d'air par heure en vertu de la norme CSA F-326.

- Tous les corridors des bâtiments, sauf pour un immeuble d'Ottawa, sont dotés d'un dispositif mécanique d'air de compensation. La capacité en service de ces dispositifs, qui variait entre 20 et 80 L/s.m² par appartement, répondait aux exigences de ventilation de l'ASHRAE énoncées dans la norme 62-1989 de cet organisme ou les excédait. Les débits d'air mesurés pour le dispositif d'air de compensation des corridors variaient entre 55 % et 99 % de la capacité nominale en service de l'installation de ventilation du bâtiment.

- L'air de ventilation du corridor qui pénètre dans les appartements par la porte était négligeable dans cinq des huit bâtiments à l'étude en raison du coupe-froid placé autour de la porte d'entrée de l'appartement. Dans les trois autres bâtiments, l'air de ventilation s'infiltrant dans les appartements à partir du corridor variait de 13 à 27 L/s. L'apport d'air de ventilation dans les appartements est moindre que ce que recommande la norme CSA F-326, dont la fourchette varie de 20 à 35 L/s par appartement.

- Tous les appartements étaient pourvus de ventilateurs de salle de bains et de hottes de cuisinière. Dans tous les bâtiments, la capacité nominale de ces ventilateurs d'extraction satisfont aux exigences établies par la CSA F-326. Toutefois, les débits d'air mesurés des ventilateurs d'extraction de la salle de bains et de la cuisine ont fait ressortir que la plupart des ventilateurs de salle de bains évacuent l'air dans une proportion de 30 à 85 % de leur capacité nominale. La performance des hottes de cuisinière était légèrement supérieure à celle des ventilateurs de salle de bains, mais n'était pas acceptable pour autant. Les hottes de cuisinière évacuaient l'air dans une proportion de 50 à 90 % de leur capacité nominale.

- Les sondages menés auprès des occupants ont montré qu'environ 82 % des occupants utilisent régulièrement leur hotte de cuisinière tandis que 41 % des occupants utilisent régulièrement le ventilateur de la salle de bains.

- Ces observations ont confirmé que les bâtiments résidentiels de moyenne hauteur possèdent les dispositifs de ventilation et d'extraction requis pour respecter les exigences du Code. Cela dit, l'évaluation de la performance a mis en lumière que ces dispositifs ne fonctionnent pas au niveau de performance requis et qu'ils produisent un très faible mouvement d'air dans l'immeuble. Les dispositifs d'air de compensation fournissent de l'air frais aux corridors, mais cet air finit par retourner à l'extérieur faute d'un mécanisme de transfert approprié entre le corridor et les appartements. Ce rendement insuffisant des installations de ventilation semble aussi occasionner de hauts taux d'humidité relative, des concentrations élevées de dioxyde de carbone, de la condensation sur les fenêtres ainsi qu'une prolifération de moisissures dans plusieurs bâtiments.

Milieu intérieur

- Les sondages menés auprès des occupants ont permis d'apprendre qu'environ 16 % des occupants de certains immeubles estiment qu'ils souffrent de problèmes de santé à cause de la mauvaise qualité de l'air intérieur. Quelque 39 % des occupants se plaignent de problèmes de condensation aux fenêtres, 14 % éprouvent des problèmes de moisissures et seulement 57 % des occupants croient que la qualité de l'air de leur immeuble est acceptable.

- Dans plusieurs bâtiments, l'humidité relative et les concentrations de dioxyde de carbone dépassent les limites normales acceptables établies par Santé Canada. Les appartements de ces bâtiments présentent aussi une ventilation et un mouvement d'air insuffisants. Les plaintes des occupants sont également fréquentes. Ceux-ci semblent se plaindre le plus souvent de la mauvaise qualité ou de l'absence de ventilation et de distribution d'air.

- Les quantités de formaldéhyde et de composés organiques volatils émises par les matériaux de construction sont très inférieures aux limites acceptables dans tous les bâtiments.

- L'enquête sur le terrain a aussi permis de constater que les champs électromagnétiques sont très inférieurs à 8 milligauss dans tous les appartements analysés. Ontario Hydro recommande des niveaux maximums de 20 milligauss près de l'équipement et d'environ 8 milligauss à 0,3 m de la source.
- Les niveaux d'éclairage dans les aires communes des immeubles d'appartements de moyenne hauteur sont généralement conformes aux règles de l'art et aux exigences du Code ou les excèdent.

Utilisation de l'énergie dans les bâtiments

- L'énergie achetée dans les immeubles de moyenne hauteur varie entre 146 et 263 kWh/m² de surface de plancher par année. Le coût annuel de l'énergie varie entre 6,76 $/m² et 20,05 $/m², la moyenne oscillant autour de 10 $/m². La facture d'énergie pour chaque appartement varie de 461 $ à 1 683 $ par année. La facture d'énergie moyenne par appartement s'est établie à environ 746 $ par année si l'on en croit les données de coût disponibles pour l'année 1994.
- L'analyse des gains thermiques durant la saison de chauffage a montré que les gains solaires comblaient environ 10 % des besoins de chauffage des locaux (11,5 ± 3,1 kWh/m²) tandis que les gains internes représentaient 19 % (21,4 ± 4,7 kWh/m²) du chauffage requis pour les locaux. En moyenne, l'énergie achetée pour les besoins de chauffage des locaux est de 112,8 ± 23,6 kWh/m².
- Les déperditions thermiques durant la saison de chauffage sont réparties comme suit (pourcentage de la déperdition totale) : murs (16 %); toiture (7 %); déperditions sous la surface du sol (8 %); portes et fenêtres (30 %); fuites d'air (23 %); ventilation mécanique (16 %).
- L'analyse du bilan énergétique a montré que pour les huit immeubles à l'étude, la consommation d'énergie se répartit ainsi :

  - l'énergie achetée varie de 146 à 263 kWh/m², pour une moyenne de 184,6 ± 40,7 kWh/m²
  - le chauffage des locaux représente 43,5 % ± 8,8 %;
  - le chauffage de l'eau correspond à 25,3 % ± 2,6 %;
  - l'éclairage représente 14,8 % ± 4,8 %;
  - les besoins divers en énergie (appareils ménagers, climatisation et autres équipements) correspondent à 15,8 % ± 5,1 %.

- La comparaison montre que la valeur moyenne de la consommation énergétique pour une tour d'habitation et un immeuble résidentiel de moyenne hauteur est pratiquement la même. Comparativement à une maison individuelle, les appartements des immeubles de moyenne hauteur consomment environ 10 % moins d'énergie par unité de surface en dépit du fait que ces appartements présentent beaucoup moins de surfaces exposées que les maisons individuelles.

Dans l'ensemble, l'enquête sur le terrain et les analyses énergétiques ont fourni un grand nombre de nouvelles données sur les immeubles résidentiels de moyenne hauteur. Ces données devraient contribuer à la conception, à la construction et à la mise en service des immeubles d'appartements. De plus amples travaux seront nécessaires pour élaborer les critères de conception, les détails de construction, les installations de ventilation efficaces, les méthodes de contrôle de la qualité et de mise en service et, surtout, des directives complètes pour bien intégrer le confort des occupants avec l'efficacité énergétique dans les immeubles résidentiels de moyenne hauteur.

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FIELD INVESTIGATIONS OF INDOOR ENVIRONMENT AND ENERGY USAGE IN MID-RISE RESIDENTIAL BUILDINGS

FINAL REPORT — AUGUST 1997

1. INTRODUCTION

During the last 20 years, the percentage of multi-unit residential building stock in Canada has been increasing at a faster rate than other forms of housing. The compact design and high densities offered by multi-unit residential buildings allow for better utilization of transportation and utility infrastructure in urban settings. In 1994, there were 3.19 million dwelling units provided by multi-unit residential buildings (31% of the total) in Canada. From this 3.19 million, 936,000 dwelling are in high-rise apartments (7 storey or higher). The multi-unit residential building (MURB) sector consumed about 335 PJ of energy (24% of the residential use) in 1994[1].

The multi-unit residential stock includes a variety of building types. The MURB is generally defined as a building with more than 600 m^2 of floor area, and 3 storeys or more. The stock includes (1) mid-rise buildings of three to four storey apartment buildings which may not have elevators; (2) mid-rise buildings of five to seven storeys; (3) high-rise buildings with seven to thirty storeys; and (4) few tall apartment towers with more than 30 storeys.

Over last several years CMHC and other public and private sector agencies have undertaken pioneering studies to gain information on the existing status of the multi-unit residential building stock. These studies are generally focused on evaluating the performance of the building shell, energy use patterns, indoor air-quality, and more interestingly, the existing building conditions. Some of the relevant findings are:

- the majority of the multi-family housing stock, both public and private, was built between 1960 to 1980;
- the energy consumption of multi-unit buildings is significantly high alluding to poor thermal performance of shell, mechanical and electrical equipment and, above all, dismal performance of ventilation systems;
- the indoor air-quality in multi-unit housing is a concern in more than half of the building stock; and
- there is a significant potential for improving the general performance of multi-unit housing stock with regard to energy efficiency, building performance and comfort for occupants.

The focus of the present study is to evaluate the thermal and indoor environment performance of mid-rise buildings, more specifically three to five storey apartments. For these mid-rise buildings, the design and construction guidelines are not always clear — requirements fall somewhere in between the prescriptive requirements for low-rise buildings as defined in Part IX of the National Building Code of Canada and the general, good design practice, guidelines for high-rise buildings found in Part III and IV of National Building Code.

[1] Energy Efficiency Trends in Canada: Energy Efficiency Indicators, Demand Policy and Analysis Division, NRCan, 1996.

Apartment buildings are notorious for the spread of odours from one suite to another. This is indicative of the quality of the air and the performance of ventilation system in the building. Occupant surveys as well as detailed data collection were combined to characterize the air quality in mid-rise buildings, the results of which can be used in future design decisions.

The purpose of this research project was to collect indoor air quality and energy consumption data on new mid-rise residential buildings in order to help characterize this housing category. The research plan included the development of test and evaluation protocols for indoor environment parameters, energy consumption patterns and ventilation system performance parameters for mid-rise buildings. As part of the field work, a total of eight buildings were chosen for detailed evaluation; four buildings in Vancouver, two in Ottawa and two in Toronto. All the buildings were built in the last five years (1990 or later) to reflect current design and construction practices.

The detailed analysis of energy gain and loss mechanisms in mid-rise apartment buildings presented in this report should be useful to utilities, government agencies, building owners and managers, building consultants and private sector associations, such as Associations of Condominium Managers and Canadian Condominium Managers Association, in developing and implementing energy retrofit strategies. The indoor environment surveys emphasize the need for maintaining human comfort both for the purpose of occupant comfort and for sustaining the rental occupancy.

1.1. OBJECTIVES

The main objective of the study was to evaluate the indoor environment and energy consumption patterns of a selection of typical mid-rise residential buildings.

1.2. APPROACH

The following work tasks were undertaken to meet the project goals:

1) Selection of appropriate sample of 8 mid-rise apartment buildings of which 2 located in Ottawa, 2 located in Toronto and 4 located in Vancouver.
2) Development of a detailed indoor environment survey and energy audit test protocols.
3) Survey of building occupants and maintenance staff for the identification of energy and air quality related issues. A tenant questionnaire was distributed and used to determine which suites were suitable for detailed IAQ testing.
4) The following IAQ measurements were recorded in selected suites:
   - Temperature, relative humidity, CO and CO_2 data logging for a one week period
   - Formaldehyde sampling for a one week period (average concentration)
   - Volatile Organic Compounds sampling for a one week period (TVOC in two suites, GC/MS speciated in a mid-height suite)
   - Air velocity and temperature distributions
   - Ventilation rate (volumetric flow rate of corridor make-up air, corridor air entering the suite through a door, and air flow rates of bathroom and kitchen exhaust fans)
   - Electro Magnetic Field (EMF) strength (instantaneous readings)
   - Average common area lighting levels (instantaneous readings)
   - Visual inspection for fungi, mould and mildew
5) A blower door test was used to assess the airtightness of the building envelope.

6) Information was gathered on building physical and thermal characteristics, occupancy, internal loads and operational schedules for the purpose of creating an energy simulation model of the building. As part of the field survey, verified that the information provided on the building drawings was accurate. Obtained utility billing data and weather data (to match the year(s) of billing data) for the purpose of calibrating the building simulation model.
7) Data analysis was performed for indoor environment parameters. Evaluated the energy use in the building using the DOE-2.1E hourly energy simulations program.

This report presents the findings of the field surveys and energy analysis and provides discussion with regard to the functioning of a sample of eight mid-rise residential buildings.

1.3. REPORT ORGANIZATION

The report provides a brief overview of the calculation method in Section 2. Section 3 provides the results of the indoor environment surveys and Section 4 briefly provides results of energy analyses. Section 5 provides discussion on general trends and common observations. Section 6 provides conclusions and recommendations.

Appendix A-1 to A-8 provide building reports for each test building. Appendix B documents the field test protocols and field survey forms.

2. METHOD

The project involved indoor air quality and energy performance assessments of eight mid-rise multi-residential buildings. The following sections contain an outline of the methods used in evaluating the indoor air quality and energy consumption patterns of eight buildings.

2.1. CONSIDERATIONS

The following aspects were considered for reliably obtaining field data and accurately establishing the IAQ and energy performance of mid-rise multi unit residential buildings:

- *Test protocols.* Development of a detailed indoor air quality audit protocol for conducting uniform IAQ assessments in all buildings. Data gathering forms were prepared for the energy analysis using the DOE-2.1E energy simulation program.
- *Site inspection of buildings:* Each building was visited twice during the audit process.

  The first visit was an initial walk-through audit which provided general information about the building. The initial walk-through was used to become familiar with the overall building, its current use, occupant density, physical form, physical condition, mechanical and electrical systems, and accessibility. This stage of the audit was also used to collect drawings, operational logs, utility bills, and conduct surveys of building maintenance personnel.

  The detailed data collection stage included a systematic inspection and testing of the building physical, thermal, mechanical and electrical systems that affect energy consumption and quality of the indoor environment.
- *Information gathering:* The following information was gathered during the field audit:
  - physical description of the building (dimensions, orientation, etc.);
  - thermal characteristics of building components (insulation levels, solar-optical properties of windows);
  - building operation schedules for various systems (lighting, make-up air, DHW, elevators, appliances, occupancy);
  - building up-keep history for last five years and current conditions;
  - indoor air quality assessments (occupant survey and recording of IAQ parameters);
  - utility bills for at least one year, water consumption profile, and other information; and
  - the weather data for the location.
- *Energy analysis:* A detailed energy analysis was conducted using DOE-2.1E which is an hourly energy simulation model. The energy analysis involved the following aspects:
  1. Determining the base loads: Base loads are generally constant over the year. Base loads include lighting, domestic hot water, suite appliances, laundry appliances, fans and pumps, swimming pool equipment, elevators and other energy consuming equipment in the building.
  2. Performing the heat balance for the building: The heat balance analysis assists in determining the need for purchased energy for space heating to maintain the comfort conditions. The heat balance analysis takes into account the heat gains and heat losses through the building.
  3. Verifying the energy analysis with the actual utility bills: It is important to compare the energy consumption profile with actual utility data for the study period. If the

difference between the model and the actual data is more than 5%, the input data to the energy gain and loss model need to be re-examined and modified.

4. Developing the energy balance for the building: Using the base loads and the heat balance analysis an energy balance sheet is developed to determine various points of energy use in the building.

2.2. TEST PROCEDURES

The information regarding indoor air quality and energy consumption in these apartment buildings was essentially collected in three different steps.

The first step involved the distribution of an occupant survey. The second step involved the physical testing of the indoor environment, both instantaneous readings and the monitoring of the buildings for a period of one week. The third step involved an energy analysis of each building using simulation software, and the comparison of these results with billing data.

Each of these steps is discussed in more detail below.

2.2.1. Indoor Environment

The data collection form developed for this project is presented in Appendix B. Appendix B also contains a completed data collection form for each of the eight buildings, along with supporting documentation where appropriate.

Instantaneous measurements of temperature, relative humidity and carbon dioxide were made during the site visits. These measurements assisted in verifying the data loggers. The measured indoor environment parameters were compared with the requirements of ASHRAE Standard 55-81[2].

- **Occupant Survey:** A questionnaire was distributed to each tenant in each of the eight apartment buildings under investigation. Questions were designed to determine the opinions of the tenants with regard to the performance of the building. Questions pertained to:
  - the performance of the building in terms of indoor air quality, odour control and moisture control;
  - the use of the building including the presence of pets and smokers, and time spent at home; and
  - general health including identification of asthma and allergies.

  The questionnaire, both in English and French, is provided in Appendix B.
- **Carbon Monoxide:** Carbon monoxide (CO) was monitored for the period of one week using instruments such as the 'Toxilog Personal Atmospheric Monitor' by biosystems inc., the 'PhD^2 Multi Gas Detector' by biosystems inc., or the 'STX70 Personal Gas Monitoring Instrument' by Industrial Scientific Corporation. These instruments are capable of storing data. They were placed in or near the living room of the apartments. In each case a location was chosen so as not to interfere with tenant activity while monitoring representative air.
- **Temperature:** Air temperature was monitored in the suites using a YES-203 datalogger[3]. The dataloggers were placed in or near the living room, and left in place for the period of one week. Along with relative humidity and carbon dioxide, temperature was registered at

[2] ASHRAE Standard 55-81, "Thermal Environmental Conditions for Human Occupancy," ASHRAE, Inc., Atlanta, GA.

[3] YES-203 Data Recorder, by Young Environmental Systems Inc. The datalogger records temperature, relative humidity and carbon dioxide.

intervals of between 10 and 15 minutes. In each case, a location for the monitor was chosen so as not to interfere with tenant activity while monitoring representative air. Carbon dioxide levels measured in master bedroom.

- **Relative Humidity:** Relative humidity (RH) was monitored in the suites using a YES-203 datalogger[3]. The dataloggers were placed in or near the living room, and left in place for the period of one week. Along with temperature and carbon dioxide, RH was registered at intervals of between 10 and 15 minutes. In each case, a location for the monitor was chosen so as not to interfere with tenant activity while monitoring representative air.

- **Carbon Dioxide:** Carbon Dioxide (CO_2) was monitored in the suites using a YES-203 datalogger[3]. The dataloggers were placed in or near the living room, and left in place for the period of one week. Along with temperature and relative humidity, CO_2 was monitored at intervals of between 10 and 15 minutes. In each case, a location for the monitor was chosen so as not to interfere with tenant activity while monitoring representative air.

- **Volatile Organic Compounds (VOCs):** In this study, the concentration of total volatile organic compounds (TVOC) was determined in each of the apartments using "badges" that essentially absorb VOCs for subsequent analysis.

  Scanada Consultants purchased monitoring badges from Ortech Corporation. The badges were placed in the apartments for a period of one week and then returned to Ortech for analysis. The amount of contaminant absorbed by the badge is determined and the concentration of TVOC calculated using the amount of time the badge was exposed (the times at which devices are uncapped and recapped are recorded). TVOC results are expressed in units of milligrams of TVOCs per cubic metre (mg/m^3).

  The badges were placed with one of the other monitors in the apartments (formaldehyde, temperature, relative humidity, carbon dioxide or carbon monoxide) for the period of testing.

- **Formaldehyde:** Dosimeters are used to measure the levels of formaldehyde gas. The test-tube-like devices are uncapped and hung in or near the living room. At the end of the test period, for this project, one week, the caps are replaced. The times at which the tubes are uncapped and recapped are recorded for use in the analysis of formaldehyde gas concentrations. The tubes are sent to the lab for analysis. Results are reported in parts per million (ppm).

2.2.2. *Ventilation*

Ventilation was tested in several ways: whole building air leakage tests to determine the airtightness of the building shell and air leakage rates, the measurement of passive tracer sources for the period of one week to determine the effectiveness of air movement, and the instantaneous measurement of air flow from the corridor make-up air units, the exhaust fans in bathrooms and kitchens, and the flow around apartment doors.

- **Air Leakage Tests:** Airtightness was evaluated in each of the buildings using blower door tests, based on the procedure as described in CMHC's report, "Establishing the Protocols for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings"[4] and the CGSB Standard "Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method"[5].

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[4] "Establishing the protocols for measuring air leakage and air flow patterns in high-rise apartment buildings", prepared by R.J. Magee and C.Y. Shaw of National Research Council of Canada for Canada Mortgage and Housing Corporation, Ottawa, Ontario, 1990.

[5] CGSB 149.10 Standard — Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method, Canadian General Standards Board, Ottawa, Ontario.

The number of fans used for depressurization of the whole building varied with size of building. One person per floor was used in each building to "stand watch" while the suite doors were open, and one person operated each fan. Small wood blocks were used to keep each suite door ajar (about 4 inches) and wood/cardboard shims to keep the hallway doors fully open. Retrotec, Minneapolis and Infiltech blower doors were used. Coordination between fan operators was accomplished using phones and walkie talkies.

Pressure readings were taken in 2 to 5 Pa decrements from the maximum pressure that could be achieved (no greater than 60 Pa). Between 7 and 10 readings were obtained for each building. The spreadsheets or data sheets used in the calculation of building air leakage are provided in Appendix B.

- **Passive Sampling Devices for Air Movement Tests:** The Toronto and Vancouver buildings were tested using the system from Brookhaven National Laboratories. The Brookhaven National Laboratory Air Infiltration Measurement System (BNL/AIMS) employs a passive perfluorocarbon tracer (PFT) source and a capillary adsorption tube sampler (CATS)[6]. A time averaged concentration of the tracer is determined, and together with the source rate and the volume of the zone, an average air change rate is calculated. The lowest suite in each building was selected in order to limit the influence of air infiltration from other apartments.

  The tracer source used in these tests was meta-P-dimethylcyclohexane (m-PDCH). In each apartment, the source and the sampler were placed according to instructions provided by BNL. Some degree of error might have occurred since each apartment was considered to be one zone. More accuracy might have been achieved had the bedroom area in each unit been provided with a different tracer source. It is possible that the air change is actually slightly higher than that recorded. It was felt, however, at the initiation of the project, and in consultation with BNL, that one source and one sampler would provide a good indication of the average air change rate in each apartment.

  A similar system to the BNL/AIMS was used in Ottawa buildings (Ottawa 'B' and Ottawa 'R'). The main differences between this procedure and that described previously is that 2 emitters were deployed in each apartment, and three apartments in the building were tested. The emitters were typically placed in the living room and the bedroom, with the sampler in the living room.

- **Corridor Make-Up Air:** The corridor make-up air velocity was measured at the supply grilles on each floor using an instrument such as the TA5 Anemometer by Airflow Developments Limited. A grid pattern was used to measure the air flow at least 8 measurements taken. The volume of air supplied per grille was calculated based on the average air velocity and the free area of the grille opening.

  The air entering the apartment around the corridor door was measured using the same air velocity meter. At least four locations were measured at the bottom of the door and six to eight locations on the sides of the door. In some cases, where the door appeared to have no, or very little, leakage area, measurements were not taken. An average air velocity was determined and combined with the estimated leakage area around the door, resulting in an estimated air flow into the apartment.

- **Kitchen and Bathroom Exhaust Fans:** The kitchen and bathroom exhaust air velocities were measured at the exhaust grilles using an instrument such as the TA5 Anemometer by Airflow Developments Limited. A grid pattern was used to measure the air flow at between eight and sixteen locations each. Average air velocities were measured and the air flow (L/s) was calculated based on the size of the exhaust openings. The effective free area of duct

6 Dietz R.N., "Brookhaven Air Infiltration Measurement System," Brookhaven National Laboratory, Upton, NY 11973, April 1989.

was determined using the method described in the 1993 ASHRAE Handbook of Fundamental[7]. Using the effective free area and the average air velocity, flow rate was determined. In two Ottawa buildings, fan flows were also determined using the CMHC's Duct Test Rig. This is a calibrated apparatus which provides the volumetric flow rate. Air flow measurements compared well with both these methods.

2.2.3. *Electromagnetic Fields (EMFs)*

The test protocol for EMF testing was based on a report prepared for IEEE[8]. Electromagnetic fields were measured in suites using a single axis measuring device, held at waist height, in three different orientations, x, y and z, where x and y are at right angles (device held parallel to the floor), and z is perpendicular. The equation $R=(X^2+Y^2+Z^2)^{1/2}$ is used to determine the resultant magnetic fields. Where possible, EMFs were measured with and without the suite power turned on in order to get the background levels as well as the 'actual' levels.

2.2.4. *Lighting*

Lighting in common areas only was measured for this study using the IES test protocol. A hand-held light meter, such as a General Electric 214 Triple Range Light Meter, was used. Lighting levels were measured to obtain average or typical levels as well as to identify areas of low lighting levels, if any.

2.3. ENERGY CONSUMPTION

The energy analysis was performed using the DOE-2.1E energy simulation program[9]. One of the first steps in energy analysis is to obtain the architectural and mechanical drawings for the building to be simulated. It is important to note that the goal is to create a model of the building in order to analyze thermal energy flows and not to describe in minute detail what the building looks like architecturally. The energy simulation programs (including DOE-2.1E) do *not* attempt to reconstruct the space geometrically from the input data description of the bounding surfaces. Rather, energy analysis program calculates the flow of energy *only through the surfaces which are described* in the input. Therefore, input files should be prepared for the building from an energy perspective rather than from an architectural perspective.

The DOE-2.1E documentation explains the energy simulation methods[10] and procedures for data inputs and evaluation of results[11]. The majority of information required to perform energy analyses of the buildings came from the as-built drawings. This information was complemented and/or confirmed with the completion of the energy audit forms (included as part of the air quality audit forms, see Appendix B) at the time of the site visit.

Information regarding all aspects of a building that affect energy consumption was collected, including information on lighting, occupancy, mechanical equipment and use, domestic hot water equipment and use, and electrical equipment and use, building envelope assembly, building size and building

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7 ASHRAE 1993. 1993 ASHRAE Handbook of Fundamentals. Published by ASHRAE, Inc. Atlanta, Georgia.

8 A Protocol for Spot Measurements of Residential Power Frequency Magnetic Fields, A Report of the IEEE Magnetic Field Task Force of the AC Fields Working Group of the Corona and Field Effects Subcommittee of the Transmission and Distribution Committee. 92 SM 460-6 PWRD, IEEE/PES 1992 Summer Meeting, Seattle. 1992.

9 LBL 1994. DOE-2.1E Energy Simulation Program, Developed by Lawrence Berkeley Laboratory, January 1994.

10 LBL 1994. DOE-2.1E Basics. Developed by LBL and Hirsch & Associates. 1994.

11 PRC-DOE2 Energy Simulation and Analysis Documentation, The Partnership for Resource Conservation, Boulder, Colorado. 1994.

scheduling. Air leakage data from the blower door tests were used in the program as well. The air leakage data obtained from blower door tests were modelled using the single-zone method to determine average normal air changes rates based on temperature difference and average wind speeds. The method was compared using the trace gas air change method for mid-rise apartments.[12]

The time periods used in the simulations varied depending upon the billing data that was available for each building, which was also dependent upon construction and occupancy schedules. Summaries have been used in those instances where individual apartments are metered. Billing data from as many apartments as possible were used to determine the estimated energy consumption for each of these buildings.

The purpose of the energy analyses is to determine what each of the components of each building consumes in terms of energy. Conclusions can then be drawn regarding potential for improvement for each of these components. The results of the analyses are compared with actual billing data for the buildings to ensure that the model is working correctly.

Appendix A provides a detailed evaluation of eight test buildings. Each building report is organized as per the following outline:

1) Description of Field Survey
2) Air Leakage and Ventilation Systems
   - Air Leakage Test
   - Air Change Rate Test
   - Corridor Make-up Air System
   - Kitchen and Bathroom Exhaust Fans
3) Indoor Environment Parameters
   - Occupant Survey
   - Indoor Air Temperature
   - Relative Humidity
   - Carbon Dioxide
   - Carbon Monoxide
   - Electro-Magnetic Fields (EMFs)
   - Volatile Organic Compounds (VOCs)
   - Formaldehyde
   - Lighting Levels
4) Energy Performance of the Building
   - Utility Bills
   - Energy Analysis Results
5) Discussion and Comments

[12] Ontario Hydro 1993. Air Leakage Control Assessment Procedure - Users Manual, Appendix A: Calculation Procedures for Mid-Rise Apartment Buildings, Prepared by Scanada Consultants Limited, Ottawa.

3. SURVEYS OF INDOOR ENVIRONMENT

This section briefly summarizes the indoor air quality indicators detected in the test buildings. The detailed evaluation of indoor air quality measurements for each test building is given in Appendix A. Based on field evaluation, the following discussion is provided to decipher general trends and common observations.

3.1. DESCRIPTION OF TEST BUILDINGS

The project team selected eight mid-rise residential buildings which ranged from 17 to 45 units. Two buildings are located in Ottawa, two in Toronto and four test buildings are located in Vancouver. Table 3-1 shows the detailed characteristics of the test buildings. The following are salient features:

- These test buildings were built during 1990 to 1994.
- The floor levels ranged from 3 to 4 storeys with or without basement level(s).
- The number of units ranged from 17 to 45 units.
- The majority of units were single bedroom units specifically designed for seniors.
- The wood frame construction is a popular choice for mid-rise apartments especially for three to four storey buildings. Six of the buildings had wood-frame construction.
- The glazing area ranged from 18% to 33% of the building wall area.
- Except two buildings, all others had underground parking garages either covering the full or partial area of the building foot print.
- Electric baseboards provide space heating in four buildings while natural gas central hydronic radiators provide the space heating in the other four buildings.
- Seven buildings had corridor make-up air systems. In most of the buildings, the make-up air fans operate continuously.
- The corridor make-up air heating is accomplished using the natural gas in seven buildings while the remainder building did not have any corridor make-up air system.
- The domestic hot water heating is supplied by natural gas central hydronic system in six buildings while the other two buildings have individual electric hot water tanks in units.
- Each unit has a kitchen exhaust fan and a bathroom exhaust fan which can be used by the occupant when needed.
- There was no dedicated suite ventilation systems found in any of these test buildings.
- Three buildings use energy efficient lighting fixtures (T8, compact fluorescent lamps, low-wattage exit signs) in common areas and exterior lighting while the other five buildings have conventional lighting fixtures. The survey showed that conventional lighting fixtures are used by occupants.
- All buildings have common laundry and washing facilities.

Table 3-1: Characteristics of Test Buildings.

			Ottawa 'B'	Ottawa 'R'	Toronto 'L'
1	**Location**		Ottawa	Ottawa	Toronto
2	**Year of Construction**		1990	1991	1991
3	**Number of Floors**		3.5	4	4
4	**Type of Construction**		Wood frame construction. Factory-built modules assembled at the site.	Brick veneer steel studs	Brick veneer steel studs
5	**Type of occupancy**		Family	Seniors/Family	Seniors/Family
6	**Suites**	Bachelor suites		1	
		1-bedroom	12	12	12
		2-bed-room	11	14	17
		3 or more bedroom suites		8	22
		Total	23	35	51
		Underground parking garage	No	Yes	Yes
7	**Dimensions**	Floor area, m2	1,629	2,937	4,301
		Volume, m3	3,788	6,408	10,365
		Exposed building envelope area, m2	1,409	1,919	3,002
		Window area, m2	183	269	879
		Exterior door area, m2	155	88	128
		Percentage of glazing/wall area	24.0%	18.6%	33.5%
8	**Space Heating System**	Main space heating fuel	Electric	Electric	Natural gas
		Type of system	Electric baseboards	Electric baseboards	Central hydronic system
		Operation schedule	Individually thermostat controlled	Individually thermostat controlled	Indoor/outdoor temperature controller and in suite thermostats
9	**Make-up air heating system (Corridor air)**	Type of fuel	None	Natural gas	Natural gas
		Type of system	None	Forced-air corridor system	Forced-air corridor system
		Operation schedule	None	supply air temperature thermostat	supply air temperature thermostat
10	**DHW System**	Type of fuel	Electric	Electric	Natural gas
		Type of system	Individual electric water tank	Individual electric water tank	Central hydronic DHW
		Operation schedule	Thermostat set at 60 °C.	Thermostat set at 60 °C.	Thermostat set at 65 °C.
11	**Ventilation System**	Make-up air system (Corridor air)	None	Forced-air corridors	2 Forced-air; 1,982 L/s and 1,382 L/s
		Suite ventilation	None	None	None
		Kitchen hood fans	Individual fans each rated at 40 L/s	Individual fans each rated at 80 L/s	Individual fans each rated at 40 L/s
		Bathroom exhaust fans	Individual fans each rated at 25 L/s	Individual fans each rated at 25 L/s	Individual fans each rated at 25 L/s
		Garage/service room exhausts	None	Parking garage exhaust fans CO controlled	Parking garage exhaust fans timer controlled - runs @ 12 hrs a day
		Other	Basement corridor has a manually operated exhaust fan (80 L/s).		
12	**Envelope characteristics (Effective values determined using DOE-2.1E calculations)**	Measured airtightness	2.31 L/s.m2 at ΔP of 75 Pa	2.23 L/s.m2 at ΔP of 75 Pa	3.43 L/s.m2 at ΔP of 75 Pa
		Walls	RSI 2.64	RSI 2.14	RSI 2.68
		Roof	RSI 4.54	RSI 3.37	RSI 3.46
		Windows	RSI 0.32	RSI 0.28	RSI 0.22
		Exterior Doors	RSI 0.36	RSI 0.40	RSI 0.48
13	**Lighting System**	Type of common area lights	Compact fluorescent and ee lamps	Conventional lamps	Conventional lamps
		Typical suite lamps	Conventional lamps	Conventional lamps	Conventional lamps
14	**Elevators**	Number	None	2	2
		Type of equipment		Conventional electric	Conventional electric
15	**Appliances**	Common area	Laundry and washing	Laundry and washing	Laundry and washing
		Suites	kitchen + entertainment appliances ,	kitchen + entertainment appliances	kitchen + entertainment appliances
16	**Other comments**		Observed severe window condensation	Found some window condensation	

Table 3-1: Characteristics of Test Buildings.

			Toronto 'S'	Vancouver 'LV'	Vancouver 'MV'
1	Location		Toronto	Vancouver	Vancouver
2	Year of Construction		1994	1992	1993
3	Number of Floors		3	4	3
4	Type of Construction		Wood frame construction.	Wood frame construction.	Wood frame construction.
5	Type of occupancy		Seniors	Seniors	Seniors
6	Suites	Bachelor suites	11		
		1-bedroom	6	45	45
		2-bed-room			
		3 or more bedroom suites			
		Total	17	45	45
		Underground parking garage	Partial	Partial	Partial
7	Dimensions	Floor area, m2	871	3,060	3,268
		Volume, m3	2,601	7,466	7,966
		Exposed building envelope area, m2	890	2,599	2,690
		Window area, m2	142	468	538
		Exterior door area, m2	18	113	99
		Percentage of glazing/wall area	18.0%	22.3%	23.7%
8	Space Heating System	Main space heating fuel	Natural gas	Natural gas	Electricity
		Type of system	Central hydronic system	Central hydronic, radiant floor heating	Electric baseboards
		Operation schedule	Indoor/outdoor temperature controller and in suite thermostats	in suite thermostats	in suite thermostat
9	Make-up air heating system (Corridor air)	Type of fuel	Natural gas	Natural gas	Natural gas
		Type of system	Forced-air corridor system	Forced-air corridor system	Forced-air corridor system
		Operation schedule	supply air temperature thermostat	supply air temperature thermostat	supply air temperature thermostat
10	DHW System	Type of fuel	Natural gas	Natural gas	Natural gas
		Type of system	Central hydronic DHW	Central hydronic DHW	Central hydronic DHW
		Operation schedule	Thermostat set at 60 °C.	Thermostat set at 65 °C.	Thermostat set at 65 °C.
11	Ventilation System	Make-up air system (Corridor air)	1 Forced air fan, 2,500 CFM	Two forced air fans, each 3,800 CFM	Two forced air fans, each 750 CFM
		Suite ventilation	None	None	None
		Kitchen hood fans	Individual fans each rated at 40 L/s	Individual fans each rated at 100 L/s	Individual fans each rated at 100 L/s
		Bathroom exhaust fans	Individual fans each rated at 25 L/s	Individual fans each rated at 100 L/s	Individual fans each rated at 50 L/s
		Garage/service room exhausts	Exhaust fan, 100 CFM	Exhaust fan, 300 CFM	Exhaust fan, 400 CFM
		Other			
12	Envelope characteristics (Effective values determined using DOE-2.1E calculations)	Measured airtightness	3.35 L/s.m2 at ΔP of 75 Pa	3.03 L/s.m2 at ΔP of 75 Pa	3.60 L/s.m2 at ΔP of 75 Pa
		Walls	RSI 2.52	RSI 2.52	RSI 2.62
		Roof	RSI 3.25	RSI 3.25	RSI 3.25
		Windows	RSI 0.30	RSI 0.25	RSI 0.25
		Exterior Doors	RSI 0.60	RSI 0.40	RSI 0.40
13	Lighting System	Type of common area lights	Energy efficient fixtures	Energy efficient fixtures	Conventional fixtures
		Typical suite lamps	Conventional lamps	Conventional lamps	Conventional fixtures
14	Elevators	Number	None	2	2
		Type of equipment		Conventional	Conventional
15	Appliances	Common area	Laundry and washing	Laundry and washing	Laundry and washing
		Suites	kitchen + entertainment appliances	kitchen + entertainment appliances	kitchen + entertainment appliances
16	Other comments				

Table 3-1: Characteristics of Test Buildings.

			Vancouver 'SB'	Vancouver 'W'
1	Location		Vancouver	Vancouver
2	Year of Construction		1993	1993
3	Number of Floors		4	4
4	Type of Construction		Wood frame construction.	Wood frame construction.
5	Type of occupancy		Seniors	Seniors
6	Suites	Bachelor suites		
		1-bedroom	30	36
		2-bed-room		
		3 or more bedroom suites	1	
		Total	31	36
		Underground parking garage	None	Yes
7	Dimensions	Floor area, m2	2,705	2,519
		Volume, m3	6,739	6,138
		Exposed building envelope area, m2	2,409	2.139
		Window area, m2	434	342
		Exterior door area, m2	95	95
		Percentage of glazing/wall area	21.9%	20.4%
8	Space Heating System	Main space heating fuel	Electricity	Natural gas
		Type of system	Electric baseboards	Central hydronic
		Operation schedule	in suite thermostat	in suite thermostats
9	Make-up air heating system (Corridor air)	Type of fuel	Natural gas	Natural gas
		Type of system	Forced-air corridor system	Forced-air corridor system
		Operation schedule	supply air temperature thermostat	supply air temperature thermostat
10	DHW System	Type of fuel	Natural gas	Natural gas
		Type of system	Central hydronic DHW	Central hydronic DHW
		Operation schedule	Thermostat set at 65 °C.	Thermostat set at 65 °C.
11	Ventilation System	Make-up air system (Corridor air)	One forced air fan, 1,500 CFM	Two fans, 2,300 and 2,700 CFM
		Suite ventilation	None	None
		Kitchen hood fans	Individual fans each rated at 80 L/s	Individual fans each rated at 80 L/s
		Bathroom exhaust fans	Individual fans each rated at 50 L/s	Individual fans each rated at 100 L/s
		Garage/service room exhausts		Supply fan for garage lobby 300 CFM, and an exhaust fan, 300 CFM
		Other		
12	Envelope characteristics (Effective values determined using DOE-2.1E calculations)	Measured airtightness	3.58 L/s.m2 at ΔP of 75 Pa	3.49 L/s.m2 at ΔP of 75 Pa
		Walls	RSI 2.52	RSI 2.32
		Roof	RSI 3.25	RSI 3.25
		Windows	RSI 0.25	RSI 0.25
		Exterior Doors	RSI 0.40	RSI 0.40
13	Lighting System	Type of common area lights	Conventional fixtures	Conventional fixtures
		Typical suite lamps	Conventional fixtures	Conventional fixtures
14	Elevators	Number	2	2
		Type of equipment	Conventional	Conventional
15	Appliances	Common area	Laundry and washing	Laundry and washing
		Suites	kitchen + entertainment appliances	kitchen + entertainment appliances
16	Other comments			

3.2. AIR LEAKAGE AND VENTILATION SYSTEMS

3.2.1. Air Leakage Characteristics

The air leakage characteristics of the building envelope was determined using whole building airtightness tests. These airtightness tests were conducted using the test protocol developed by National Research Council for CMHC[13]. The airtightness test results were evaluated using the analytical procedures described in the CGSB Standard 149.10.[14] Table 3-2 and Figure 3-1 shows the air leakage characteristics of buildings. As shown, the air leakage rate ranged from 2.23 L/s.m^2 to 3.60 L/s.m^2 at 75 Pa pressure difference. It is interesting to note that the air change rate per hour at the 50 Pa pressure difference, which is commonly used in describing the airtightness for low-rise residential buildings, did not correlate in a similar fashion as that of the envelope airtightness expressed in terms of a unit envelope area. The AC/hr at 50 Pa pressure difference varied from as low as 1.78 to 4.10 for these buildings.

The measured values of airtightness for various buildings are significantly higher than what can be expected in buildings with properly designed, installed and constructed air barrier systems which should range from as low as 0.3 to 1.7 L/s.m^2 at 75 Pa pressure difference. The 1995 National Building Code suggests a range of 0.05 to 0.15 L/sm^2 at 75 Pa pressure difference. The measured results, however compared well with some of the findings for older apartment buildings. For example, according to a CMHC report[15] average airtightness values for apartment buildings are between 0.68 and 10.9 L/s.m^2 at a pressure difference of 75 Pa across the exterior wall. The wall corners, roof/wall joint, window and wall joints, balcony door frame and wall joints, and basement/ground floor connections seem to be the cause of the poor airtightness in most buildings.

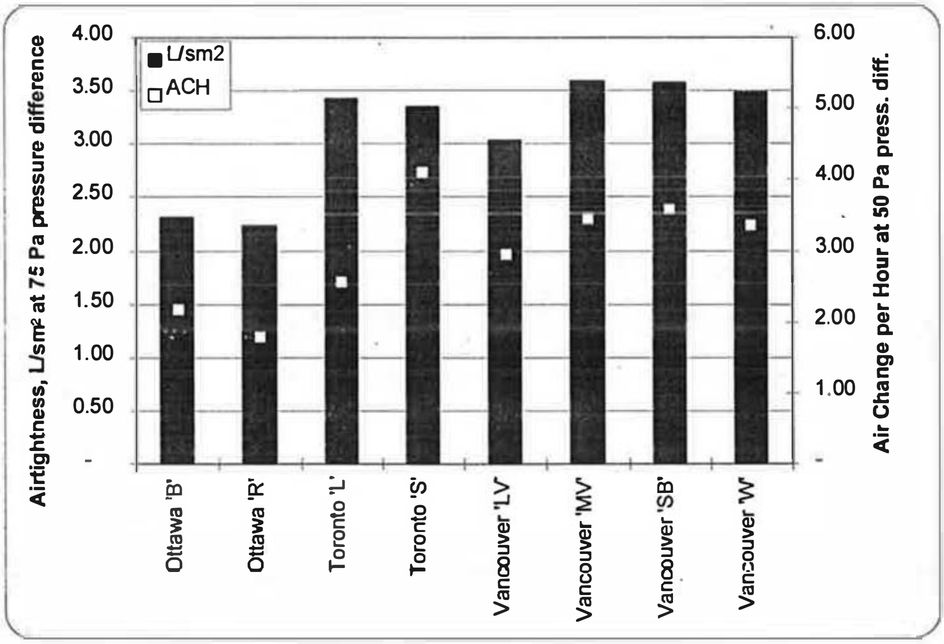

Figure 3-1: Air leakage characteristics of mid-rise buildings.

[13] CMHC 1990. Establishing the protocols for measuring air leakage and air flow patterns in high-rise apartment buildings. Prepared by R.J. Magee and C.Y. Shaw of IRC/NRC for CMHC, Ottawa.

[14] CGSB 1988. CGSB Standard 149.10 (new draft - 1994) — Determination of Airtightness of Building Envelopes by the Fan Depressurization Method, Canadian General Standards Board, Ottawa, Ontario.

[15] "Field Investigation Survey of Airtightness, Air Movement and Indoor Air Quality in High-Rise Apartment Buildings - Summary Report, CMHC, 1993.

Table 3-2: Air leakage characteristics of buildings.

Building	Airtightness of Envelope		Air Change/ hour
	L/sm² at 50 Pa	L/sm² at 75 Pa	at 50 Pa
Ottawa 'B'	1.72	2.31	2.17
Ottawa 'R'	1.65	2.23	1.78
Toronto 'L'	2.45	3.43	2.55
Toronto 'S'	2.56	3.35	4.10
Vancouver 'LV'	2.34	3.03	2.94
Vancouver 'MV'	2.84	3.60	3.45
Vancouver 'SB'	2.78	3.58	3.58
Vancouver 'W'	2.67	3.49	3.35
Average	**2.38**	**3.13**	**2.99**

3.2.2. Air Change Rate Test

The air change rate was determined in three units using the passive sampling devices (PFT) for a period of one week. Table 3-3 shows the normal air change rate measured during the one week period. The air change rate includes effects of both the natural air change due to the air leakage, interzone air movement and the mechanical ventilation in the building. It should be noted that occupants of test units were requested to close windows during the sampling period; however, the results showed that some occupants did not comply with the request.

Table 3-3 presents the measured results of the PFT analysis. Estimations of the air leakage and mechanical ventilation components were determined using the ALCAP method based on measured airtightness data. As shown, in seven buildings the mechanical ventilation rate is lower than what is required by Standards CSA F-326 and ASHRAE 62. The 1990 NBC Part VI refers to CSA F-326 for the ventilation requirements in suites. It should be noted that the requirements in the Standards are for the ventilation rates or air change provided by *intentional* systems such as windows. The air infiltration may vary for individual suites as shown in the table for Ottawa 'B' and Ottawa 'R' building.

Table 3-3: Air change rates based on passive sampling methods.

Building	Unit	Measured	Estimated		Requirements (Normal Air Change Rate)	
		Result (AC/hr)	Air Leakage (AC/hr)	Mechanical (AC/hr)	CSA F-326, (AC/hr)	ASHRAE 62, AC/hr)
Ottawa 'B'	5	0.75	0.63	0.12	0.30	0.35
	15	1.10	0.89	0.21	0.30	0.35
	19	2.04	1.87	0.17	0.30	0.35
Ottawa 'R	106	1.06	0.39	0.67	0.30	0.35
	207	0.60	0.36	0.24	0.30	0.35
	404	0.47	0.37	0.10	0.30	0.35
Toronto 'L'	111	0.71	0.45	0.26	0.30	0.35
	209	0.62	0.42	0.20	0.30	0.35
	405	0.55	0.46	0.09	0.30	0.35
Toronto 'S'	103	1.06	0.80	0.26	0.30	0.35
	205	0.71	0.56	0.15	0.30	0.35
	306	0.86	0.59	0.27	0.30	0.35
Vancouver 'LV	111	0.09	0.35	-0.26	0.30	0.35
Vancouver 'M	112	0.47	0.35	0.12	0.30	0.35
	217	0.55	0.32	0.23	0.30	0.35
	304	0.62	0.36	0.26	0.30	0.35
Vancouver 'SB	203	0.75	0.60	0.15	0.30	0.35
Vancouver 'W'	203	1.00	0.66	0.34	0.30	0.35
	306	0.91	0.46	0.45	0.30	0.35
	403	0.72	0.41	0.31	0.30	0.35

* Ottawa 'B' Unit 19: It seems that occupants kept the window opened during the test period.

** Vancouver 'LV' Unit 111: The PFT concentration was significantly higher than the other buildings (almost ten-fold higher) which means that the ventilation rate was almost ten-fold lower. It is felt that the results for this building may not be accurate due, perhaps, to contamination of the sampler by the source either prior to or after the test period.

3.2.3. Corridor Make-Up Air

The purpose of the measurements of the corridor make-up air flows were to determine the performance of make-up air ventilation systems. In measuring the flow of the corridor make-up air, grilles were left as found; that is, if they were partially closed, they were left that way. The required make-up air listed in the table below is the ventilation capacity as stated on the mechanical drawings or capacity of fans noted from the field survey.

As shown in Table 3-4 and Figure 3-2, the make-up ventilation system provided the necessary air flows to corridors. Review of building drawings showed that the design capacity was generally based on 20 to 80 L/s per suite. For one bedroom units, the design capacity is about 20 to 25 L/s and 40 to 80 L/s per suite for more than one-bedroom suites. Measured air flows showed that in some buildings, the make-up air system needs balancing. The measured results showed that systems provided 55% to 99% of the rated capacity in the buildings. It is suspected that the unaccounted air flow capacity is either lost in distribution system or the fan capacity has reduced.

Table 3-4: Measurements of corridor make-up air.

Building	Floor	Measured Air Flow (L/s)	Required by Designer (L/s)	Percentage of Capacity
Ottawa 'B'*	bsm't	n/a	none	
	2nd	n/a	none	
	3rd	n/a	none	
Ottawa 'R'	1st	440	526	84%
	2nd	223	526	42%
	3rd	640	526	122%
	4th	440	526	84%
Toronto 'L' **	1st	606	826	73%
	2nd	677	826	82%
	3rd	521	826	63%
	4th	716	826	87%
Toronto 'S' **	1st	255	393	65%
	2nd	280	393	71%
	3rd	295	393	75%
Vancouver 'LV' **	1st	450	897	50%
	2nd	479	897	53%
	3rd	602	897	67%
	4th	634	897	71%
Vancouver 'MV' **	1st	381	315	121%
	2nd	291	315	92%
	3rd	180	315	57%
Vancouver 'SB' **	1st	35	177	20%
	2nd	174	177	98%
	3rd	70	177	40%
	4th	111	177	63%
Vancouver 'W' ***	1st	618	400	155%
	2nd	586	645	91%
	3rd	611	645	95%
	4th	508	645	79%
	garage lobby	118	142	83%

* Corridor male-up not required by designer as well as not installed.

** The drawings indicate capacity of the ventilation equipment, which has been divided equally between the floors.

*** The drawings indicate design air flow per floor.

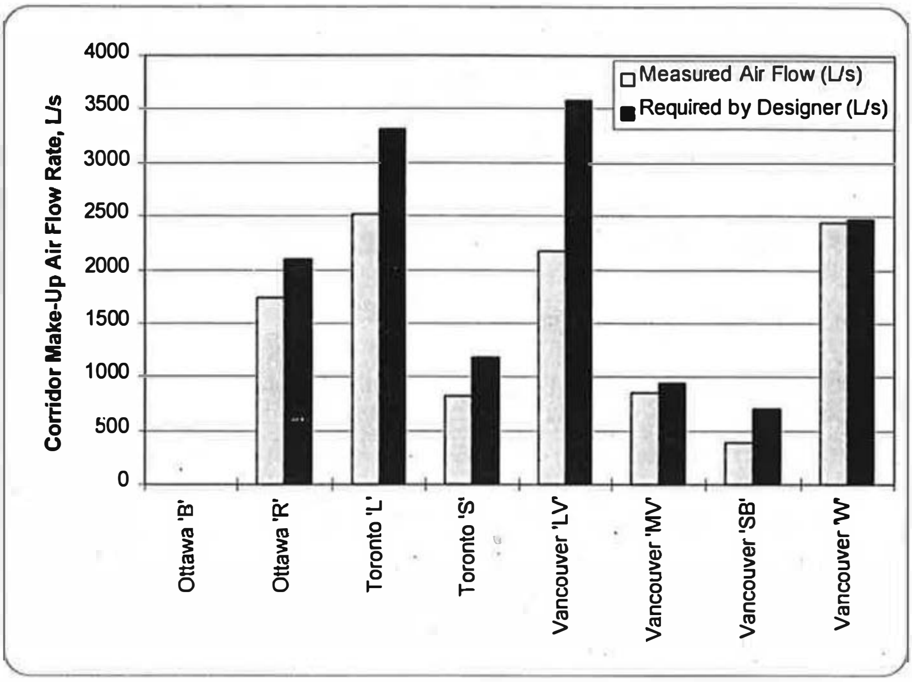

Figure 3-2: Performance of corridor make-up air system in mid-rise buildings.

Table 3-5: Air supply to suites from the apartment doorway.

Building	Unit	Flow (L/s)	Required Air Supply as per F-326 (L/s)
Ottawa 'B'	5	0	25
	15	0	25
	19	0	30
Ottawa 'R'	106	17	35
	207	18	35
	404	13	25
Toronto 'L'	111	13	30
	209	20	30
	405	17	35
Toronto 'S'	103	19	25
	205	27	25
	306	15	20
Vancouver 'LV'	111	1	25
	301	1	25
	404	0	25
Vancouver 'MV'	112	7	25
	217	9	25
	304	6	25
Vancouver 'SB'	203	5	25
	304	5	25
	403	0	25
Vancouver 'W'	203	1	25
	306	13	25
	403	0	25

The measured air flow around each of the apartment corridor doors is presented in Table 3-5. The required air flow is calculated based on the requirements in Standard F326 as determined by specific room requirements[16] (e.g., living rooms require 5 L/s, master bedrooms require 10 L/s, etc.). It is difficult to measure the gap area around the apartment door; however, these areas have been calculated as carefully as possible.

It should be noted that in several buildings, the suite door leading to the corridor is weatherstripped. These units had negligible air flows through the apartment door.

3.2.4. Kitchen and Bathroom Exhaust Fans

The air flow rates were measured for kitchen and bathroom exhaust fans in the test units. Table 3-6 shows the measured air flows of kitchen and bathroom fans in test units. As per the Standard F-326, the kitchen fan should have a minimum designed capacity of 50 L/s and bathroom fan with 25 L/s. In some units the air flow rates through kitchen and bathroom fans exceeded the minimum requirements. In some cases, although the design capacity of fans was higher than what is required, the fans were significantly handicapped in meeting the minimum requirements. The reason for the under-performance of these fans was not investigated due to the scope and nature of the present study.

Table 3-6: Performance of kitchen and bathroom exhaust fans.

Building	Unit	Kitchen		Bathroom
		Flow (High) (L/s)	Flow (Low) (L/s)	Flow (L/s)
Ottawa 'B'	5	6	n/a	7
	15	8	n/a	6
	19	9.5	n/a	7.5
Ottawa 'R'	106	51	n/a	16
	207	67	n/a	12
	404	35	n/a	18
Toronto 'L'	111	24		16
	209	15		12
	405	27		20
Toronto 'S'	103	19		16
	205	35	33	21
	306			23
Vancouver 'LV'	111	75	56	79
	301	86	58	79
	404	91	67	108
Vancouver 'MV'	112	141	73	41
	217	n/a	n/a	62
	304	101	72	52
Vancouver 'SB'	203	86	53	88
	304	86	68	76
	403	89	65	80
Vancouver 'W'	203	62	56	78
	306	72	52	71
	403	73	61	88

[16] CAN/CSA-F326-M91. "Residential Mechanical Ventilation Requirements," Table 1, Published by Canadian Standards Association.

3.3. INDOOR ENVIRONMENT PARAMETERS

The indoor environment surveys were conducted in each building. Indoor air quality samplers were placed in three representative occupied units in the building. Appendix B provides details of field test protocols and the criteria used in selecting the test units in the building.

3.3.1. Occupant Survey

A questionnaire was distributed to each tenant in each of the eight apartment buildings under investigation. Questions were designed to determine the opinions of the tenants with regard to the performance of the building and status of the indoor air quality. The sample questionnaire, both in English and French, is provided in Appendix B. Questions pertained to:

1) the performance of the building in terms of indoor air quality, odour and moisture control;
2) the use of the building including the presence of pets and smokers, and time spent at home; and
3) general health including identification of asthma and allergies.

The survey questionnaire was distributed to all 284 apartments in eight buildings. Completed survey forms were returned by 170 tenants. The response rate ranged from 20% to 94% and averaged at about 60% as shown in Table 3-7.

Table 3-7: Questionnaire Response Rate

Building	Total # Units	# Responses	Response Rate (%)
Ottawa 'B'	23	11	48%
Ottawa 'R'	35	19	54%
Toronto 'L'	51	10	20%
Toronto 'S'	17	13	76%
Vancouver 'LV'	47	25	53%
Vancouver 'MV'	45	30	67%
Vancouver 'SB'	30	28	93%
Vancouver 'W'	36	34	94%
Total	**284**	**170**	**60%**

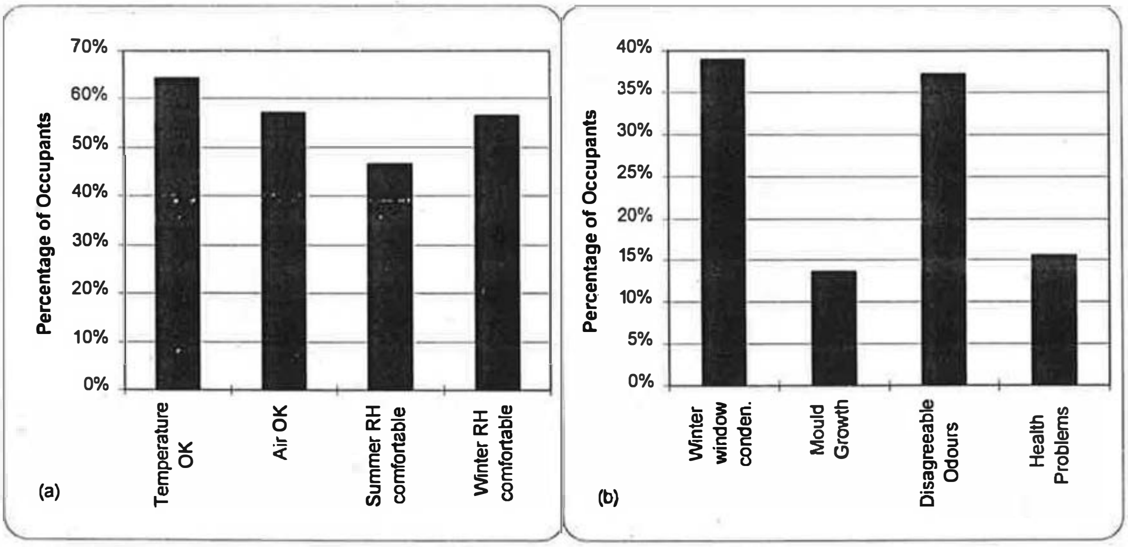

Figure 3-3: Occupant responses: (a) reply to temperature and RH parameters, and (b) reply to comfort criteria.

Table 3-8: Summary of Tenant Surveys

	Ottawa 'B'	Ottawa 'R'	Toronto 'L'	Toronto 'S'	Vancouver 'LV'	Vancouver 'MV'	Vancouver 'SB'	Vancouver 'W'
Temperature OK	**27%**	**47%**	**80%**	**54%**	**68%**	**93%**	**50%**	**59%**
too hot	9%	0%	10%	23%	4%	3%	4%	29%
too cold	0%	21%	0%	0%	4%	3%	4%	0%
inconsistent	64%	21%	10%	23%	12%	0%	43%	15%
Air OK	**27%**	**58%**	**50%**	**69%**	**44%**	**97%**	**57%**	**47%**
stale	0%	16%	10%	8%	12%	0%	21%	21%
stuffy	55%	26%	30%	15%	36%	0%	11%	29%
drafty	18%	5%	10%	0%	4%	3%	7%	6%
Summer RH comfortable	**18%**	**32%**	**20%**	**46%**	**48%**	**90%**	**61%**	**50%**
too dry	9%	5%	10%	8%	20%	10%	21%	21%
too humid	73%	53%	60%	15%	24%	0%	11%	24%
Winter RH comfortable	**27%**	**42%**	**50%**	**46%**	**72%**	**73%**	**54%**	**65%**
too dry	18%	16%	50%	46%	12%	17%	29%	29%
too humid	55%	42%	0%	0%	12%	7%	11%	3%
Tenants with								
Winter window condensation	91%	84%	80%	8%	4%	10%	21%	15%
Mould Growth	45%	26%	20%	0%	4%	7%	14%	0%
Disagreeable Odours	91%	53%	40%	31%	20%	13%	32%	44%
Health Problems attributed to building	9%	16%	30%	31%	16%	7%	4%	12%
Use of a Humidifier								
Never	**55%**	**37%**	**60%**	**85%**	**88%**	**70%**	**79%**	**85%**
Occasionally	27%	26%	30%	15%	8%	23%	18%	12%
At night	9%	0%	10%	0%	0%	0%	0%	0%
Frequently	9%	32%	0%	0%	0%	7%	4%	3%
Use of kitchen exhaust								
Never	0%	5%	0%	0%	8%	7%	4%	3%
Only when cooking	73%	95%	80%	100%	64%	83%	89%	85%
Frequently	27%	0%	20%	0%	28%	7%	7%	12%
Use of bathroom exhaust								
Never	0%	5%	0%	0%	16%	10%	14%	3%
Occasionally	27%	0%	60%	46%	36%	47%	50%	50%
Frequently	73%	5%	40%	46%	44%	37%	32%	44%
On with the lights	0%	89%	0%	8%	4%	3%	4%	3%

Please note that the total sum of percentage may not add to 100% due to non response of some questions by occupants.

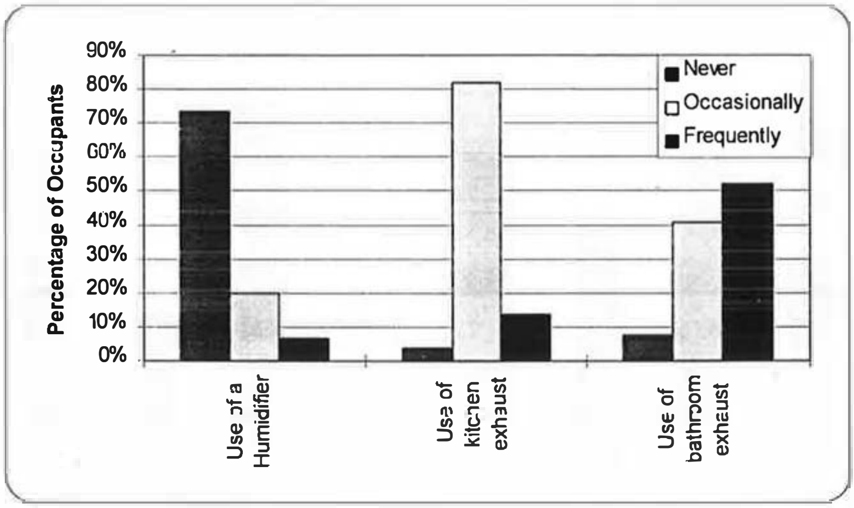

Figure 3-4: Responses of occupants with regard to the use of common exhaust and humidification issues.

Table 3-8 shows the detailed summary of responses received from tenants with regard to indoor air quality parameters in each building. Figure 3-3 and Figure 3-4 show the summary of responses with regard to indoor environment in the building. The general trends were as follows:

- *Indoor air temperature:* About 64% of occupants felt that indoor temperature was acceptable. From building to building, the occupant response for acceptable air temperature ranged from 27% to 93%.
- *Perceptions for general quality of air in the building:* About 57% of occupants felt that quality of indoor air was acceptable. From building to building, the occupant response for acceptable air quality ranged from 27% to 97%.
- *Relative humidity during summer months:* About 47% of occupants felt that RH level during summer months was acceptable. From building to building, the occupant response for acceptable levels of RH ranged from 18% to 90%.
- *Relative humidity during winter months:* About 57% of occupants felt that RH level during winter months was acceptable. From building to building, the occupant response for acceptable levels of RH ranged from 27% to 73%.
- *Problems of window condensation in the building:* About 39% of occupants complained about window condensation mostly during heating season. From building to building, the occupant complaints for window condensation ranged from 4% to 91%.
- *Problems of mold growth in the building:* About 14% of occupants reported mold growth in suites. From building to building, the occupant complaints for mold growth ranged from none to 45%. It is interesting to note that mold growth complaints were higher where the winter RH levels were also significantly high.
- *Complaints of disagreeable odours in the building:* About 37% of occupants complained about disagreeable odours. From building to building, the occupant complaints for odours ranged from 13% to 91%. The response to the question did not correlate the response to a question pertaining to general quality of air in the building.
- *Attribution of building indoor environment to health problems:* About 16% of tenants reported that their poor health symptoms were due to indoor air quality in the building. From building to building, the occupant complaints regarding the health problems related to indoor air quality ranged from 4% to 31%. Most tenants, however, did not respond to questions pertaining to specific health symptoms.
- *Use of humidifier:* About 74% of occupants never used humidifiers and the remaining may have used humidifier sometimes. The use of humidifier was prominent in buildings providing seniors accommodation.
- *Use of kitchen exhaust fans:* About 82% of occupants did use kitchen fans while cooking, and about 4% never used any kitchen exhaust fan.
- *Use of bathroom exhaust fans:* About 41% of occupants did use bathroom exhaust fans while using bathrooms, and about 8% never used any bathroom exhaust fan.

The occupant survey revealed that a significant portion of tenants did not find indoor air quality acceptable to their liking. The use of occupant-controlled exhaust fans was also low in many buildings. It seems that ventilation and air movements were major causes of occupant discomfort.

3.3.2. *Indoor Air Temperature*

Indoor air temperatures were measured in three test units in each apartment building. The continuous data loggers were set to record indoor air temperature at 10 minutes intervals for a period of seven to ten days. Figure 3-5 shows ranges of indoor air temperature in test suites. As shown in this graph, the indoor air temperature varied from as low as 15.5 °C in an apartment unit to 28.7 °C in another. In each suite, the variation in indoor air temperature ranged from 2.2 °C to 8 °C.

According to ASHRAE Standard 55-1992[17], the indoor air temperature should be 21 to 24.5 °C during winter months, and 22.5 to 26 °C during summer months. This requirement is based criteria that 80% of the occupants will be satisfied with such comfort conditions. Figure 3-5 shows that in most units, the indoor air temperature remained within the comfort zone.

Table 3-9 shows a list of identifiers of suite numbers for each building. This list of identifiers is used in subsequent analysis of other parameters.

Table 3-9: Identification tags for buildings and units.

Building	Unit Number	Identification Tag
Ottawa 'B'	5	OB-5
	15	OB-15
	19	OB-19
Ottawa 'R'	106	OR-106
	207	OR-207
	404	OR-404
Toronto 'L'	111	TL-111
	209	TL-209
	405	TL-405
Toronto 'S'	103	TS-103
	205	TS-205
	306	TS-306
Vancouver 'LV'	111	VLV-111
	301	VLV-301
	404	VLV-404
Vancouver 'MV'	112	VMV-112
	217	VMV-217
	304	VMV-304
Vancouver 'SB'	203	VSB-203
	304	VSB-304
	403	VSB-403
Vancouver 'W'	203	VW-203
	306	VW-306
	403	VW-403

3.3.3. *Relative Humidity*

Relative humidity measurements were taken in three test units in each apartment building. The continuous data loggers were set to record RH values every 10 min interval for a period of seven to ten days. Figure 3-6 shows ranges of relative humidity in the test suites. As shown in this graph, the relative humidity varied from as low as 8% in an apartment unit to 61% in another. In each suite, the variation in RH ranged from 10% to 40%.

According to ASHRAE Standard 55-1992[17], the indoor RH should be 20% to 40% during winter months, and 40 to 60% during summer months. Figure 3-6 shows that in buildings located in Ontario, the indoor relative humidity remained below the acceptable range. Indoor air was found to

[17] ASHRAE 1992. "Thermal Environmental Conditions for Human Occupancy," ASHRAE Standard 55-1992. Published by ASHRAE.

be too dry in Ontario buildings. The RH levels in Vancouver buildings were found to be within acceptable limits.

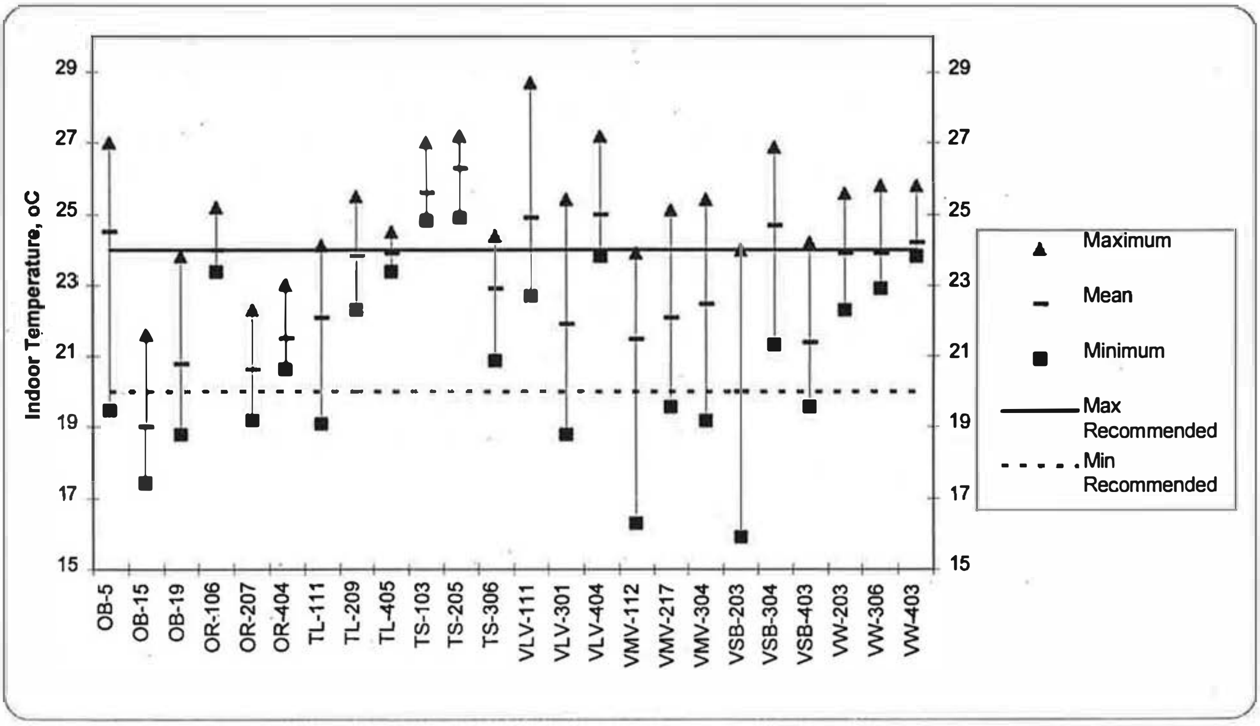

Figure 3-5: Range of variations in indoor air temperature in test apartments.

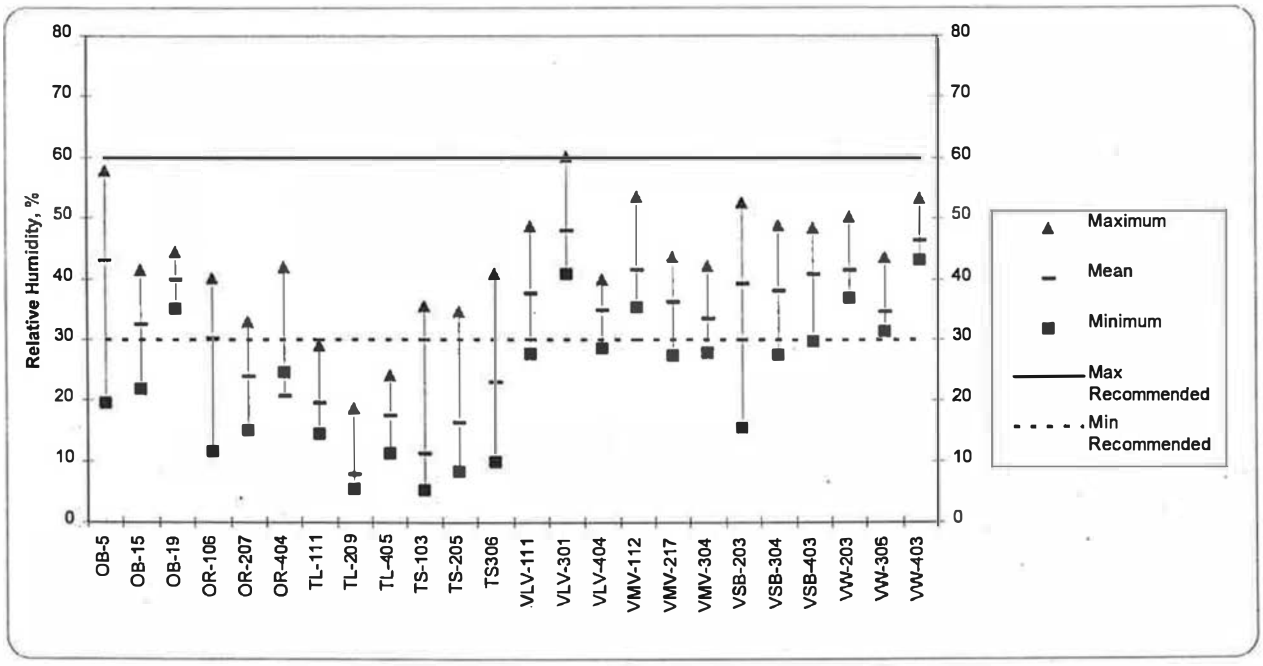

Figure 3-6: Range of variations in indoor relative humidity in test apartments.

3.3.4. Carbon Dioxide

The carbon dioxide readings were taken in three suites in each building for a period of seven to ten days using a continuous data logger. Data was collected at a 10 minutes interval. Figure 3-7 shows a range of carbon dioxide levels measured in test units.

The measured readings were compared with two Standards. The ASHRAE Standard 62-1989 stipulates that the CO_2 levels must be below 1,000 ppm for maintaining human comfort.[18] Except for the buildings located in Ottawa, the majority of other buildings had CO_2 levels substantially lower than 1,000 ppm. This graph also shows the maximum limit set by Health Canada at 3,500 ppm. In one unit (OB-15), high levels of CO_2 were measured which might be due to higher levels of occupancy and lack of ventilation and air leakage. It is also interesting to see that the mean value of CO_2 over the monitoring period exceeded the acceptable levels of 1,000 ppm while in the other 20 units, the mean values of CO_2 were substantially lower than the acceptable set value. The instantaneous measurements of outdoor CO_2 levels ranged from 230 to 425 ppm.

A comparison showed that CO_2 levels were high in those units where ventilation flow rates (corridor air, and bathroom and kitchen exhausts) were significantly low. Ventilation and air movement plays an important role in removing metabolic pollutants.

3.3.5. Carbon Monoxide

The carbon monoxide readings were taken in three suites in each building for a period of seven to ten days using a continuous data logger. Data was collected at a 10 minutes interval. Figure 3-8 shows the maximum reading of carbon monoxide level measured in test units.

The measured readings were compared with the Health Canada guidelines. The guidelines suggests a permissible exposure limit of 25 ppm for one hour period and average 11 ppm over 8 hour period. In all buildings, the maximum value of CO levels ranged from negligible to about 7 ppm.

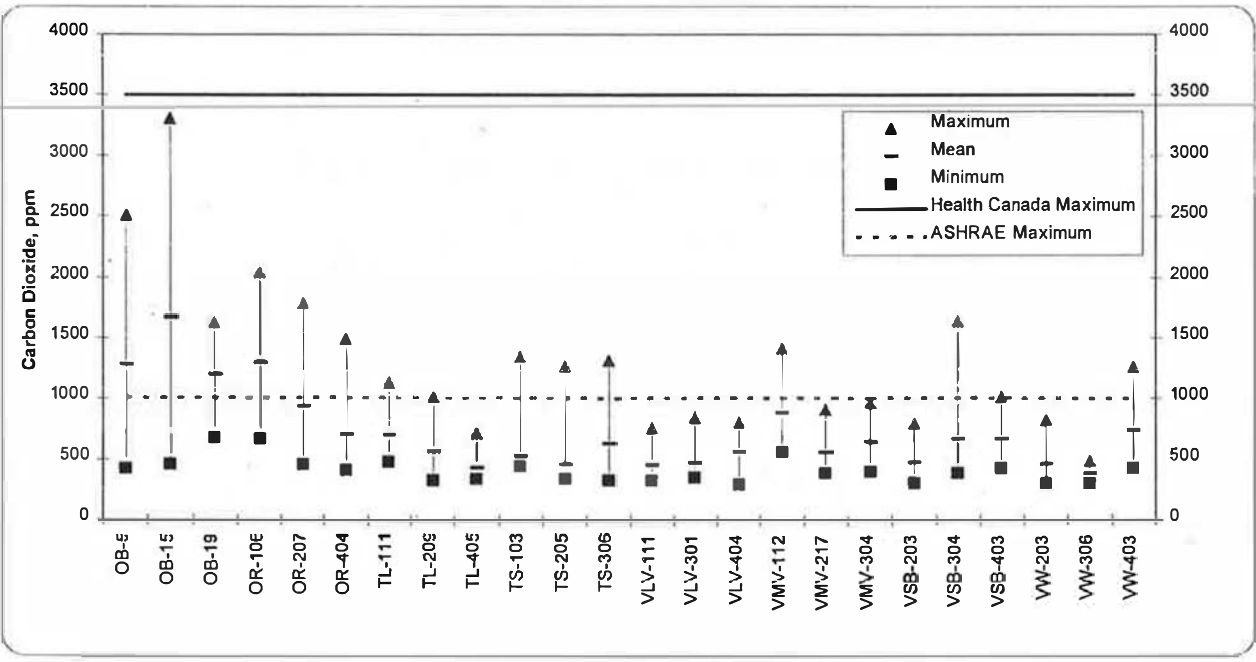

Figure 3-7: Range of variations in indoor carbon dioxide levels in test apartments.

[18] ASHRAE 1989. "Ventilation for Acceptable Indoor Air Quality," ASHRAE Standard 62-1989. Published by ASHRAE.

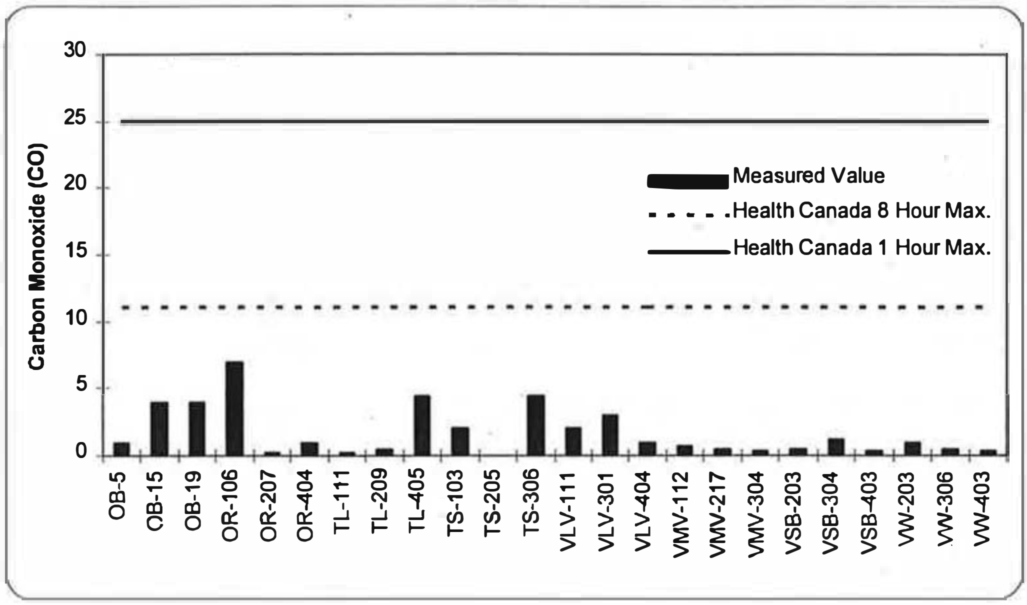

Figure 3-8: Maximum levels of carbon monoxide readings measured in test units.

3.3.6. *Formaldehyde*

Two AQR dosimeters were placed in 3 apartment units for a period of seven days in each building to measure the formaldehyde concentration. As shown in Figure 3-9, formaldehyde concentration ranged from 0.01 ppm to 0.06 ppm in the test units. The formaldehyde levels were significantly lower than acceptable upper limit of 0.05 ppm suggested by Health Canada. Health Canada guidelines also suggests an action level of 0.10 ppm at which one should implement remedial measures. In three test units, formaldehyde levels were more than 0.05 ppm. Higher values of formaldehyde were noticed in units with low ventilation flow rates.

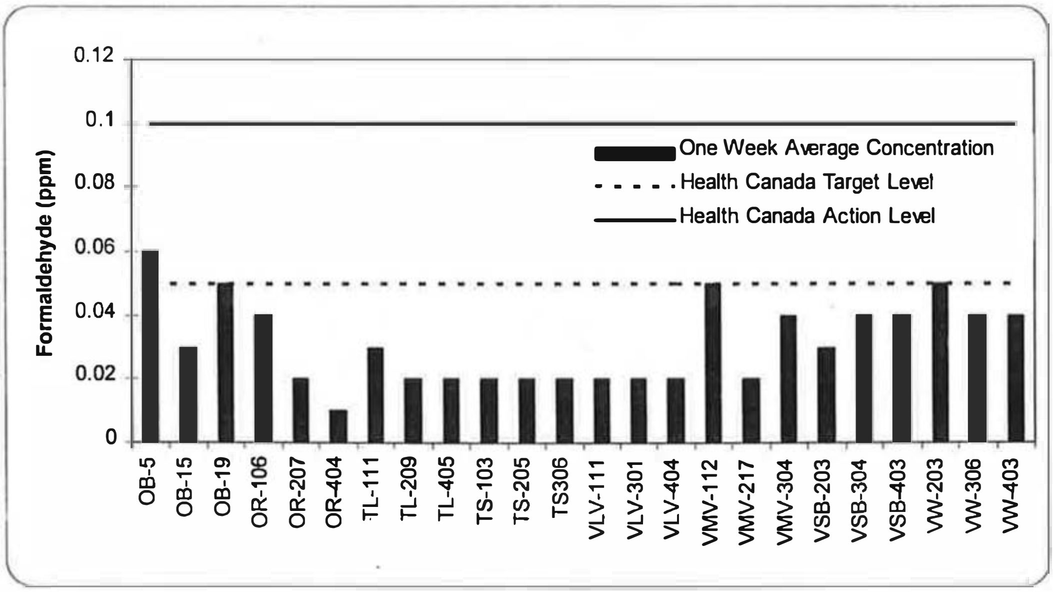

Figure 3-9: Measurements of formaldehyde concentrations in test units.

3.3.7. Volatile Organic Compounds (VOCs)

The VOCs were sampled in three apartment units for a period of one week in each building. The apartment in each building with the highest TVOC was chosen for further analysis. The VOC badges from these units were also analyzed to determine the concentration of the following target compounds.[19]

n-hexane	α-pinene	m-xylene	hexachloroethane
dichloromethane	tetrachloroethylene	o-xylene	p-dichlorobenzene
benzene	toluene	d-limonene	1,1,2,2-tetrachloroethane
n-decane	1,2-dichloroethane	1,3,5-trimethylbenzene	1,2,4-trichlorobenzene
trichloroethylene	ethylbenzene	m-dichlorobenzene	naphthalene
chloroform	p-xylene	pentachloroethane	

Table 3-10 and Figure 3-10 show the measurements of volatile organic compounds. As shown in the figure, the TVOC concentration ranges from almost negligible to about 0.72 mg/m^3 in apartments. As shown in the figure, the TVOC levels were significantly lower than targets set by various Standards and guidelines.

In Ottawa 'B' building TVOC testing was conducted two times. First test was conducted in April 1995 which showed the TVOC level of 2.21 mg/m^3. Subsequent testing for TVOC in April 1996 showed the TVOC value of 0.72 mg/m^3. Outdoor environmental conditions and emission rates from building materials may well have influenced the readings of TVOC.

Table 3-10: Target Volatile Organic Compounds (VOCs)

Building	Unit	Target Compound	Result (mg/m^3)
Ottawa 'B'	15	x-pinene d-limonene	0.16 0.47
Ottawa 'R'	404	chloroform benzene toluene perchloroethylene ethyl benzene m-p xylenes oxylenes styrene dichlorobenzene d-limonine hexane 1,2,4 trimethylbenzene	0.002 0.070 0.27 0.001 0.024 0.078 0.030 0.002 0.001 0.38 0.071 0.026
Toronto 'L'	111	benzene toluene ethylbenzene m-p xylenes o-xylenes dichlorobenzene d-limonene	0.006 0.015 0.001 0.004 0.001 0.013 0.054
Toronto 'S'	206	all	too low for individual detection
Vancouver 'LV'	111	toluene xylenes benzenes	too low for individual detection
Vancouver 'MV'	112	all	too low for individual detection
Vancouver 'SB'	304	all	too low for individual detection
Vancouver 'W'	203	all	too low for individual detection

[19] Conversion factor: mg/m^3 = atomic mass/24 * ppm

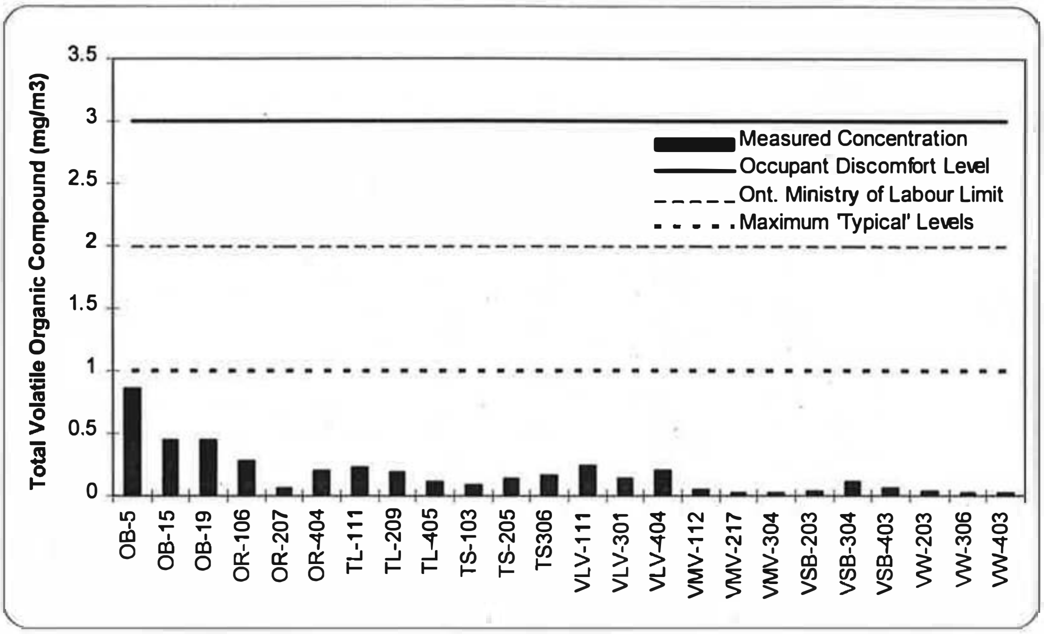

Figure 3-10: Measurements of TVOCs in test units. Maximum typical level for residential occupancy is suggested by CMHC.

3.3.8. *Electromagnetic Fields (EMFs)*

Instantaneous readings of electro magnetic fields were taken using the standard protocol suggested by Ontario Hydro. Measurements of EMFs were taken in the middle of each of the rooms listed in the Table 3-11 below. Note that "with" means with the suite power as found, and "without" means that the suite power was turned off.

There are no agreed set limits for EMF emissions. Ontario Hydro recommends a level up to 20 milligauss near the equipment and about 8 milligauss at 0.3 m away from the source. A recent Swedish study suggested health risks at 3 milligauss of EMF in residential occupancies. Table 3-11 shows that EMF values were much lower than 20 milligauss and few readings were more than 3 milligauss.

3.3.9. *Lighting Levels*

Lighting levels were measured in common areas and corridors. Table 3-12 summarizes the average levels of lighting in the building. Lighting levels were measured using a hand held light meter. The measured lighting levels were compared with the recommended good practices as defined in Ontario Hydro's Energy Manual Fundamentals[20]. The lighting levels were also consistent with OBC 1990 and 1990 NBC. Comparison showed that lighting levels were adequate in most cases. It was also observed that the outside lighting was controlled by photo-cells or time clocks in all buildings.

[20] Ontario Hydro 1987. Ontario Hydro Commercial Electric Energy Manual Fundamentals and Applications, Chapter 16, Ontario Hydro, 1987.

Table 3-11: Measurements of Electro Magnetic Field in Apartment Units.

		Living Room (milligauss)		Master Bedroom (milligauss)		Kitchen (milligauss)		Bathroom (milligauss)	
Building	Unit	with	without	with	without	with	without	with	without
Ottawa 'B'	5	1.18				1.19			
	15	1.67	1.41						
	19	4.38	3.4			3.78	3.01		
Ottawa 'R'	106	1.52		1.6		1.62			
	207	1.92	1.08					3.00	2.27
	404	1.5	0.49						
Toronto 'L'	111	1.64		1.27		4.31		8.45	
	209	1.01		0.9		1.12		1.02	
	405	0.74		0.47		1.34		0.34	
Toronto 'S'	103	2.09		2.13		2.14		2.08	
	205	2.88*		2.44		2.75		2.34	
	306	2.13		1.68		1.42		2.16	
Vancouver 'LV'	111	2.21	2.2	2.2	2.38	2.02	1.92	2.19	2.07
	301	0.22	0.25	0.2	0.27	0.26	0.19	0.34	0.27
	404	0.78	0.31	0.36	0.35	0.64	0.6	0.46	0.38
Vancouver 'MV'	112	0.71**	0.47	0.52	0.52	0.43	0.43	0.42	0.43
	217	0.39**	0.36	0.64	0.37	0.82	0.57	0.42	0.36
	304	0.34	0.33	0.33	0.35	0.46	0.31	0.29	0.33
Vancouver 'SB'	203	1.44	1.41	1.28	1.21	1.19	1.3	1.57	1.41
	304	1.05	1.06	0.88	0.81	0.76	0.74	0.47	0.58
	403	1.12	1.07	1.02	1.03	1.22	0.83	2.19	0.94
Vancouver 'W'	203	0.45	0.33	0.66	0.5	0.38	0.22	0.29	0.21
	306	0.43	0.32	0.52	0.52	0.82	0.45	0.45	0.45
	403	0.24	0.35	0.37	0.29	1.11	0.4	0.35	0.24

* Baseboard heater on. ** TV on

Table 3-12: Lighting levels in apartment buildings.

Building	Lighting Level (Foot-candles)						
	Corridors	Front Lobby	Elevators	Elevator Lobbies	Stairwells	Laundry Room	Rec. Room
Ottawa 'B'	12	8	none	none	32	none	none
Ottawa 'R'	10	10	30	10	40	35	20
Toronto 'L'	11-90		20	7-80			
Toronto 'S'	5-20	10	none	none	22	20-55	5-50
Vancouver 'LV'	2	6	20	3	50	170	
Vancouver 'MV'	1.5	6	6	1.5	12-50	50	25
Vancouver 'SB'	3	12-25	25	12	12	50	12
Vancouver 'W'	6-12	3	25	3	3-25	50	6
Good practices	**9-14**	**9-14**	**10-15**	**10-15**	**15-25**	**30-50**	**50-75**

The lighting levels in the front lobbies, stairwells, laundry rooms and recreation rooms were not measured in Toronto 'L' since they all had large windows and the lighting levels were those of the exterior and not the installed artificial lights.

conversion factor: 1 foot-candle = 10.76 lux

4. ENERGY ANALYSIS

The energy consumption in each of the buildings was simulated using the DOE-2.1E program[9], and reconciled, where possible, to the billing data. The following items summarizes energy analysis procedure:

- Building Description: Input data files were prepared using the building description, field audits, and architectural and mechanical drawings. For generating the input files, buildings were described on the basis of energy flow perspective rather than from an architectural perspective. Thermal zones were defined as follows:
  - at least four external zones (one for each exposure) per floor; and
  - at least one internal zone (central core, elevators and corridors) per floor.

  The above classification of thermal zones also separated the types of heating and ventilation systems for multi-unit residential buildings.
- Field Data: The field survey provided the data on the performance of make-up air systems, and kitchen and bathroom exhaust systems. Operation schedules for the make-up air system, exhaust fans, elevators and DHW system were obtained during the site visit. Occupancy profiles were estimated based on the type and number of occupants in each building.
- Weather Data: Annual hourly weather data for the location were obtained from Atmospheric Environment Services Branch of Environment Canada.
- Utility Bills: Utility bills were obtained from building managers for a period of one to two years. Utility bills were used to determine the monthly and annual energy consumption patterns of each building.

Results from the energy simulations are provided for each test building in Appendix A.

4.1. ENERGY USE IN BUILDINGS

Utility bills were used for determining the energy use profiles in each test building. Table 4-1 shows the summary of energy use in buildings. As shown in the table, the annual total energy use ranges from 146 to 263.2 kWh/m^2 of floor space. Figure 4-1 graphically presents the comparison of energy use and energy costs for each building.

The average unit costs of electricity and natural gas are given in Table 4-2. It should be noted that the average unit cost includes the fuel supply charges, rental charges and Goods and Service Tax (GST). The average unit cost; however, do not include the payment penalty or interest charges. In effect, the cost of energy is what the building owner will pay for. The equivalent cost of natural gas is about two to four times lower than electricity costs. The difference in fuel costs affects the annual energy costs in the building. As shown in Table 4-1, the annual cost of energy used in the buildings ranges from \$6.76/m^2 to \$20.05/m^2 with an average of \$10.04/m^2.

The energy use survey included a total of 284 suites in eight buildings. The utility bills for each suite ranged from \$461 to \$1,683 per year. The average utility bill per suite was about \$746 per year based on costing data available for the year 1994.

Table 4.1: Summary of Energy Use in Mid-Rise Apartment Buildings.

	Description	Ottawa 'B'	Ottawa 'R'	Toronto 'L'	Toronto 'S'	Vancouver 'LV'	Vancouver 'MV'	Vancouver 'SB'	Vancouver 'W'	Average	Std. Deviation
1	Location	Ottawa	Ottawa	Toronto	Toronto	Vancouver	Vancouver	Vancouver	Vancouver		
2	Year of construction	1990	1991	1991	1994	1992	1993	1993	1993	1,992	1.4
3	Number of floors	3.5	4	4	3	4	3	4	4	3.7	0.5
4	Number of suites	23	35	51	17	45	45	31	36	35	12
	Utility Bills										
5	Annual electricity consumption (kWh)	244,472	654,269	348,303	51,040	256,341	247,813	206,600	230,667	279,938	172,314
6	Annual natural gas consumption (m3)	-	25,884	50,879	29,123	25,778	29,821	18,682	33,897	26,758	14,296
7	Annual energy cost ($)	18,775	58,898	39,321	9,305	20,744	23,043	18,285	21,028	26,175	15,634
8	Electricity energy use, kWh /m2	150.0	222.8	81.0	58.6	83.8	75.8	76.4	91.6	105.0	54.7
9	Fuel energy use, kWh/m2	-	40.4	89.3	160.9	69.0	100.0	69.6	107.9	79.7	47.8
10	Equivalent energy use, kWh/m2	150.0	263.2	170.3	219.5	152.8	175.8	146.0	199.5	184.6	40.7
11	$/m2	11.52	20.05	9.14	10.68	6.78	7.05	6.76	8.35	10.04	4.42
12	$/suite	816.28	1,682.80	771.00	547.35	460.98	512.07	589.84	584.11	745.55	398.06
	Heat Gains During Heating Season (Estimated with DOE-2.1E)										
13	Solar gains, kWh/m2	13.1	13.4	15.1	12.8	8.7	13.5	8.9	6.3	11.5	3.1
14	Internal gains, kWh/m2	23.0	24.5	21.4	23.7	10.1	21.7	22.3	24.3	21.4	4.7
15	Space heating, kWh/m2	64.2	102.2	91.7	106.0	77.9	88.3	51.7	57.5	79.9	20.5
16	Total heat gains, kWh/m2	100.2	140.1	128.1	142.5	96.7	123.4	83.0	88.1	112.8	23.6
	Heat Losses During Heating Season (Estimated with DOE-2.1E)										
17	Walls, kWh/m2	12.3	26.0	6.9	29.4	28.1	16.7	14.1	9.3	17.8	8.8
18	Roof, kWh/m2	5.8	14.8	4.5	11.7	6.2	6.2	4.3	7.3	7.6	3.7
19	Below grade, kWh/m2	5.7	10.9	22.2	10.1	5.4	12.6	0.8	4.9	9.1	6.6
20	Windows and doors, kWh/m2	30.7	41.8	48.9	50.5	25.2	22.2	23.2	32.2	34.3	11.3
21	Ventilation, kWh/m2	6.9	21.2	21.4	17.1	12.7	24.0	17.2	18.8	17.4	5.5
22	Air leakage, kWh/m2	39.1	25.4	24.3	23.7	19.1	41.6	23.4	15.5	26.5	9.1
23	Total heat losses, kWh/m2	100.4	140.1	128.1	142.5	96.7	123.4	83.0	88.1	112.8	23.6
	Other Energy Use Components (Percentage of annual utility bills reconciled with DOE-2.1E estimates)										
24	Space heat	42.9%	37.9%	53.8%	48.3%	50.9%	50.2%	35.4%	28.8%	43.5%	8.8%
25	DHW	25.9%	26.2%	28.4%	23.5%	20.4%	24.5%	28.4%	25.3%	25.3%	2.6%
26	Lighting	20.4%	20.1%	9.7%	11.8%	12.0%	9.4%	14.5%	20.4%	14.8%	4.8%
27	Miscellaneous	14.2%	14.2%	11.6%	14.3%	14.9%	9.9%	22.3%	24.7%	15.8%	5.1%
28	Unaccounted	-3.4%	1.6%	-3.5%	2.1%	1.8%	6.0%	-6.0%	8.0%	0.8%	4.8%
29	Total, kWh/m2	150.0	263.2	170.3	219.5	152.8	175.8	146.0	199.5	184.6	40.7
30	Total, kWh/ft2	13.9	24.4	15.8	20.4	14.2	16.3	13.6	18.5	17.2	3.8

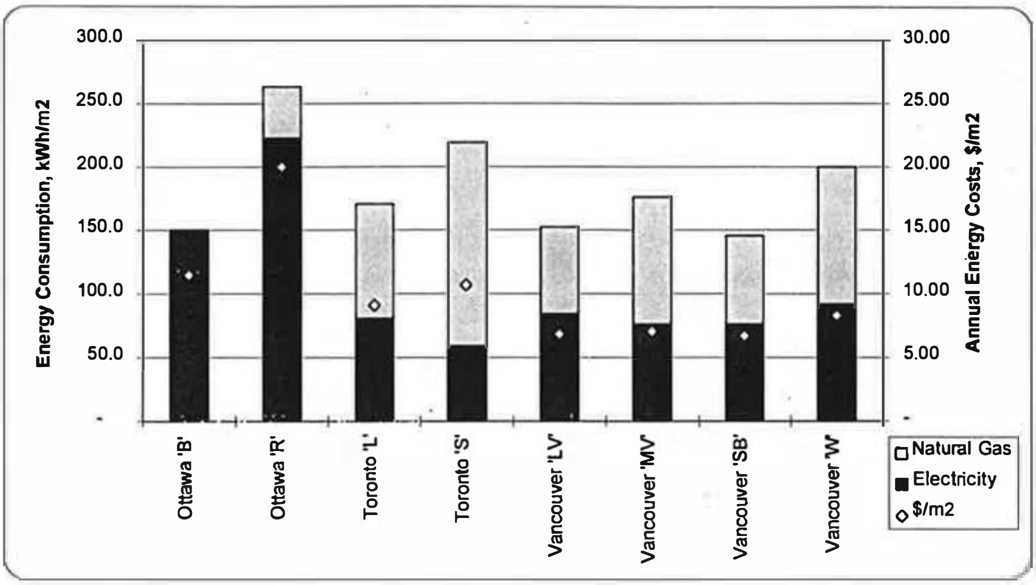

Figure 4-1: Annual energy use in mid-rise apartment buildings.

Table 4-2: Marginal cost of electricity and natural gas.

	Electricity $/kWh	Natural Gas $/kWh (equivalent)
Ottawa 'B'	0.077	-
Ottawa 'R	0.074	0.025
Toronto 'L'	0.074	0.038
Toronto 'S'	0.067	0.027
Vancouver 'LV'	0.059	0.024
Vancouver 'MV'	0.064	0.029
Vancouver 'SB'	0.072	0.018
Vancouver 'W'	0.063	0.018

4.2. ANALYSIS OF HEAT GAINS AND HEAT LOSSES DURING THE HEATING SEASON

Using the energy simulation results with DOE-2.1E, heat gains and heat losses profiles were developed for each building. The heat gain and heat loss balance includes the heating season only. The heat gains in the building includes the solar radiation; internal gains due to occupancy, lighting, hot water use and other energy consuming equipment; and auxiliary space heating to maintain the comfort conditions. Heat losses include the conductive heat losses through walls, windows, roof and below grade components; and convective heat losses associated with air leakage and ventilation in the building.

Figure 4-2 shows the heat gains during the heating season for eight test buildings. As shown in these figures, the availability of solar gains ranged from 6.3 to 15.1 kWh/m^2 of floor area depending on the orientation and window area of the building. The internal gains ranged from 10.1 to 24.5 kWh/m^2 of floor area for the sample of buildings. The auxiliary heating requirements ranged from 51.7 to 106 kWh/m^2 of floor area.

Figure 4-3 shows the total heat losses through building envelope components during the heating season. Conduction heat losses through walls, windows, doors, roof and below grade accounted for 42.4 to 101.7 kWh/m^2 of floor area. Heat losses associated with air leakage and ventilation ranged from 31.8 to 65.6 kWh/m^2 for the set of test buildings. Figure 4-4 shows a typical heat balance for a mid-rise residential building. As shown in the heat gains and losses balance, conduction losses accounted almost 61% of total heat losses and ventilation and air leakage accounted for about 39% of total losses. Auxiliary heating requirements are about 71% of the total heat gains in the building.

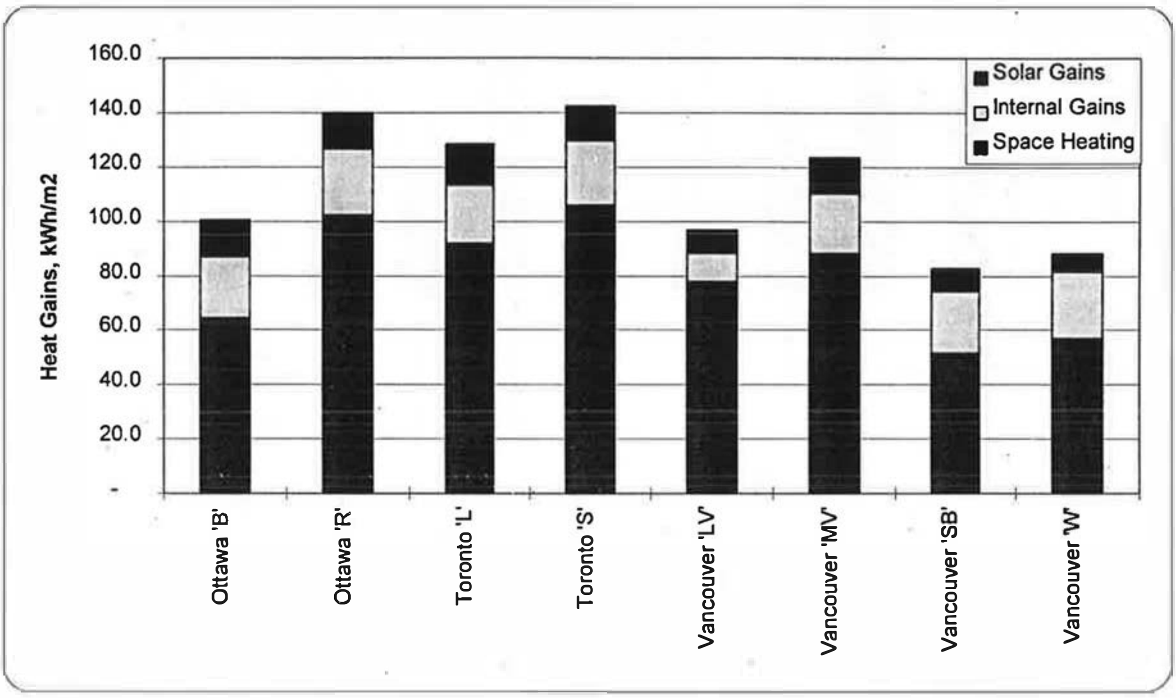

Figure 4-2: Heat gains in buildings during the heating season.

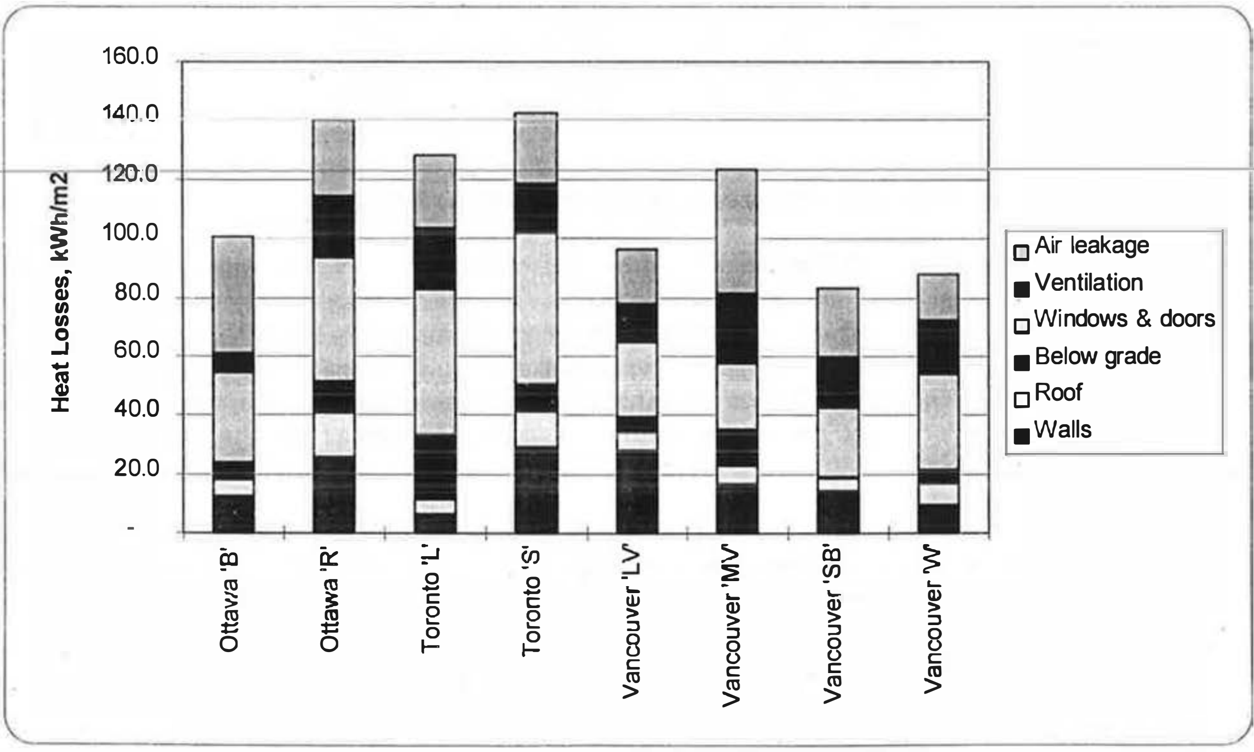

Figure 4-3: Profile of heat losses during the heating season in mid-rise residential buildings.

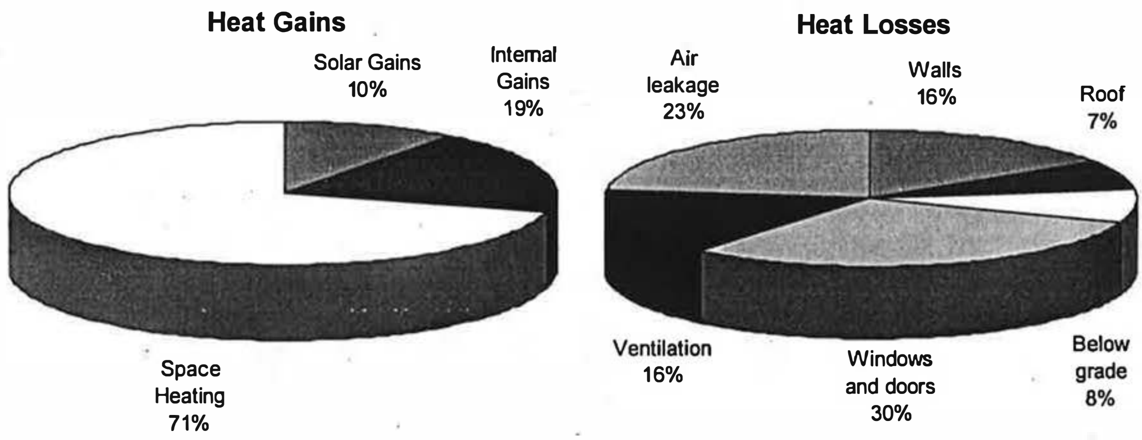

Figure 4-4: A typical balance of heat losses and heat gains in a mid-rise apartment building during the heating season.

4.3. COMPONENTS OF ENERGY USE

The DOE-2.1E simulations also provided useful evaluation of different components of annual energy use in the test buildings. Figure 4-5 shows the evaluation of various energy use components for eight test buildings.

The space heating requirement ranged from 28.8% to 53.8% of the annual energy requirements. The energy use for domestic hot water heating (includes pumping and distribution parts) ranged from 20.4% to 28.4% of the annual energy use in buildings. The lighting energy use ranged from 9.4% to 20.4% of the total energy use. The miscellaneous component which ranged from 9.9% to 24.7% included the energy used by elevators, laundry equipment, suite appliances (freezer, stove, entertainment etc.), and air conditioners.

The reconciliation of DOE-2.1E estimates and actual utility bills was also undertaken as part of the energy simulation work. The unaccounted portion showed the difference between the actual utility bills and DOE-2.1E estimates. The unaccounted portion ranged from -6% to +8% for the test buildings with an aggregate average of about 1% for the whole sample.

Figure 4-6 shows a typical profile of annual energy use in a mid-rise apartment building. As shown, the space heating and domestic hot water use in the building may account for more than 68% of the total energy use in the building. For a building, which uses natural gas for heating, the energy costs attributed to space heating and domestic hot water use may account for less than 49% of the total energy costs. The cost difference between the unit prices of natural gas and electricity should be one of the prime consideration for the type of heating equipment.

Figure 4-7 shows the annual energy costs associated with the air leakage and ventilation in test buildings. Ventilation component includes the fan energy and conditioning of the fresh outdoor air. Ventilation and air leakage costs ranged from 11% to 26% of the annual energy costs in test buildings.

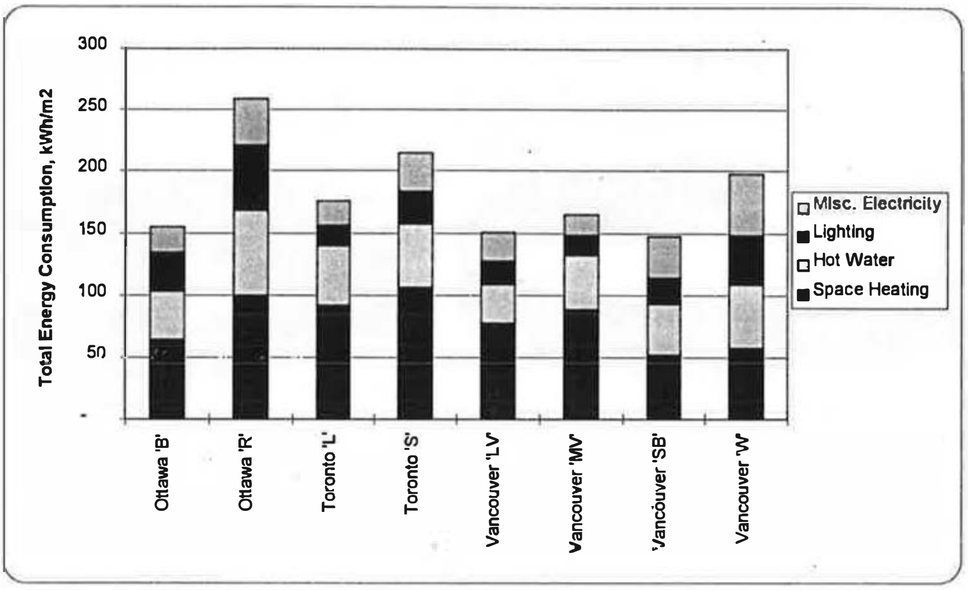

Figure 4-5: Components of annual energy use in test buildings.

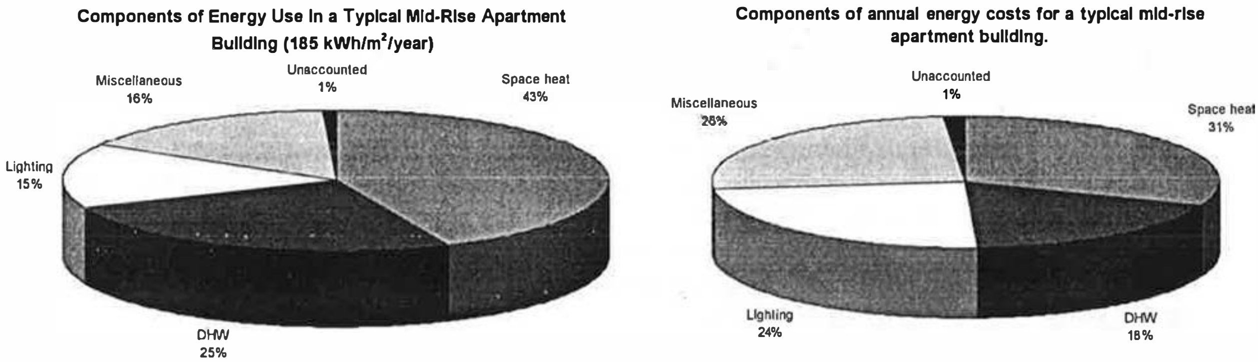

Figure 4-6: A profile of annual energy use (kWh) and energy cost ($) in a typical mid-rise apartment building.

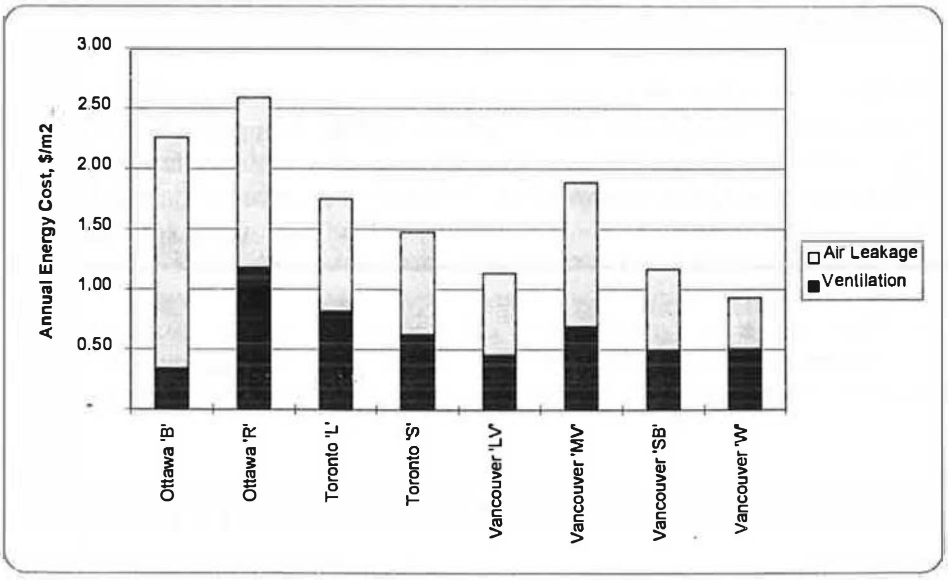

Figure 4-7: Annual energy cost attributed to air leakage and ventilation in test buildings.

5. OBSERVATIONS AND DISCUSSIONS

The test buildings were built from 1990 to 1994. Out of four Ontario buildings, 3 buildings were built as per the requirements of 1990 Ontario Building Code and one building as per the requirements of 1993 Ontario Building Code. All four Vancouver buildings were built as per the requirements of 1990 BC Building Code. One of the objective of the present study was to evaluate the 'as is' performance of the air barrier requirements and ventilation requirements necessitated by codes. Detailed evaluation of IAQ and energy use is given in preceding sections (section 3 and 4). Based on a field survey and investigations of indoor air quality and energy use of eight buildings, the following points provide general trends and operating status of the mid-rise residential buildings.

- **Air barrier:** Field surveys showed that all buildings had 6 mil polyethylene air barrier installed for walls, roof and below grade components. As per the recommendations in good design practices for air barrier system in tract building, the air leakage rate is expected to be about 0.7 to 1.6 L/s.m^2 at 75 Pa pressure difference. The airtightness tests of the eight older high-rise buildings showed that the envelope air leakage rate ranged from 2.23 to 3.60 L/s.m^2 at 75 Pa pressure difference. High air leakage through the envelope is attributed to the following:
  - poor detailing of air barrier at critical junctions such as window and wall, door and wall, wall corners, and roof and wall joints;
  - air leakage through window weatherstripping and door weatherstripping seem to be exceptionally high in several buildings thereby affecting the overall airtightness of the building shell; and
  - penetrations through building envelope are not properly sealed (in one building, electrical baseboard heater cables penetrate through the air barrier).

  For new construction of MUR buildings, the following remedial actions should be considered:
  - Architectural drawings should provide details of various critical joints and explain details with proper notes.
  - The construction trade needs proper training with regard to installation of air barriers.
  - Better quality control and inspection procedures should be followed during the construction phases.

- **Thermal and Insulation Levels:** The survey of eight buildings showed that all buildings were insulated as per local practices. Ontario buildings had insulation levels just meeting the Part IX requirements for their respective zones. It was noticed that although walls were constructed using proper levels of insulation, the placement of insulation and the framing (shell) structure created significant thermal bridging in several buildings. Due to significant thermal bridging, the effective thermal resistance of insulation was reduced substantially, in one building almost by 30%.

- **Ventilation and Air Movement:** Mechanical ventilation is provided by two systems: (1) Independent or in-suite kitchen and bathroom fans generally operated by tenant on manual control; and (2) make-up air to corridors which is then fed to the suites through the apartment door perimeter leakage.

  All buildings had kitchen and bathroom fans installed in the suites. As per the survey of tenants, about 82% occasionally use the kitchen exhaust fans while cooking, and about 41% of occupants use bathroom exhaust fans regularly. These exhaust fans should be used almost 100% of time when the kitchen and bathrooms are being used. Lower and irregular use of these exhaust fans can create higher humidity in the building, affect the occupant comfort and also cause window condensation and associated mold growth problems.

Except one building (Ottawa 'B'), all buildings have a dedicated make-up air system. Review of the equipment and distribution system for make-up air ventilation showed that these systems were designed as per the current practices and have the capability to provide ventilation in the building as specified by CSA F-326 for suites and ASHRAE 62-1989 for corridors. In most cases, the installed equipment capacity exceeded by 10% to 25% of the design requirements. The performance measurements showed that the make-up air system delivered 40% to 100% of the installed capacity. In most cases, corridors received some amount of ventilation air; however, not adequate based on applicable codes and standards.

Air supply to suites from the apartment doorway was also measured in all buildings. A sample of three suites were selected in each building to evaluate the amount of air entering the suite from the corridor. Except in three buildings (Ottawa 'R', Toronto 'L' and Toronto 'S'), suite doors leading to the corridor were weatherstripped in all buildings thus allowing negligible quantity of ventilation air from the corridor to the suite. In the other three buildings, the ventilation flow rate was about 15 to 20 L/s, well below the CSA F-326 requirements of 20 to 30 L/s per suite. Air change rate tests in about 12 units in eight buildings showed that the mechanical ventilation rates were well below the CSA F-326 requirements.

From the above observations, we found that these mid-rise residential buildings had the necessary ventilation and exhaust equipment installed to meet the code requirements. However, the performance evaluation showed that these exhaust and ventilation systems could not be expected to reliably ventilate individual suites in the buildings. Make-up air systems delivered fresh air to the corridors which eventually escaped to outside due to lack of proper transfer mechanism between the corridor and the suites. The under-performance of ventilation systems also seem to be associated with high levels of relative humidity, high levels of carbon dioxide, window condensation and mold growth in several buildings.

- **Occupant Comfort:** A survey of occupants provided information on the general operating conditions in the test buildings. Occupant surveys showed that a significant portion of tenants did not find the indoor air quality acceptable. Our observation is based on the definition of 'acceptable comfort level.' According to ASHRAE Standard 55, the acceptable comfort level is defined on the basis of acceptance of 80% of total occupants. Anything below this level of 'comfort acceptance' is considered unsatisfactory. The major causes for occupant discomfort are mainly related to poor indoor air movement and lack of ventilation in living area (suites). It is also notable that about one in six occupants reported that, in their opinion, their health problems are due to the poor air quality in the building.

- **Energy Consumption Profiles:** Energy analysis of eight mid-rise residential buildings showed that the purchased total energy consumption ranged from 146 to 263 kWh/m^2 with an average of 185 ± 41 kWh/m^2 of floor space per year. In contrast, the energy consumption for high-rise residential buildings ranged from 152 to 309 kWh/m^2 with an average of 222 ± 60 kWh/m^2 of floor space per year[21]. A survey of about 200 single family houses built during 1989-93 showed that the average energy consumption was 140 to 220 kWh/m^2 per year[22].

  Figure 5-1 shows the comparison of energy consumption index, based on kWh/degree-day/m^2 of the floor space, for mid-rise, high-rise and single family housing stock. As shown in the figure, the mean value of the energy consumption for a high-rise and mid-rise building is almost the same. Compared to a single family houses, the mid-rise residential units had about 10% less energy consumption per unit area despite the fact that mid-rise units had significantly less exposed surface area than single-family houses.

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[21] CMHC 1996. Energy Audits of High-Rise Residential Buildings. Report prepared by Scanada Consultants Limited for the Research Division of Canada Mortgage and Housing Corporation, Ottawa.

[22] NRCan 1997. Airtightness and Energy Efficiency of New Conventional and R-2000 Housing in Canada. Report prepared by Tom Hamlin and John Gusdorf, Natural Resources Canada

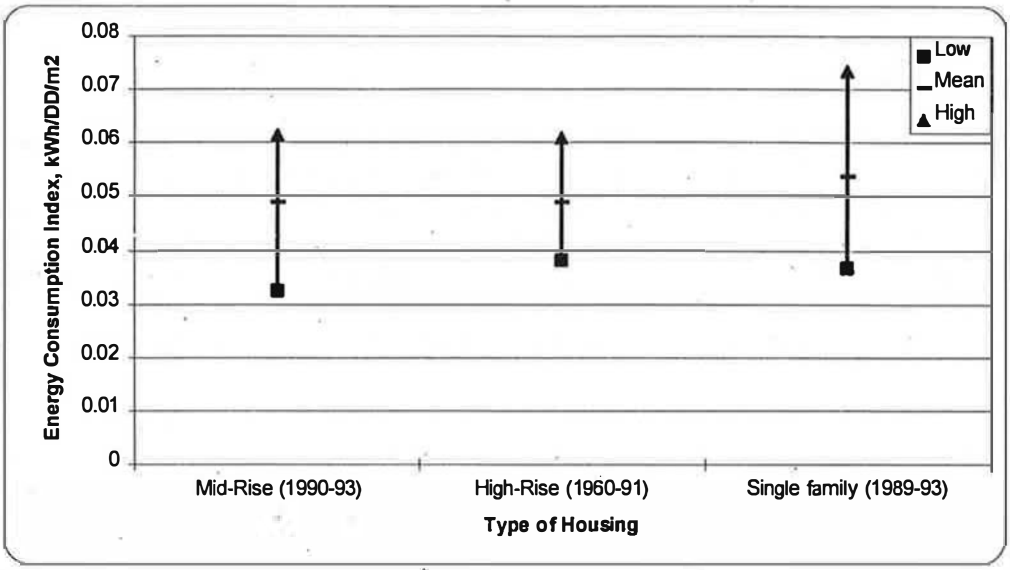

Figure 5-1: Comparison of energy consumption index for different types of housing.

- **Lessons Learned from the Field Survey:** The following summarizes the project team's experiences with regard to conducting detailed field investigations of residential buildings:
  - To be successful, a field survey requires full cooperation from building owners, operators and, most importantly, tenants. During the survey, the project team was able to get full cooperation from building owners and operators and in most cases from tenants. It was helpful to keep open communication with all involved and explanations to tenants regarding the project goals.
  - The airtightness testing using the multiple blower doors required significant amount of preparation and tenant cooperation.
  - One to one discussion with tenants and help of the building owners assisted in high return of occupant surveys. To be successful in conducting the survey, one must design the questions in simple format without being too intrusive on the personal information.
  - Indoor air quality testing using the continuous dataloggers provide operating insights. However, this option is relatively costly due to the sophisticated equipment.
  - Energy analysis was undertaken using DOE-2.1E hourly energy simulation program. In retrospect, this model requires significant amount of building information, layouts for HVAC systems and operating schedules. The simulation of energy flows seems to be insightful and provides detailed evaluation of energy use in the building. It should be noted that it required a significant amount of effort and time to undertake the energy simulation task. It took more than five person days to prepare input for the simulation and about four days to reconcile the results of energy analysis with actual metered utility bills. This can be translated as about $4,500 in efforts per building for an experienced user of the energy analysis program. Other simple and, of course, less costly methods should be evaluated to perform energy analysis of apartment buildings.
  - Overall, the field survey and energy analyses provided significant new insights into the mid-rise apartment buildings. This should help in future design, construction and commissioning of buildings. Further work is needed to develop design criteria, construction details, effective ventilation systems, quality control and commissioning procedures and, above all, a comprehensive guidelines for interweaving occupant comfort and energy efficiency in mid-rise residential buildings.

6. CONCLUSIONS

The purpose of the project was to evaluate indoor air quality and energy consumption of new mid-rise residential buildings. The research plan included the development of test and evaluation protocols for indoor environment parameters, energy consumption patterns and ventilation system performance parameters for mid-rise buildings. As part of the field work, a total of eight buildings were chosen for detailed evaluation; four buildings in Vancouver, two in Ottawa and two in Toronto. All the buildings were built in the last five years (1990 or later) to reflect current design and construction practices. The detailed evaluation of eight mid-rise residential buildings showed the following trends:

Air Leakage and Ventilation Performance:

- The airtightness of the building shell ranged from 2.23 L/s.m^2 to 3.60 L/s.m^2 at 75 Pa pressure difference. The wall corners, roof/wall joints, window and wall joints, balcony door frame and wall joints, basement/ground floor connections, and window and door weatherstripping seem to be the cause for poor airtightness in several of the test buildings.
- The air change rate tests using the passive sampling devices showed that the mechanical ventilation accounted for 0.1 to 0.67 air changes per hour in occupied suites. In several buildings, the estimated mechanical ventilation rate was substantially lower than the required rate of 0.30 air changes per hour as per CSA Standard F-326.
- All except one Ottawa building have a corridor make-up air ventilation system. The installed capacity of these systems met or exceeded the ventilation requirements set by ASHRAE Standard 62-1989 which was about 20 to 80 L/s per suite. Measured air flow rates for the corridor ventilation system ranged from 55% to 99% of the installed ventilation capacity.
- The corridor ventilation air entering the suite through the door was negligible in five of the eight buildings due to weatherstripping of the suite/corridor entry door. Ventilation air entering the suite through the corridor in the other three buildings ranged from 13 to 27 L/s. The supply of ventilation air in suites fall short off the requirements set by CSA F-326 which ranged from 20 to 35 L/s per suite.
- All suites had bathroom exhaust and kitchen exhaust fans. In all buildings, the installed capacity of bathroom and kitchen exhaust fans met the requirements set by CSA F-326. However, the measured air flow rates of kitchen and bathroom exhaust fans showed that most bathroom fans exhausted 30% to 85% of their rated capacity. The performance of kitchen fans was slightly better. Kitchen fans exhausted 50% to 90% of their rated capacity.
- Occupant surveys showed that about 82% occupants regularly used kitchen exhaust fans while 41% of occupants regularly used bathroom exhaust fans.
- From the above observations, we found that mid-rise residential buildings had the necessary ventilation and exhaust equipment installed to meet the code requirements. However, the performance evaluation showed that these exhaust and ventilation systems did not function to the required level and generated significantly low air movement in the building. Make-up air system provided the fresh air in corridors which eventually dumped to outside due to a lack of proper transfer mechanism between the corridor and the suites. The under-performance of ventilation systems also seem to cause high levels of relative humidity, high levels of carbon dioxide, window condensation and mold growth in several buildings. This problem demonstrates short comings in conventional approaches to mechanical ventilation in MURBs. The problem is two fold: (1) Failure to provide adequate ventilation distribution at the design stage; and (2) failure to anticipate that occupants do not like, noise, light and odour transfer

around suite doors. There is a need to revisit and rethink the whole issue of MURB ventilation systems.

Indoor Environment:

- Occupant surveys reported that about 16% of tenants feel that they suffer from health problems due to poor indoor air quality in some buildings. About 39% of tenants complained about window condensation; 14% of occupants complained about mold growth in their suites; and only 57% of occupants felt that the quality of indoor air was acceptable in their buildings.
- In several buildings, relative humidity and carbon dioxide levels exceeded the normal acceptable limits. These buildings also had insufficient ventilation and air movement in the suites. Occupant complaints are also high. The occupant complaints in these building seem to be due to improper and/or lack of adequate ventilation and air distribution.
- The emissions of formaldehyde and VOCs from building materials were substantially low, and within acceptable limits in all buildings.
- Field survey also showed that the electromagnetic field were much lower than 8 milligauss in all test units. Ontario Hydro recommends a level up to 20 milligauss near the equipment and about 8 milligauss at 0.3 m away from the source.
- Lighting levels in common areas of a mid-rise apartment building generally met the requirements set by good practices.

Energy Use in Buildings:

- The purchased energy in mid-rise buildings ranged from 146 to 263 kWh/m^2 of floor area per year. The annual energy cost ranged from \$6.76/m^2 to \$20.05/m^2 with an average of about \$10/m^2. The utility bill for each suite ranged from \$461 to \$1,683 per year. The average utility bill per suite was about \$746 per year based on costing data available for the year 1994.
- The analysis of heat gains during the heating season showed that solar gains contributed about 10% (11.5 ± 3.1 kWh/m^2) of space heating requirements while the internal gains accounted for 19% (21.4 ± 4.7 kWh/m^2) of the space heating needs. The purchased space heating energy requirements was about 112.8 ± 23.6 kWh/m^2.
- The heat loss components during the heating season were as follows: walls accounted for 16%; roof at 7%; below grade losses at 8%; windows and doors at 30%; air leakage at 23% and the mechanical ventilation at 16% of total heat losses.
- Energy balance analysis showed that for eight test buildings the energy use was as follows:
  - purchased energy ranged from 146 to 263 kWh/m^2 and average of 184.6 ± 40.7 kWh/m^2.
  - space heating accounted for 43.5% ± 8.8%;
  - domestic hot water use accounted for 25.3% ± 2.6%;
  - lighting accounted for 14.8% ± 4.8%;
  - miscellaneous energy use (suite appliances, air-conditioning and other equipment) accounted for 15.8% ± 5.1%.
- Comparison showed that the mean value of the energy consumption for a high-rise and mid-rise building is almost the same. Compared to a single family housing, the mid-rise residential units had about 10% less energy consumption per unit area despite the fact that mid-rise units had significantly less exposed surface area than single-family houses.

The multi-unit residential buildings are as energy intensive as single family houses despite their lower volume/surface area ratios, central systems, and high occupancy densities. Future research and application work must be directed to improve the energy and indoor environmental performance of multi-unit residential buildings.