RESEARCH REPORT

Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High Rise Residential Buildings

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Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High-Rise Residential Buildings

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Abstract

This report characterizes ventilation in residential suites located in ten buildings in major metropolitan areas of Canada. All buildings were between six (6) and thirty-two (32) stories high and were built between 1990 and 1995.

Ventilation in mid- and high-rise residential buildings is a particularly complex issue to investigate and to discuss in a report.

This report answers three key questions:

- What are the key parameters that characterize suite ventilation?
- What field tests are required to collect data that determine these parameters?
- Based on field tests of ten suites, what are their ventilation characteristics?

The field performance tests showed suite ventilation to be highly influenced by weather, suite location within the building, and treatment of both interior and corridor access doors. As a result, ventilation within a suite at any given time is very difficult to predict. The test results also showed there are substantial amounts of transfer air entering the test suites.

To ensure suite ventilation is both controlled and adequate under normal operating conditions, the building industry will need to develop and follow a strict set of ventilation design practices.

Disclaimer

Acknowledgments

The authors gratefully acknowledge the financial assistance of the Canada Mortgage and Housing Corporation in making this project possible. We also wish to extend our appreciation to the building owners, designers, managers, and occupants who cooperated with us during the design reviews and testing. In particular, we thank the ten families who vacated their suites so that we could conduct our in-suite field tests. Finally, we wish to acknowledge the following researchers who assisted us during the long days and nights of field tests across Canada: Mr. Donald Fast, Mrs. Amanda Sinnige, Ms. Michelle Nokken, Mr. Jean Villeneuve, Mr. John Hockman, and Mr. Ted Lightly.

Executive Summary

This report provides a snapshot of suite ventilation in recently constructed mid- and high-rise residential buildings in Canada. Sheltair Scientific Ltd. carried out the work during 1996 and 1997 for the Innovation Centre for Highrise and Multiples, of Canada Mortgage and Housing Corporation (CMHC).

The purpose of this study was to clarify if current code requirements and HVAC design practices are ensuring that suites are being properly ventilated under typical operating conditions.

This study examined one suite in each of ten buildings that are located in major cities across Canada. Field performance tests showed suite ventilation to be highly influenced by weather, location within the building, and treatment of both interior and corridor access doors. As a result, ventilation within a suite at any given time is very difficult to predict. Furthermore, for all intents and purposes, ventilation in these buildings is uncontrolled.

The greatest concern raised by this study is the amount of transfer air that is part of ventilation air in the suites tested. Large amounts of transfer air from other occupied suites in the building may compromise the quality of ventilation air entering suites. Although not part of this study, large amounts of transfer air during a fire emergency may also increase the danger to occupants as fire and smoke spread within the building.

To ensure suite ventilation is both controlled and adequate under normal operating conditions, the building industry will need to develop and follow a strict set of ventilation design practices. New practices should not compromise safety or create excess energy use.

A list of our key findings follows:

Corridor Supply Airflows

- There is a wide variation in the design specifications for corridor supply airflows.
- Measured corridor supply airflows are significantly lower than the design flows.
- There can be substantial variations in actual corridor supply airflows over the course of a day in some buildings.
- The airtightness of the building envelope and suite access door affects the corridor supply airflows.

Suite Exhaust Capacities

- There is a wide variation in the design specifications for total suite exhaust capacities.
- Measured exhaust capacities were always considerably lower than the design exhaust capacities.
- Design corridor supply airflows are usually much lower than the design suite exhaust capacities.
- Measured corridor supply airflows and suite exhaust capacities were usually slightly closer together than the design airflows and capacities.
- Designer's did not ensure there is always sufficient leakage between the corridor and suite for the transfer of makeup air that includes the corridor supply air.

- Designer's did not ensure that additional makeup air for exhaust can always be provided by infiltration from outdoors.

Comparison of Supply Airflows with ASHRAE and CSA Requirements

- Design corridor supply airflows on a per suite basis usually significantly exceed ASHRAE minimum outdoor air capacity requirements.
- Measured corridor supply airflows on a per suite basis often were closer to ASHRAE minimum outdoor air capacity requirements.
- Design corridor airflows on a per suite basis often significantly exceed CSA minimum outdoor air capacity requirements.
- Measured corridor supply airflows on a per suite basis were often significantly less than CSA minimum outdoor air capacity requirements.

Comparison of Exhaust Capacities with ASHRAE and CSA Requirements

- Design suite exhaust capacities always exceed ASHRAE and CSA minimum exhaust requirements.
- Measured suite exhaust capacities usually were significantly lower than ASHRAE and CSA minimum requirements.

Leakage Areas of Suite Access Doors

- Measured leakage areas of suite access doors are large and highly variable.
- The measured leakage areas of the suite access doors were usually within allowable NFPA limits for fire doors, but always exceeded allowable NBC limits for fire doors, and always exceeded allowable NFPA limits for smoke-control doors.
- Weather-stripping modifications by occupants can affect leakage areas of suite access doors.
- There are significant differences between theoretical and measured door leakage areas in some buildings.

Airflows through Suite Access Doors

- Wide variation from building to building in "measured" airflows from corridor through test suite access doors.
- For some test suites, measured corridor supply airflows on a per suite basis are significantly lower than "measured" airflows from the corridor through the suite access doors.
- Airflows were reversed into the corridor for some suites.
- Using the leaks around suite access doors to supply ventilation air to suites is not a reliable system.

Air Exchange Rates

- Compared to existing ventilation standards, most rooms of the test suites are well-ventilated, but some are marginal or under-ventilated.
- Large suite to suite variation in room air exchange rates.

- Airflows from the corridor through the suite access doors are primarily responsible for the air exchange in most of the test suites.
- Distribution of air varies in suites, but usually room air exchange rates are fairly uniform.

Comparison of Two Suites in Same Building

- Closing interior doors within the test suite can have complex effects, including reducing the suite volume that is directly open to flows from the suite access door and increasing the airtightness of these open volumes.
- Air exchange rate for the open living room and kitchen increased due to the reduced open volume of the suite.
- Bathroom air exchange rate increased when its door was closed, possibly due to changes in the mixing patterns within this room.
- Bedroom air exchange rate decreased when its door was closed due to increased flow resistance between open areas and outdoors through bedroom.
- The similarity of air exchange patterns and rates above and below the neutral pressure plane for this building may be fortuitous.

Inter-Suite Transfer Air Fractions

- Most of the test suites had some transfer air flowing into them from other suites.
- Large variation in inter-suite transfer air fractions.
- Corridor supply air systems do not always meet their primary design intent, because they are incapable of always preventing inter-suite transfer airflows.

Résumé

Cette étude brosse un tableau de la ventilation des appartements dans les immeubles de grande et de moyenne hauteur construits récemment au Canada. La firme Sheltair Scientific Ltd. a dirigé les travaux en 1996 et 1997 pour le compte du Centre d'innovation pour les immeubles collectifs et tours d'habitation de la Société canadienne d'hypothèques et de logement (SCHL).

Cette étude avait pour but d'établir si les exigences du Code du bâtiment et les pratiques actuelles en matière de conception des installations de chauffage, de ventilation et de climatisation font en sorte que les appartements sont correctement ventilés dans des conditions de fonctionnement normales.

Les chercheurs ont examiné un appartement dans chacun des 10 immeubles étudiés, lesquels étaient situés dans de grandes villes canadiennes. Les essais en service ont montré que la ventilation des appartements est fortement influencée par les conditions climatiques, l'emplacement de l'appartement à l'intérieur de l'immeuble et le traitement des portes d'accès intérieures et extérieures. C'est pourquoi il est très difficile de prévoir l'efficacité de la ventilation dans un appartement à un moment donné. De plus, la ventilation dans ces immeubles est pratiquement impossible à régler.

La plus grande préoccupation que soulève cette étude est la quantité d'air de transfert qui compose l'air de ventilation des appartements étudiés. Lorsqu'il se produit un important transfert d'air entre les appartements occupés d'un immeuble, la qualité de l'air de ventilation admis dans les appartements peut être compromise. Bien que la question ne fasse pas partie de l'étude, un transfert d'air considérable dans le cas d'un incendie pourrait aussi accroître le danger que courent les occupants lorsque le feu et la fumée se propagent dans l'immeuble.

Pour s'assurer que la ventilation des appartements est à la fois maîtrisée et appropriée dans des conditions normales de fonctionnement, l'industrie de la construction va devoir mettre au point et suivre une série de pratiques rigoureuses en matière de conception des installations de ventilation. Les nouvelles pratiques ne devraient pas compromettre la sécurité ou entraîner une consommation excessive d'énergie.

La liste qui suit fait des état des principaux résultats obtenus :

Débits d'air d'alimentation dans les corridors

- Les spécifications relatives à la conception des débits d'air d'alimentation dans les corridors sont extrêmement variables.
- Les débits d'air d'alimentation mesurés dans les corridors sont beaucoup plus faibles que les débits de calcul.
- Dans certains bâtiments, les débits d'air d'alimentation mesurés peuvent varier considérablement dans les corridors au cours d'une journée.
- L'étanchéité à l'air de l'enveloppe du bâtiment et des portes d'accès des appartements influe sur les débits d'air d'alimentation des corridors.

Capacités d'extraction des appartements

- Les spécifications de calcul touchant les capacités d'extraction totales des appartements varient beaucoup.
- Les capacités d'extraction mesurées étaient toujours très inférieures aux capacités de calcul.
- Les débits d'air de calcul pour l'alimentation des corridors sont habituellement bien inférieurs aux capacités d'extraction de calcul des appartements.
- Les débits d'air d'alimentation des corridors et les capacités d'extraction des appartements, mesurés en service, se rapprochaient légèrement plus que les débits d'air et les capacités de calcul.
- Les concepteurs ne se sont pas assurés qu'il y aurait toujours suffisamment de fuites entre les corridors et les appartements pour un transfert d'air de compensation qui inclut l'air d'alimentation du corridor.
- Les concepteurs n'ont pas fait en sorte qu'il soit toujours possible d'obtenir de l'air de compensation additionnel pour l'extraction par infiltration d'air extérieur.

Comparaison des débits d'air d'alimentation avec les exigences de l'ASHRAE et de la CSA

- Les débits d'air de calcul pour l'alimentation des corridors en fonction de chaque appartement excèdent habituellement de beaucoup les exigences minimales de l'ASHRAE en matière de capacité pour l'air extérieur.
- Les débits d'air mesurés relatifs à l'alimentation des corridors en fonction de chaque appartement étaient souvent plus près des exigences minimales de l'ASHRAE en matière de capacité pour l'air extérieur.
- Les débits d'air de calcul des corridors en fonction de chaque appartement excèdent habituellement de beaucoup les exigences minimales de la CSA en matière de capacité pour l'air extérieur.
- Les débits d'air d'alimentation mesurés pour les corridors, en fonction de chaque appartement, étaient souvent très inférieurs aux exigences minimales de la CSA en matière de capacité pour l'air extérieur.

Comparaison des capacités d'extraction avec les exigences de l'ASHRAE et de la CSA

- Les capacités d'extraction de calcul des appartements excèdent toujours les exigences minimales de l'ASHRAE et de la CSA en matière d'extraction.
- Les capacités d'extraction mesurées des appartements étaient habituellement très inférieures aux exigences minimales de l'ASHRAE et de la CSA.

Surfaces de fuite des portes d'accès des appartements

- Les surfaces de fuite mesurées des portes d'accès des appartements sont importantes et très variables.
- Les surfaces de fuite mesurées des portes d'accès des appartements respectaient habituellement les limites fixées par la NFPA au chapitre des portes coupe-feu, mais excédaient toujours les limites permises par le CNB en ce qui concerne les portes coupe-feu ainsi que les limites permises par la NFPA visant les portes coupe-fumée.

- Les modifications apportées aux coupe-froid par les occupants peuvent influencer les surfaces de fuite des portes d'accès des appartements.
- Dans certains bâtiments, on note des différences considérables entre les surfaces de fuite théoriques et les surfaces de fuite mesurées pour les portes.

Débits d'air par les portes d'accès des appartements

- D'un bâtiment à l'autre, on constate de larges écarts pour ce qui est des débits d'air «mesurés» entre le corridor et la porte d'accès des appartements d'essai.
- Pour certains appartements étudiés, les débits d'air mesurés pour l'alimentation des corridors sont, sur une base individuelle, beaucoup plus faibles que les débits d'air «mesurés» entre le corridor et les portes d'accès des appartements.
- Les débits d'air ont été inversés pour certains appartements, c'est-à-dire que l'air se déplaçait de l'appartement au corridor.
- L'utilisation des fuites autour des portes d'accès des appartements n'est pas fiable pour fournir de l'air de ventilation aux appartements.

Taux d'échange d'air

- Comparativement aux normes de ventilation en vigueur, la plupart des pièces des appartements d'essai sont bien ventilées, quoique certaines ne le soient que tout juste, voire pas assez.
- Les taux d'échange d'air des pièces d'un appartement à l'autre variaient considérablement.
- Dans la plupart des cas, les débits d'air entre le corridor et la porte d'accès des appartements sont la principale source d'échange d'air.
- La distribution de l'air varie dans les appartements mais, habituellement, les taux d'échange d'air pour les pièces sont relativement uniformes.

Comparaison de deux appartements dans le même bâtiment

- Le fait de fermer les portes intérieures dans les appartements peut avoir des répercussions complexes, notamment la réduction du volume de l'appartement directement exposé à la circulation d'air en provenance de la porte d'accès ainsi que l'augmentation de l'étanchéité à l'air de ces volumes ouverts.
- Le taux d'échange d'air du séjour et de la cuisine, deux espaces ouverts, a augmenté par suite d'une réduction du volume ouvert de l'appartement.
- Le taux d'échange d'air de la salle de bains a augmenté lorsque sa porte était fermée, probablement en raison de changements subis par les profils de mélange au sein de cette pièce.
- Le taux d'échange d'air de la chambre a diminué lorsque sa porte était fermée à cause de l'augmentation de la résistance à la circulation de l'air entre les zones ouvertes et l'extérieur par l'intermédiaire de la chambre.
- La similarité des profils d'échange d'air et des taux supérieurs et inférieurs au plan de pression neutre pour ce bâtiment pourrait n'être que fortuite.

Fractions de transfert d'air entre les appartements

- La plupart des appartements d'essai subissaient un certain transfert d'air provenant des autres appartements.
- On a relevé une importante variation des fractions de transfert d'air entre les appartements.
- Les installations d'alimentation en air des corridors n'atteignent pas toujours le but pour lequel elles sont conçues, car elles sont incapables de toujours prévenir les transferts d'air qui surviennent entre les appartements.

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1.0 Introduction

Ventilation in mid- and high-rise residential buildings is a particularly complex issue to both investigate and to discuss in a report.

This report is organized to answer three key questions:

- What are the key parameters that characterize suite ventilation?
- What field tests are required to collect data that determine these parameters?
- Based on field tests of ten suites, what are their ventilation characteristics?

To explain how suites are ventilated and to identify the key parameters that affect suite ventilation, Section 2 provides a theoretical examination of the following: the compartmentation of mid- and high-rise residential buildings, the nature of the leakage openings that connect the compartments within the building and to outdoors, the nature of the three driving forces that cause flow through these openings, and the nature of the ventilation air sources.

Readers are encouraged to refer to the glossary of terms in Appendix A to avoid issues concerning the interpretation of technical terms.

A set of six performance tests was designed to characterize ventilation within a suite. Design, development, and validation of these performance tests were accomplished in January 1996 in a newly built and partially occupied 32-storey building in Vancouver. Section 3 describes the purpose, design, and protocols for each of these performance tests. Step-by-step test protocols are presented in Appendix B.

Detailed design reviews were completed on 25 mid- and high-rise residential buildings occupied between 1990 and 1995. These buildings were located as follows:

- five Quebec buildings in Montreal and surrounding suburbs,
- five Ontario buildings in Metropolitan Toronto,
- six Manitoba buildings in Winnipeg and its surrounding communities, and
- nine British Columbia (BC) buildings in the Greater Vancouver Regional District.

Ten of these buildings were chosen for field performance testing. Summary information regarding the ten buildings can be found in Section 4.

In this study, only one suite in each building was tested. This approach offered two advantages: a wide mix of suite types and locations, as well as extensive measurements and analysis for each test suite. Appendix C shows a floor plan of each test suite.

The results and key findings from the field tests are also reported in Section 4. Conclusions arising from this study are contained in Section 5.

2.0 Theoretical Examination of Suite Ventilation

2.1 Introduction

Ventilating suites in mid- and high-rise residential buildings is a complex process, which is affected by many parameters (ASHRAE 1992, 1997; Hutcheon and Handegord 1995). These types of buildings are subdivided into a number of compartments. There are numerous leakage openings in the separations between compartments. These openings provide paths for ventilation airflows between the building and outdoors and also between compartments within the building.

Airflows through the leakage openings are driven by differences in pressure regimes within and around the building. These regimes result from the interaction of temperature-, wind-, and mechanically-induced forces. The combined magnitude and distribution of these forces, in combination with the degree of isolation between compartments, determine the magnitude and direction of the airflows through leakage openings.

The magnitude of flow through a leakage opening can be represented by the following empirical equation (Sherman 1980):

$$q = C\,(\Delta P)^n \qquad \textit{(Equation 1)}$$

where

q = airflow rate through leakage opening, m^3/s,
C = flow coefficient for leakage opening, $m^3/(s \cdot Pa^n)$,
ΔP = pressure difference across leakage opening, Pa, and
n = flow exponent for leakage opening, dimensionless.

The flow coefficient and exponent in Equation 1 are parameters that characterize the size (leakage area) of the opening. The magnitude of the flow exponent also characterizes the type of flow through the leakage opening. This exponent is usually in the range of 0.5 (fully-turbulent flow) to 1.0 (fully-laminar flow).

The direction of flow through a leakage opening is determined by the relative magnitudes of the pressures on either side of the leak. Specifically, flow is from the region of high pressure to the region of lower pressure. The resulting flow through any particular opening is not necessarily in the direction intended by the designers, because designers typically do not account for all of the driving forces.

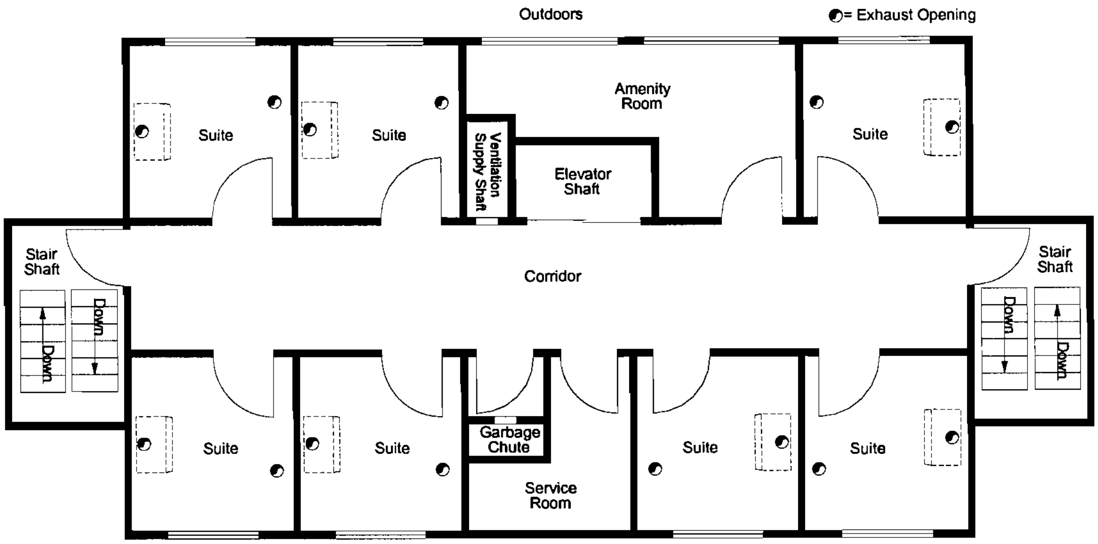
To explain how suites are ventilated and to identify the key parameters that affect suite ventilation, the following theoretical examination discusses: the compartmentation of mid- and high-rise residential buildings, the nature of the leakage openings that connect the compartments within the building and to outdoors, the nature of the three driving forces that cause flow through these openings, and the nature of the ventilation air sources.

2.2 Building Compartmentation

The building envelope can be thought of as a shell enclosing one large compartment. It separates the conditioned interior of the building from outdoors. The envelope consists of the roof, exterior walls (including above- and below-grade walls), exterior windows, exterior doors, and the lowest floor.

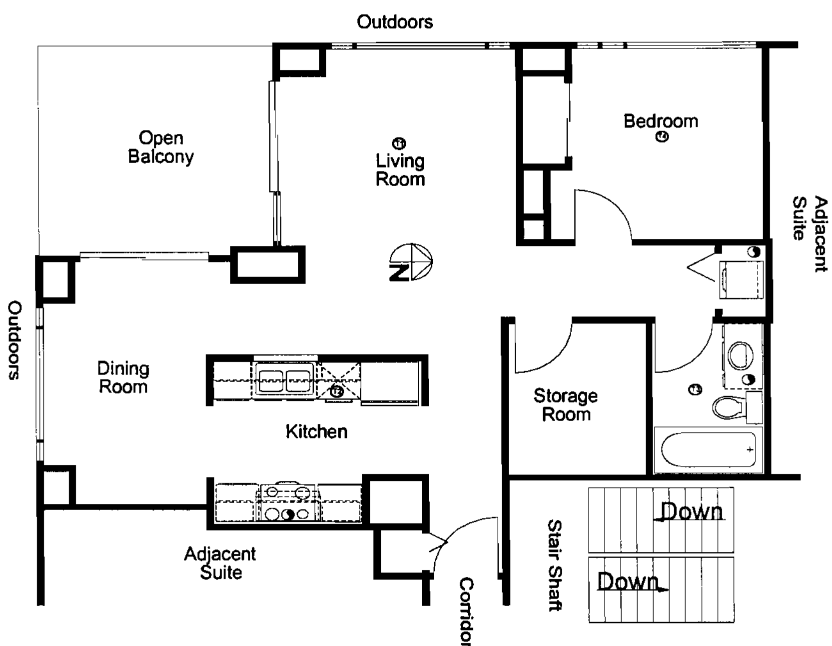
Inside the building envelope, the interior is subdivided into many storeys, each with smaller compartments. Figure 1 shows a schematic of a typical storey.

Figure 1: Schematic of Typical Storey



Suites are one type of compartment within the building. A suite is an enclosed space that has one or more rooms in close proximity to one another. The rooms have access to each other directly through doorways or indirectly through internal corridors or vestibules that are located within the suite. Figure 2 shows a floor plan of a typical suite.

Figure 2: Typical Suite Floor Plan



Other compartment types include: corridors between suites, service and amenity rooms, parking facilities, elevator and stair shafts, garbage chutes, and shafts containing ducts, pipes, and electrical wires. These compartments are typically not occupied. Some mid- and high-rise residential buildings also contain separate spaces for commercial or retail facilities, which are usually located on the ground floor.

Typically, the suites and other rooms on each storey surround the corridor, except where stair shafts are located on exterior walls. Access to the suites, elevator shafts, and stair shafts is through openable doors. In this configuration, the corridors act as plenums for air movement between the various shafts, suites, and other rooms.

The vertical shafts connect the corridors of each storey from the ground floor to the roof. Sometimes these shafts also extend down to the basement or parkade. However, for reasons of security or to prevent the spread of fire, smoke, and vehicle exhaust, separate elevator and stair shafts often are used instead to access stories below the ground floor. For the same reasons, some shafts do not extend all the way to the roof from the ground floor or below.

2.3 Leakage Openings

Very little air leakage occurs through building materials themselves. However, the building elements that separate a suite from outdoors (building envelope) and from the remainder of the building have numerous leakage openings. These openings are in series or in parallel with each other and form pathways for the movement of air between the suite, outdoors, and the remainder of the building. As a result, the characteristics of these openings affect the ventilation rates and airflow patterns within the building. Each opening can be characterized by its type, location, and size. These characteristics describe how isolated the compartments are from outdoors and from one another.

Compartment isolation is desirable for a number of reasons. For example, the more isolated a suite is from the rest of the building and from outdoors, the more likely it is that a direct supply of ventilation air to the suite can be ensured and controlled. Other reasons include noise, odor, and smoke control. Unfortunately, current suites typically have haphazard isolation. This can lead to uncontrolled and sometimes inadequate or excessive ventilation. It can also result in undesirable noise transmission, odor transport, and smoke entry from other regions of the building.

Therefore, it is necessary to determine the characteristics of the leakage openings when assessing suite ventilation. The following two Sections (2.3.1 and 2.3.2) discuss the various types, locations, and sizes of leakage openings that are typically found in mid- and high-rise residential buildings.

2.3.1 Leakage Opening Types and Locations

There are two major classes of leakage openings: unintentional and intentional openings. Within each of these two classes, there are several different types of openings. These openings can be located in the building envelope or in the separations between compartments.

In terms of suite ventilation, the most important leakage openings and flow paths are those in the separations between a suite and outdoors, between the suite and its surrounding compartments, between the corridor and the vertical shafts, and the vertical shafts themselves. Leakage openings between the suite and corridor are especially important, because they are typically the only entry paths into the suite for outdoor air from the corridor supply air system.

Unintentional Openings

Unintentional openings are gaps between building elements that are joined together. Due to material imperfections or construction practices, the joints are not completely sealed.

Specifically, openings of this type in the building envelope include gaps at joints between the walls, floors, and ceilings, and between the walls and frames of windows and doors. They also include gaps between fixed elements of window and door assemblies, such as between a fixed window and its frame. Gaps between the building envelope and mechanical and electrical components that penetrate the envelope are another example of this type of opening.

For the interior compartments, unintentional leaks are similar in type to those found in the building envelope. Examples are the gaps at joints between the floor and the walls that separate a suite from the corridor or from adjacent suites. Within a suite, there are also several unintentional inter-compartment leaks. These leaks typically occur at floor and wall penetrations for mechanical and electrical services.

Intentional Openings

Intentional openings are deliberate openings in or between building elements. These openings are intended to allow the passage of people, materials, or mechanical and electrical services.

Specifically, openings of this type in the building envelope include: intakes for air supply to corridors and mechanical rooms, outlets for air exhaust from suites and mechanical rooms, combustion appliance vents from suites or mechanical rooms, smoke control system exhaust vents and relief dampers, open windows and doorways, and gaps such as the clearance around a closed window or door. Intake openings that are intended for direct outdoor air supply to a suite are rare. Other examples include elevator shaft penetrations at the roof and rooftop stairwell doors.

Intentional openings between the interior compartments tend to be different from those located in the building envelope. There are three important subtypes of intentional leakage openings inside the buildings.

One subtype includes the intentional gaps around interior doors that separate the rooms of each suite, the suites from the corridors, and the corridors from the vertical shafts. The gaps include the spaces between the door and its frame as well as deliberate door undercuts. These gaps and especially the larger bottom gap are sometimes weather-stripped. When there is weather-stripping, its type, amount, and condition can vary throughout a building, especially from suite to suite (due to occupant attempts at draft, noise, or odor control).

The second subtype includes horizontal transfer ducts that connect compartments. An example is the transfer duct that is sometimes used to connect a corridor to an adjoining suite.

The third subtype includes all of the various vertical shafts. These shafts act as large leaks in the floors and ceilings of each storey. Along with stair shafts, elevator shafts, garbage chutes and plumbing chases, these shafts include the common supply ducts for corridor supply air systems and the common exhaust ducts for suite exhaust (where central exhaust systems are used).

2.3.2 Leakage Opening Sizes

The sizes of unintentional leaks in a building are variable and often unknown. Their sizes depend on building design, construction quality, and building maintenance. These leaks tend to be small, but because they are numerous, their combined size can be significant.

Intentional leaks tend to be larger than unintentional leaks. Their sizes are also variable and depend on building design. However, the variation in size of a particular leak is more dependent on building operation and maintenance than on construction quality. Specifically, intentional leak sizes depend on factors such as damper positions, on the amount of window or door opening, and on the amount and condition of weather-stripping around the windows and doors.

There are only limited amounts of quantitative data in literature regarding the size of leakage openings in mid- and high-rise residential buildings. The lack of data is largely due to the difficulty and expense of carrying out field measurements to collect these data.

The following discussion provides an insight into the relative magnitudes and distribution of the leakage openings for a suite. It also discusses the leakage area of shafts as an aid to understanding which leaks are most important for suite ventilation.

Suite Leakage

Shaw and Magee (1991) carried out airtightness tests on ten suites in one mid-rise apartment building. The whole-suite leakage flow was in the range of 4.8 to 6.8 L/s per m^2 of exterior wall area for a 10 Pa pressure difference. Based on Shaw and Magee's data, the equivalent leakage area (ELA) of the suites appeared to be in the range of 340 to 370 cm^2 (average of 360 cm^2). These flow and ELA data indicate that there can be a variance in the airtightness of suites within a single building. The variance may be due to inconsistent construction quality or building maintenance, which causes non-uniformity in the size and distribution of leaks from suite to suite.

Shaw and Magee also determined the component leakage distributions for six of the ten suites they tested. The following component leakage fractions are based on the total leakage flows for individual test suites (not including the suite access door from the corridor): corridor wall, 7 to 19 %; exterior wall, 34 to 64%; ceiling and floor, 0 to 19%; and inter-suite partition walls, 12 to 36%. It appears from these data that the corridor wall, ceilings, and floors are minor leakage sites, whereas the exterior walls are major leakage sites. Partition walls are somewhere in the lower to middle leakage range. These fractions can be misleading however, because it is not clear how the leakage of suite access doors affects the leakage distribution. Leakage data for these doors were not provided by the authors. The following literature review and analyses provide some insight into the leakage of suite access doors and its importance.

Shaw (1980a) tested the airtightness of exterior wall assemblies in five mid- and high-rise apartment buildings by depressurizing the entire building using a single large fan. This depressurization caused air to flow from the suites and into the corridors. Some of his tests were conducted with the suite access doors open and then closed. Shaw's tests found that door position had no significant impact on exterior wall airtightness, which indicates that the leakage of the access doors was significantly higher than the exterior wall leakage. This finding is important. It indicates that the suite access door can be a major airflow path between the corridor and suite. Consequently, the leakage of the suite access door needs to be determined in assessing the performance of suite ventilation.

Tamura and Shaw (1976a) tested the airtightness of stair shafts and their doors in eight mid- and high-rise buildings. The doors they tested were similar in size to suite access doors. Our analysis of the reported test data indicates the ELA of these doors was in the range of 140 to 374 cm^2. The corresponding average gap between these doors and their frames was reported to be in the range of 2.0 to 4.6 mm. It is not clear if these average gaps were related to only the top and side gaps between the door and its frame or if they were related to the gaps around the entire perimeter of the door (including the gap between the door and the floor or threshold plate).

Colliver, Murphy, and Sun (1994) presented a database of effective leakage areas (4 Pa reference pressure difference and a reference discharge coefficient of 1.0) for components of low-rise residential buildings. Their database includes data for single doors without weather-stripping (12 to 53 cm^2 per door). Assuming a flow exponent of 0.5, these values represent an ELA range (10 Pa reference pressure difference and reference discharge coefficient of 0.611) of 20 to 87 cm^2 per door, which appears to be too low for typical suite access doors that do not have weather-stripping.

Colliver et al's database also indicates that the leakage between a door and its frame (such as for the suite access door) can be larger than the range of values described above for the single door. The reason for the discrepancy is unknown. They reported effective leakage areas of 8 to 10 cm^2/m of door jamb perimeter and 2 to 24 cm^2/m of door threshold length. For comparison purposes, we converted the effective leakage areas per unit length to ELA. The conversion assumed a typical suite access door is 0.9 m wide and 2.0 m high and has a flow exponent of 0.5. Our analysis of these data indicates that the total ELA between the door and its frame is in the range of 79 to 326 cm^2. These values are slightly lower than those determined from Tamura and Shaw's data. The door and gap sizes for Colliver et al's data were not provided.

ASHRAE has also published the Colliver et al data described above in the ASHRAE Fundamentals Handbook (ASHRAE 1993a, ASHRAE 1997). It is important to note that the 1993 I-P Edition of the ASHRAE data contained errors. Specifically, the door leakage data described above in the 1993 ASHRAE data set were about a factor of ten too high compared to the Colliver et al publication. The errors appear to have been corrected in the 1997 I-P Edition of this handbook. The errors did not appear in the S-I editions of these handbooks.

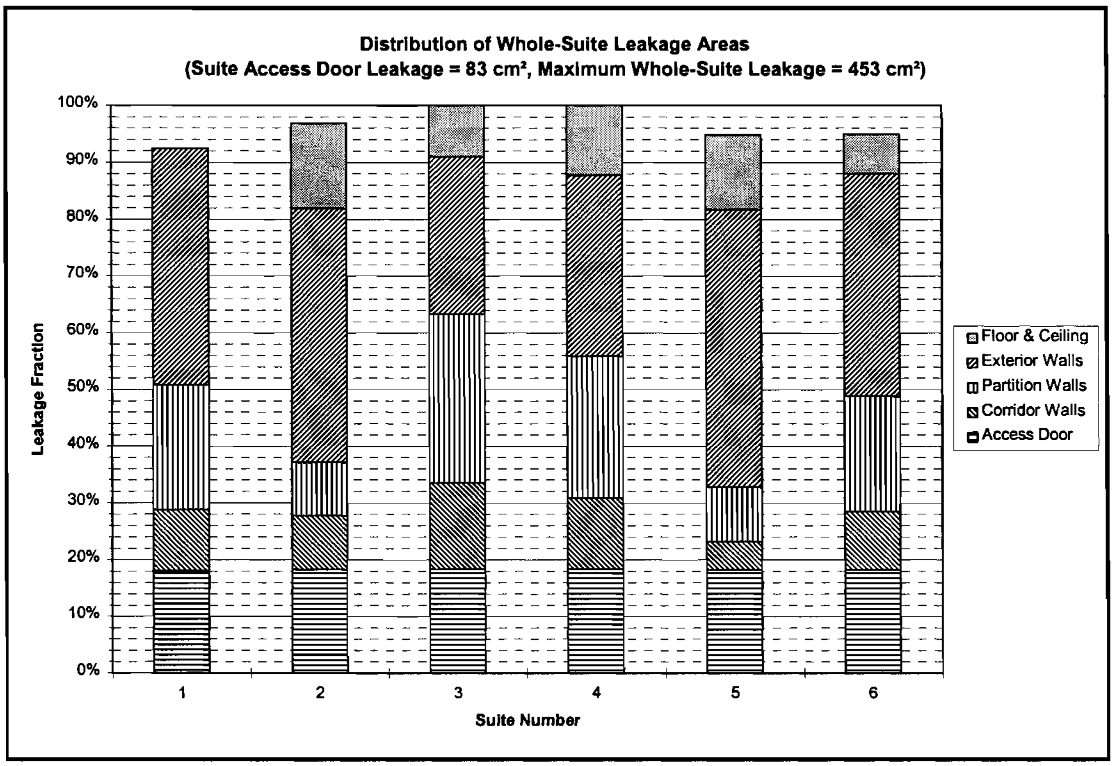
The door leakage data from Tamura and Shaw and from Colliver et al that are described above are useful, but incomplete. To determine whether these data are reasonable representations of suite access door leakage, we examined a theoretical method for calculating this leakage. ASHRAE (1992) presents a method developed by Gross and Haberman for calculating the ELA of gaps between doors and their frame. The method uses empirical relationships between flow and pressure difference. These relationships depend on the geometry of the door frame and on the size of the gaps between the door and its frame.

Using the ASHRAE method, we calculated the ELA for a hypothetical suite access door assuming a typical door is 0.9 m wide, 2.0 m high, and 45 mm thick. We also assumed the top and side gaps are in the range of 2 to 5 mm, the bottom gap is in the range of 2 to 20 mm, the door stop thickness (parallel to the door) is 15 mm, and there is no weather-stripping on the door. We expect that correctly-installed weather-stripping would tend to significantly reduce the ELA of the suite access door. The calculated ELA range for the hypothetical door is 83 to 496 cm^2 (average 290 cm^2).

The calculated ELA range includes all of the data reported by Tamura and Shaw and most of the data reported by Colliver et al. Therefore, it appears that the leakage data by Tamura and Shaw and by Colliver et al. are reasonable approximations for the ELA of suite access doors without weather-stripping. Furthermore, the ELA of suite access doors is evidently highly sensitive to the size of the door and to the size of the gaps around it. These sizes must be reported with the door ELA (including the reference pressure and reference discharge coefficient of the ELA) for the leakage data to be meaningful.

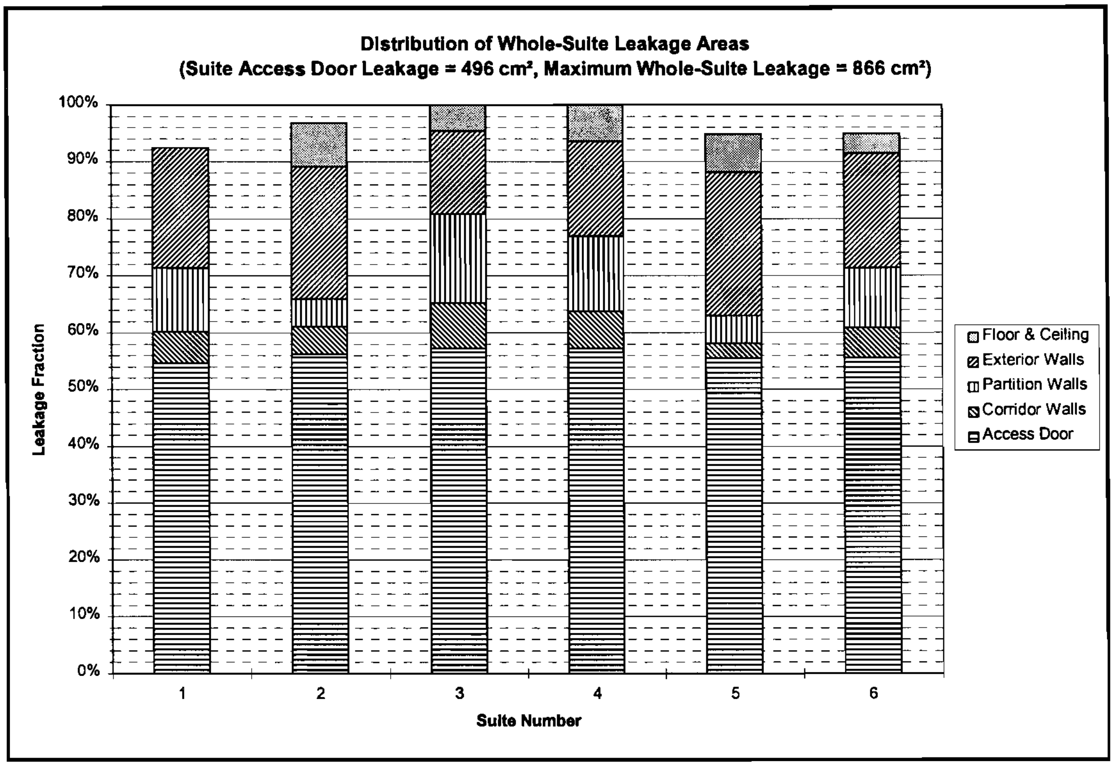
Figures 3 and 4 show the expected distribution of component leakage areas when Shaw and Magee's data are combined with the minimum and then the maximum leakage areas that we calculated for the suite access doors.

Figure 3: Suite Leakage Area Distribution (Tightest Door)



The distributions shown in Figures 3 and 4 indicate that the leakage between the suite and corridor is significant, that half to almost all of this leakage can be attributed to the suite access door, and that this leakage can be significantly lower or greater than the exterior wall leakage. This finding is consistent with Shaw's test results (1980a).

Figure 4: Suite Leakage Area Distribution (Leakiest Door)



More recent data by Shaw et al. (1990) also help to support this finding. They tested the airtightness of two suites, one in each of two high-rise apartment buildings. Their test data indicate the equivalent leakage area (ELA) of the exterior wall (including windows and doors) was in the range of 56 to 72 cm^2 (5.1 to 6.4 cm^2/m^2 of exterior wall area). The total leakage areas of each suite and the leakage areas of the suite access doors were not reported by the authors. However, the ELA range for the exterior wall is near the lower end of the ELA range that we calculated for the suite access door (83 cm^2). This indicates that suite access door leakage can be similar to or significantly greater than exterior wall leakage.

Shaft Leakage

Several studies have examined the leakage size of vertical shafts within buildings, such as Tamura and Shaw (1976a) and Achakji and Tamura (1988). These studies have shown that leakage areas within shafts along their length are extremely large compared to the leakage areas of most other openings in buildings (including the leakage areas of walls and closed doors located between the shafts and the remainder of the building).

For example, Achakji and Tamura carried out tests of a ten-storey conventional stair shaft. They used their data to create a model of the shaft leakage from storey to storey along the length of the shaft. The model treats the shaft as a frictionless duct that is subdivided into a series of compartments. These compartments are separated by equal flow resistances (leakage areas), which are each located at the height of a floor. To illustrate this model, consider a three-storey high shaft. The shaft leakage would be represented by three compartments and two flow resistances, with one resistance located at the height of the second storey floor and the other located at the height of the third storey floor. Achakji and Tamura's results indicated that the inter-storey leakage area per storey of an unoccupied stair shaft is in the range of 21% to 24% of shaft cross-sectional area. Based on their data, the equivalent leakage area (ELA) within the stair shaft they tested is in the range of 26,000 to 30,000 cm² per storey. The large variation in leakage areas is due to differences in stair type (open versus closed treads).

Two characteristics of vertical shafts can be inferred from these data. First, vertical shafts are likely a major path for air transport within a building, because of their low resistance to airflow. Second, other openings in the building that are in series with the shafts (such as closed stair doors) will control flows in the shafts, because the leakage areas of these other openings are much smaller than the leakage areas of the shafts.

2.3.3 Summary

In summary, the available literature indicates there can be a variance in the airtightness of suites within a single building. It appears that the corridor wall, ceilings, and floors are minor leakage sites, whereas the exterior walls are major leakage sites. Partition walls between suites are somewhere in the middle of the leakage range.

Based on available data and on calculated door leakage areas, the leakage between the suite and corridor is significant and can be significantly lower or greater than the exterior wall leakage. Furthermore, half to almost all of this leakage can be attributed to the suite access door. It is also evident that the leakage area of suite access doors is highly sensitive to door size and the size of gaps around it.

Therefore, in assessing the performance of suite ventilation, it is extremely important to determine the types, locations, and sizes of the leakage openings in the suite. In particular, the geometry and leakage of the suite access door needs to be determined.

2.4 Driving Forces

The pressure difference across a leakage opening is the result of the combined effects of one or more of three types of driving forces. Two of the forces occur naturally and are uncontrollable. These are the stack and wind effects. The third force is intentional and is controllable. It is caused by the operation of mechanical ventilation equipment such as fans or combustion appliances.

The following discussion first describes each of the three driving forces in isolation and the parameters that determine their magnitudes. Finally, the effects of combining the three driving forces are discussed, along with an example of the relative magnitudes and directions of these forces.

2.4.1 Pressure Differences Caused by Stack Effect

Indoor-outdoor temperature differences cause buildings to behave like a fireplace chimney or stack. For example, during the winter, warm air inside a building is more buoyant than the cold air surrounding the outside of the building. This difference in buoyancy results in a pressure rise at the top of the building compared to outdoors and a pressure reduction at the bottom of the building compared to outdoors. The resulting indoor-outdoor pressure differences cause air to flow through leakage openings in the building envelope. This phenomenon is called the stack effect.

The theoretical stack-induced pressure difference at a leakage opening can be calculated from the following equation (ASHRAE 1992):

$$\Delta P_{s,t} = (h - h_{NPP}) \cdot \left(\frac{g \cdot P_{atm}}{R} \right) \cdot \left(\frac{1}{T_o} - \frac{1}{T_i} \right) \qquad \textbf{\textit{(Equation 2)}}$$

where

$\Delta P_{s,t}$	=	theoretical pressure difference at leakage opening due to stack effect, Pa,
g	=	gravitational constant, 9.80665 m/s^2,
P_{atm}	=	atmospheric pressure, nominally 101,325 Pa,
R	=	gas constant for air, 287.055 J/(kg·K),
T_o	=	outdoor absolute temperature, K,
T_i	=	indoor absolute temperature, K,
h	=	leakage opening elevation relative to building or storey bottom, m, and
h_{NPP}	=	neutral pressure plane elevation relative to building or storey bottom, m.

Due to pressure losses through leakage openings within the building, actual pressure differences induced by the stack effect are always less than or equal to the theoretical pressure differences determined using Equation 2. The ratio of the actual to theoretical stack-induced pressure difference is defined as the thermal draft coefficient (TDC).

The following discussion describes the various parameters that determine the magnitude and direction of the stack effect. These include the neutral pressure plane location, temperature effects, and the thermal draft coefficient. The effects of wind- and mechanically-induced driving forces are excluded from this discussion.

Neutral Pressure Plane Location

In between the top and bottom of a building, there is a set of points that have no indoor-outdoor pressure difference due to the stack effect. These points define the edges of the neutral pressure plane (NPP) for the building envelope. Leakage openings located at these points have no flow between indoors and outdoors due to the stack effect.

For openings located below the NPP, the outdoor pressure is greater than the indoor pressure. Consequently, outdoor air flows into the building through these openings. To satisfy flow continuity, the same mass of indoor air flows to the outdoors through the leakage openings located above the NPP. This flow pattern means that air from stories located below the NPP will flow upward to stories located above the NPP. Most of this airflow will occur through the low-resistance vertical shafts rather than through the higher-resistance openings in floors or ceilings of each storey.

In a mid- or high-rise residential building, this upward flow pattern can be undesirable if stack-induced pressure differences exceed mechanically-induced pressure differences. In this case, transfer air from suites located below the NPP can mix with the outdoor air that is supplied to corridors located above the NPP. The mixed air in the corridor ultimately flows into the suites located above the NPP as ventilation air.

The location of the NPP depends primarily on the vertical distribution of leakage openings over the building envelope and within the building. For an even distribution of openings, the NPP is located at the mid-height of the building. A non-uniform distribution causes the NPP to shift toward the location of the larger leaks. This shift of NPP is important, because it will cause changes in the heights of the leakage openings in the building envelope relative to the NPP. As Equation 2 shows, the changes in height will result in changes to the stack-induced pressure differences across these leakage openings.

The vertical distribution of leakage openings can vary due to occupant interactions. As a result, the location of the NPP is not static. For example, when an exterior door in the ground floor lobby of a building is opened, the NPP shifts toward the base of the building. The amount of shift will depend on the relative magnitude of the open door's leakage area compared to the magnitude of the parallel leakage area in the building envelope. A tight building envelope will be more susceptible to NPP shifts caused by door openings than a leaky envelope.

A second example of varying leakage distribution due to occupant interactions is the opening of a door between a stair shaft or elevator shaft and a corridor. In this case, the open door reduces the combined series resistance between the building envelope and shaft. As a result, the building envelope appears to be leakier at the elevation of the open door. The NPP will shift toward this elevation. The amount of shift depends on the relative magnitude of the open door's leakage area compared to the magnitude of the series leakage area for the path from the shaft to the building envelope. The smaller leakage area will control the amount of NPP shift.

Both of the above examples describe openings that are usually short-term. A third example is occupants on upper stories opening windows for longer periods of time in an attempt to improve comfort conditions within their suites (Diamond et al. 1986). This could result in prolonged upward shifts of the NPP and increased stack-induced pressure differences on lower stories of the building. A possible result is increased transfer airflows from the lower suites to the upper suites if the mechanical ventilation system has insufficient capacity to offset the increased stack effect on the lower stories.

It is important to recognize that there can be several neutral pressure planes within a building. For example, one stair shaft usually has access to the roof through a door. In some buildings, there can be substantial leaks between the door and its frame or there may be a leaky vent in the roof of the shaft. As a result, the shaft with roof access is taller and has a different vertical leakage distribution compared to the other stair shaft. In this case, the NPP in the shaft with the roof access may be located higher than in the other stair shaft. In some cases, differences in shaft characteristics could result in a NPP shift of as much as one storey for one shaft compared to another shaft. Elevator shafts with penthouse mechanical rooms are another example where this phenomenon occurs.

Temperature Effects

Variations in outdoor temperature cause the magnitude of the stack effect to vary considerably. These same temperature variations can also reverse the direction of the stack effect. During summer months, warmer temperatures outdoors can cause air to flow in through the upper leakage openings and out through the lower openings. However, the maximum magnitude of the summer stack effect is typically less than that of the winter stack effect. Maximum indoor-outdoor temperature differences tend to be higher in the winter than in the summer throughout Canada. During mild spring and fall days, there can be almost no stack effect even for openings at the top or bottom of the building, because the indoor-outdoor temperatures are near zero.

Stack effects can also occur within a building due to differences in temperatures between adjacent compartments. An example of this latter phenomenon is a cool stair shaft located on an exterior wall and adjacent to warmer interior corridors. In this case, a reverse stack effect can occur when outdoor temperatures are considerably lower than indoors and the building envelope is tight. As a result, there can be flow from upper corridors into the stair shaft and flow from the stair shaft into lower corridors. These internal stack effects can also alter the NPP location for the entire building.

Thermal Draft Coefficient

As defined immediately following Equation 2, the thermal draft coefficient (TDC) is the ratio of the actual to theoretical stack-induced pressure difference. The magnitude of the TDC depends on the leakage of the building envelope relative to the combined leakage of the interior separations (Tamura and Shaw 1976b, Shaw and Tamura 1977).

For a building with very leaky separations between stories and a relatively airtight building envelope, the TDC is near one. In contrast, a building with very tight separations between each storey and a relatively leaky building envelope, the TDC is near zero.

Interestingly at both extremes, the TDC is one. A building with a uniform distribution of envelope leakage openings of the same size and that is completely open inside has the same TDC as the same building that is completely sealed between each storey. However, the theoretical stack effects are different in each case. For the completely open building, the stack effect can extend over the entire height of the building. However, for the building with completely separated stories, each storey acts independently and the stack effect is limited to the height of one storey. Hence, the magnitude of the stack effect is generally less at the top and bottom of each storey in the latter case.[1]

TDC data are not available for mid- and high-rise residential buildings due to the difficulty of determining these data in occupied buildings of this type. However, measurements of actual stack effects in tall office buildings (ASHRAE 1997) indicate the TDC is in the range of 0.8 to 0.9 for these other buildings. In some cases, it can be as low as 0.63 (Tamura and Shaw 1976b). We expect that a mid- or high-rise residential building will have a lower TDC than an office building, because the residential building is tighter inside (fewer vertical shafts and more inter-compartment separations). Therefore, assuming the TDC is 0.8 will likely provide a conservative estimate of the stack effect in real mid- and high-rise residential buildings.

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[1] This is not true for the stories immediately above and below the NPP in a building of this type with an odd number of stories of the same height. Due to the isolation between stories, the magnitude of the stack effect in this case will be greater at the floor level of the upper storey and also at the ceiling level of the lower storey. Furthermore, each storey will have a separate NPP where the pressure difference across the envelope is zero.

2.4.2 Pressure Differences Caused by Wind Effect

When wind flows around a building, the wind speed near the building is altered. This disturbance of the wind field produces a distribution of static pressures over these surfaces. Compared to the static pressure of the undisturbed wind region, the surface static pressures are usually higher on the windward faces of the building and lower on the leeward faces and on the roof.

Due to these wind-induced surface pressures and the presence of leakage openings on the exterior surfaces, pressure differences across the envelope and pressures inside the building will change. The interior pressures will adjust so that the total amount of outdoor air flowing into windward leakage openings is equal to the total amount of indoor air flowing out of leeward leakage openings (including the roof). This phenomenon is called the wind effect.

Wind-induced flows across a building (from the windward suites to the corridor and then into leeward suites) are usually undesirable, unless the building has been deliberately designed to use this effect. This flow pattern can result when wind-induced pressures are larger than the mechanically-induced pressurization of windward suites or the corridor. The probability of this event occurring increases when windows located on windward or leeward walls are opened by occupants. With this flow pattern (in the absence of other driving forces), the flows from the corridor to the windward suites are reversed. As a result, the flows from the windward suites into the corridor can cause the contamination of both the corridor and the leeward suites.

Wind effects tend to be more complex and variable than the stack effect due to the natural variability of wind speed and direction. The wind-induced static pressure difference at a leakage opening is dependent on two pressures: the velocity pressure of the undisturbed wind and the pressure inside the building. This pressure difference can be calculated using the following equation (ASHRAE 1997):

$$\Delta P_{w,s} = \left(C_p - C_{in}\right) \cdot \left(\frac{g \cdot P_{atm}}{2 \cdot R \cdot T_o}\right) \cdot v^2 \qquad \textbf{\textit{(Equation 3)}}$$

where

$\Delta P_{w,s}$ = static pressure difference at leakage opening due to wind effect, Pa,
C_p = surface pressure coefficient, dimensionless,
C_{in} = interior pressure coefficient, dimensionless,
g = gravitational constant, 9.80665 m/s^2,
P_{atm} = atmospheric pressure, nominally 101,325 Pa,
R = gas constant for air, 287.055 J/(kg·K),
T_o = outdoor absolute temperature, K, and
v = local wind speed in undisturbed air stream, m/s.

The following discussion describes the various parameters that determine the magnitude and direction of the wind effect. These include the surface pressure coefficient, interior pressure coefficient, wind speed, outdoor temperature, and barometric pressure.

Surface Pressure Coefficient

The surface pressure coefficient for each leakage opening depends on the location of the leakage opening, on the building geometry and orientation, and on wind direction. It is independent of static pressures outside and inside the building. Surface pressure coefficients are usually in the range of -0.8 to 0.8 (ASHRAE 1992, 1997). They are generally positive for windward walls and negative for leeward walls. Winds at an angle to the walls can sometimes produce negative coefficients near the downstream edges of windward walls.

Actual surface pressure coefficients for an *existing* building can be determined by full-scale testing. However, these tests are difficult and time-consuming due to the uncontrollable natural variations in wind speed and direction. These problems are also due to the need for measuring pressures simultaneously on all four exposed walls. In most cases, the coefficients can be more conveniently determined by well-controlled boundary layer studies using a model of the building and its surroundings in a laboratory wind tunnel. For a building that is still in the *design* stage, the full-scale approach cannot be used. The laboratory modelling approach is often impractical or uneconomical during design. Both approaches were beyond the scope of this project.

As an alternative to full-scale or laboratory testing, surface pressure coefficients can be estimated using equations developed by Swami and Chandra (1988). Their equations are based on non-linear regressions of surface pressure coefficient data from various experimental sources. Correlation coefficients for their regressions are in the range of 0.80 to 0.88. Swami and Chandra indicated that the ventilation rates they calculated using their equations were within 11% of measured rates for one "low-rise" building. While the coefficients calculated using these equations are not exact, they are useful as a first approximation to demonstrate the impact of wind effects on suite ventilation in mid- and high-rise residential buildings. The use of these types of calculations has been reported by Shaw and Tamura (1977), Shaw and Jones (1979), Shaw (1979 and 1980b), Aynsley (1989), and Scanada (1991).

Swami and Chandra presented two equations: one for "low-rise" buildings and one for "high-rise" buildings. Their building type definitions are not conventional and are based on geometry rather than on the number of stories. Specifically, they defined "low-rise" buildings as those with a long- to short-wall ratio (LW/SW) between 1 and 8 and an eave-height to short-wall ratio (EH/SW) between 0.1 and 0.4. "High-rise" buildings have a narrower LW/SW range (between 1 and 4) and a considerably larger EH/SW ratio (between 1 and 8). Many buildings that are conventionally defined by their number of stories as mid-rise or even as high-rise can be represented using Swami and Chandra's "low-rise" equation due to their geometric proportions.

Each of Swami and Chandra's equations correlates surface pressure coefficients with wind angle and building geometry. For any particular face of the building, this angle is the difference between the orientation of the face and the wind direction. This angle can vary for each face as the wind direction varies over time. Both equations depend on the LW/SW ratio described above. In addition, the "high-rise" equation depends on the horizontal and vertical location of the leakage opening on the relevant wall (that containing the leakage opening of concern). Additional parameters are used in the "high-rise" equation, because spatial variations in surface pressure coefficients tend to be larger for these types of building than for "low-rise" types, particularly in the vertical dimension.

It is important to note that the published coefficients for Swami and Chandra's "high rise" equation are incorrect. The published coefficients did not produce surface pressure coefficients that were symmetrical about the vertical centerline of windward walls for winds that are perpendicular to the wall. The original 14 coefficients have been replaced with 12 new coefficients (Swami 1996). These new coefficients resolved this lack of symmetry problem.

To use Swami and Chandra's equations in characterizing wind effects on suite ventilation, it is important to collect data that characterize the building geometry. In addition to also determining building orientation and wind direction, data describing a suite's location in the building need to be collected.

Interior Pressure Coefficient

In the absence of other driving forces, static pressures inside a building are determined entirely by the wind-induced surface pressures and by the nature of the leakage openings in the building envelope and within the building.

The analysis of wind-induced interior pressures is complex, however. With several compartments per storey and with leaks between compartments, it is necessary to carry out a multi-compartment analysis of interior pressures to determine inter-suite and indoor-outdoor pressure differences and flows. To carry out a multi-compartment analysis, it is necessary to know the leakage area distribution for each storey.

Shaw and Tamura (1977) have indicated that the primary flow inside an open-plan office building is from the windward side to the leeward side with little vertical flow. Their results indicate that wind effects for individual stories can be analyzed independent of other stories. As a result, the leakage area of walls is of more importance than that of ceilings and floors in determining the magnitude of interior pressures. This simplifies the analysis of wind-induced interior pressures somewhat in that fewer leakage data are required. We expect these findings can also be applied to mid- and high-rise residential buildings.

As noted earlier in the Section 2.3, all the leakage areas in the exterior and interior walls can be highly variable, so building-specific leakage data are still required. For example, the leakage of a suite's exterior wall can be greater or less than the leakage of the corridor wall and suite access door assembly. Furthermore, the exterior wall is expected to be leakier than the partition walls that separate the suite from other suites. The primary reason for this expectation is that exterior doors, windows, and duct openings significantly contribute to the leakage of the exterior wall assembly. In contrast, the inter-suite partition wall assemblies typically do not contain these building elements.

Unfortunately, wall leakage data are not easily determined for an *existing* building. Furthermore, determining these leakage areas during building *design* is impossible. Designers must instead rely upon wall leakage data from published experimental data and on theory. Determining these leakage data was also beyond the scope of this project.

Due to the difficulties in obtaining building-specific wall leakage data, an alternative approach to multi-compartment analyses for determining interior pressures is desirable. ASHRAE (1997) and Hutcheon and Handegord (1995) have indicated that the interior pressure can be determined by spatially averaging the surface pressure coefficients for the exterior walls. The average value represents the interior pressure coefficient and is about -0.2 for most wind directions (for "low-rise" and "high-rise" buildings). The use of this coefficient assumes that leakage openings are evenly distributed on the building exterior and that internal flow resistances are insignificant. Both of these assumptions may not be completely true for all mid- and high-rise residential buildings. However, the use of the interior pressure coefficient serves as a first approximation to demonstrate the impact of wind effects on suite ventilation in these types of buildings. With an interior pressure coefficient of -0.2, the pressure coefficient difference term in Equation 3 will typically range from -0.6 to 1.0.

It is important to recognize that wind effects can shift the neutral pressure plane location, because they alter the pressure regime within and around a building. Windward walls are pressurized from outdoors, which causes the windward edges of the NPP to rise for those walls. Leeward walls are depressurized from outdoors, which causes the leeward edges of the NPP to drop. As a result, the edges of the NPP do not necessarily form a horizontal plane. In some extreme cases, an edge of the NPP can be considered as being located at or beyond the top or bottom of the building. If the edge of the NPP is located at or below the bottom of the building, then all flows through the wall with that edge are towards outdoors. Conversely, if the edge of the NPP is located at or above the top of the building, then all flows through the wall with that edge are inward from outdoors.

Wind Speed

Wind-induced static pressure differences depend on the velocity pressure of the approaching wind, which varies as the square of the wind speed. As a result, the static pressure differences are highly dependent on wind speed. Therefore, accurately knowing the on-site wind speed is extremely important.

The wind speed reference height on which surface pressure coefficients are based varies according to building type. Using Swami and Chandra's building types, the reference location is the top of the building for "low rise" buildings. For "high-rise" buildings, the reference location is the height of the leakage opening instead. As a result, wind speed data measured at a particular elevation must sometimes be interpolated or extrapolated to the appropriate reference height for the building of interest.

Wind speeds at a building site generally differ from those measured at local meteorological stations. Typically, these stations are located in open terrain with no shielding and are often a considerable distance from the building site. Wind speed measurements at these stations are usually made about 10 m above ground level. This measurement height is considerably below the tops of typical mid- and high-rise residential buildings. For normal undisturbed wind, wind speed increases with height above ground according to a power-law relationship due to boundary layer effects (ASHRAE 1997). Boundary layer depths can vary from about 300 m over open flat terrain to about 500 m over the center of large cities. This means that wind speed data from typical meteorological stations must be extrapolated for use with these types of buildings.

Terrain and shielding effects near building sites complicate the extrapolation of data from meteorological stations. These effects tend to reduce wind speeds at building sites, because the buildings are not usually located in open terrain and are sometimes shielded by other buildings. Changes in wind direction can also result from terrain and shielding effects.

Due to the numerous parameters that affect wind speed, it is difficult for designers to determine on-site wind speed from local meteorological data. In particular, the use of extrapolated wind speed data may lead to significant uncertainty when calculating wind effects for leakage openings that are located at building elevations higher than the wind measurement height. Swami and Chandra (1988) indicated that uncertainties in wind speed estimates can be greater than the uncertainties in surface pressure coefficient estimates. Therefore, it is preferable where possible to measure wind speed and wind direction on-site above the top of the actual building (Hutcheon and Handegord 1995).

Wind speeds around a building fluctuate rapidly due to turbulence in the approaching wind and due to unsteady flows that occur when the wind boundary layer separates from the building exterior. Peak speeds and surface static pressures can be significantly higher than average values. However, the relatively small size of leakage openings and large building volumes tend to attenuate the effects these peaks and other high-frequency wind speed variations on ventilation flows (Davenport and Surry 1984). As a result, wind speeds averaged over a period of about 5 to 20 minutes are considered to be appropriate in analyses of wind-induced ventilation flows (ASHRAE 1997).

Outdoor Temperature and Barometric Pressure Effects

Wind-induced pressure differences also depend on the outdoor air density. The middle term of Equation 3 represents air density and shows that it is a function of outdoor temperature and barometric pressure.

Due to the typical magnitudes of outdoor temperature and barometric pressure, variations in outdoor temperature usually have a more significant impact on air density than variations in barometric pressure. For a cold climate, the winter outdoor temperature deviations from the standard condition (293°K) can be significant (up to 60°K). These temperature variations can result in air density variations as large as 22% compared to standard conditions. Barometric pressure induced variations in air density are more likely in the range of about 2% (based on a standard condition of 101,325 Pa).

Therefore, it is important to measure the outdoor temperature on-site when analyzing wind-induced pressure effects on suite ventilation. In contrast, the average barometric pressure reported by a local meteorological station can probably be used in these analyses without significant loss of accuracy. The barometric pressure should be corrected to the elevation of the building site, because most stations report the barometric pressure corrected to sea level.

2.4.3 Pressure Differences Caused by Mechanical Equipment

Mechanically-induced pressure differences act as a controllable driving force that can supplement or counteract the pressure differences created by natural forces. This force is usually induced by the operation of mechanical ventilation systems. It can also be induced to a lesser extent by the operation of combustion equipment that is vented outdoors and that has no direct connection for combustion air supply.

The following discussion describes the impacts on suite ventilation of operating mechanical ventilation systems in mid- and high-rise residential buildings. It separates the equipment into three types: air supply systems, air exhaust systems, and in-suite circulating systems. It also describes the impact of operating combustion equipment in these types of buildings. Equipment and design installation practices discussed here are based on a review we conducted of drawings and specification documents for the ten buildings we tested in this project. They are also based on an informal survey we conducted of 25 people that design mechanical ventilation systems for Canadian mid- and high-rise residential buildings.

Mechanical Ventilation Systems

The operation of mechanical ventilation systems affects the pressures inside the building and can shift the neutral pressure plane location. Supply systems pressurize the building and suites from indoors and cause the NPP to drop. Exhaust systems depressurize the suites and building from indoors and cause the NPP to rise. In some cases, the NPP can be considered as being located at or beyond the top or bottom of the building. If the NPP is located at or below the bottom of the building, then all flows through the building envelope are towards outdoors. Conversely, if the NPP is located at or above the top of the building, then all flows through the building envelope are inward from outdoors.

Air Supply Systems

In mid- and high-rise residential buildings, one mechanical ventilation system typically supplies 100% outdoor air continuously to the corridors. Sometimes a time clock is used to shutdown this system in an attempt to conserve energy. One or more central "constant volume" fans that are mechanically powered provide the driving force in these systems. The central fans supply outdoor air through vertical ducts connected to corridors. They sometimes also supply air to equipment rooms, service rooms, elevator lobbies, and entrance lobbies. As air flows through the ducts, the static pressure within the duct decreases due to friction and turbulence effects. Designers usually size the ducts to reduce these pressure drops.

The corridor supply air system is usually designed to pressurize the corridors relative to the suites and to provide some of the makeup air required by the in-suite exhaust systems. Rarely is it designed specifically to provide ventilation for the suites. In the absence of other driving forces and when in-suite exhaust equipment is not operating, the corridor supply air system will also pressurize the suites relative to outdoors and will provide suite ventilation, because the suites are not completely isolated from the corridor or outdoors. (Section 2.3 discussed this isolation in terms of leakage opening characteristics, with particular emphasis on the effects of suite access door leakage).

The amount of air supplied to any particular corridor and surrounding suites is dependent on several parameters. These parameters include: the sizes of the intake grilles, louvers, hoods, and ducting that are upstream of the fan; the capacity and pressure created by the system fan; the distance of the specific supply air outlet from the fan; the positions of the balancing damper and the supply air outlet louvers; the corridor and building envelope leakage areas; and the static pressures in the corridor and suites.

By continuity, air can only flow into the corridor if the same amount of air flows out of the corridor and ultimately to outdoors through the building envelope. A tight corridor or building envelope will reduce the amount of air that can flow out of the corridor. This causes increased static pressures in the corridor and suites, which reduces the supply flow into the corridor. The leakage of corridor and building envelopes is not currently specified in the design of corridor supply air systems and is not controlled once the building is occupied. As a result, there is no control of corridor supply airflows or corridor pressures.

It is important to recognize that pressurizing the suites themselves (and therefore the building envelope) is undesirable. Unlike corridors, suites can have significant moisture sources. Pressurizing the suites can force moist air from the suites into the envelope, where the moisture can condense or freeze and cause damage to insulation or structural elements.

Air Exhaust Systems

One or more separate systems exhaust air from the suites to outdoors. The complexity of mechanical exhaust systems can vary from minimal (separate in-suite systems) to elaborate (central systems that connect to several or all suites). The in-suite systems usually run intermittently whereas the central systems usually run continuously. Some buildings also use time-clocks to switch off the central systems at night in attempts to conserve energy.

Intermittent exhaust systems such as in-suite kitchen or bathroom exhausts are usually occupant-controlled by a manual or humidistat-activated switch located within the suite. With the manual switch, the exhaust system only runs when the occupants feel there is need for increased ventilation. With the humidistat-activated system, the system runs whenever the humidity in the suite exceeds a preset setpoint. The setpoint is adjustable by the occupants. Intermittent exhaust systems within a suite can also include other devices such as clothes dryers vented to outdoors. These other devices are also occupant controlled.

The intermittent systems tend to use small low-pressure fans to exhaust indoor air from the suites through ducts connected to outdoors. Most of these fans are typically rated at a static pressure difference of about 25 to 60 Pa. Stall pressures for some of these devices can be in the range of 30 to 50 Pa (Caneta 1992). The ducts connected to these fans often include several elbows and are long, because the kitchens and washrooms are not usually located near exterior walls. As air flows through these ducts, the static pressure within the duct decreases due to friction and turbulence effects. Designers usually oversize the fans in an attempt to compensate for these pressure losses. However, designers rarely specify static pressure requirements for these systems.

Continuous exhaust systems typically have one or more central "constant volume" fans that are connected by vertical ducts to several or all of the suites within the building. Various other areas of the building such as common kitchens, equipment and service rooms, garbage chutes, and parkades are sometimes also connected to these systems. Often in these systems, branch ducts and exhaust grilles are installed without balancing devices, such as dampers.

All of the suite exhaust systems are intended to provide supplemental ventilation for a suite. As a result, these exhaust systems require that makeup air (primarily outdoor air) enter the suite to replace the exhausted air. The corridor supply air systems are intended to provide some of this makeup air. Designers expect that the remainder of the makeup air will be provided by outdoor air infiltration through exterior walls. Only in exceptional buildings are transfer ducts provided between the corridor and suite or between outdoors and the suite for makeup air. Consequently, makeup airflows are typically dependent on the uncontrolled leakage areas of the corridor wall, suite access door, and exterior walls. They are also dependent to a lesser extent on ceiling, floor, and inter-suite partition wall leakage.

The amount of air exhausted from any particular suite is also dependent on the suite leakage area and on the static pressure regime within and around the suite. By continuity, air can only flow out of the suite if the same amount of air flows into the suite. Small leakage areas will reduce the amount of air that can flow into the suite. This results in a decreased suite static pressure that reduces the exhaust flow from the suite. Suite leakage is not currently specified in the design of exhaust systems and is not controlled once the building is occupied. As a result, there is no control of exhaust flows from suites or of in-suite pressures.

In-Suite Circulating Systems

Mechanical systems are sometimes located inside suites of mid- and high-rise residential buildings for the purposes of circulating air within the suite. These systems include devices such as in-suite fan-coil units and heat pumps with or without ducting. The air-side components of these systems do not extend beyond the perimeter of the suite and do not connect to outdoors. As a result, these systems do not affect airflows and pressures between the suite, the corridor, other suites, and outdoors. Their only effect on ventilation airflows is to alter the distribution pattern within a suite.

Combustion Equipment

In-suite combustion equipment such as fireplaces are not common in mid- and high-rise residential buildings. However, when this type of equipment is installed, it is usually a sealed unit. This type of equipment is not expected to affect pressures or ventilation flows in suites. For suites located on the windward side of the building and below the neutral pressure plane, it is possible that combustion gases vented outdoors from lower suites could sometimes contaminate outdoor air flowing into the higher suites.

The use of atmospherically-vented central combustion equipment is common in mid- and high-rise residential buildings. Equipment types include heaters that warm the air for the corridor supply air system, as well as boilers for space and water heating. These types of equipment require large quantities of air for combustion. Typically, the combustion air is provided through an intentional opening to outdoors in the mechanical room where the equipment is located. This air is subsequently vented outdoors, along with other combustion gases and entrained room air. As a result, combustion equipment that is vented outdoors can be considered to be a large exhaust device.

If the mechanical room containing the combustion equipment does not have sufficient leakage for combustion makeup air directly from outdoors, and if the mechanical room is poorly isolated from the remainder of the building, then the operation of the combustion equipment will affect building pressures and may affect pressures within suites. Conversely, these pressures can affect the operation of the combustion equipment.

2.4.4 Pressure Differences and Airflows Caused by Combined Driving Forces

The following discussion describes the pressure differences and airflows that result from combining the stack-, wind-, and mechanically-induced driving forces. It also provides an example to illustrate the relative magnitudes of these three driving forces and their impacts on suite ventilation.

Combining Pressure Differences

The combined pressure difference across a leakage opening is the algebraic addition of the individual pressure differences caused by stack effect, by wind effect, and by the operation of mechanical equipment, as follows (ASHRAE 1997):

$$\Delta P = \Delta P_{s,a} + \Delta P_{w,s} + \Delta P_m \qquad \textbf{\textit{(Equation 4)}}$$

where

ΔP = combined pressure difference across leakage opening, Pa,
$\Delta P_{s,a}$ = actual stack-induced pressure difference across leakage opening, Pa,
$\Delta P_{w,s}$ = wind-induced static pressure difference across leakage opening, Pa, and
ΔP_m = mechanically-induced pressure difference across leakage opening, Pa.

Example

The following example is presented as an aid to understanding the effects of combining the three different driving forces. This example illustrates the relative magnitudes of these forces for a *high-rise* building. It also discusses the impact of each force on suite ventilation.

Consider a hypothetical, 100 m tall, 25 m by 25 m square building that is located in downtown Vancouver. Assume there is an even distribution of leakage openings over the building envelope. Also, assume the temperature inside the building is uniform at 20°C. Based on design winter weather conditions (ASHRAE 1997), the 99% design outdoor dry-bulb temperature is about -4°C in January and the coincident *mean* wind speed is about 11 km/h at Vancouver International Airport. These design conditions are likely to occur for only a few hours a year. The *maximum* hourly wind speed during winter for a 30 year period is 89 km/h at Vancouver International Airport (Environment Canada 1982a).

Assuming the NPP is located at the mid-height of the building and using a thermal draft coefficient of 0.8, the stack-induced indoor-outdoor pressure difference at the top of a suite located at the top of the building is about 42 Pa. A colder climate such as Winnipeg could result in a stack-induced pressure difference up to two times greater than that in Vancouver. The stack-induced pressure differences described here represent maximums and are likely to occur for only a few hours each year. Lower but still substantial pressure differences will exist throughout most of the heating season.

In addition to wind speed, terrain, and shielding, wind-induced pressure differences depend on suite horizontal and vertical location, wall orientation, and wind direction. Consider a corner suite at the top of the building with a windward wall. Based on Swami and Chandra's "high-rise" equation, on an interior pressure coefficient of -0.2, and on the *mean* wind speed of 11 km/h at the airport, the *mean* wind-induced pressure difference across the windward wall is estimated to be about 3 Pa for this suite. The pressure differences across leeward walls are generally lower compared to those across the windward wall. Vancouver has relatively low *mean* wind speeds compared to most other Canadian cities (Environment Canada 1982a). A windier city such as St. John's could result in a *mean* wind-induced pressure difference that is five times greater than that in Vancouver.

The wind-induced pressure difference for the *mean* wind speed (3 Pa) is considerably smaller than the pressure difference induced by the stack effect (42 Pa). However, the stack effect does not always dominate. For example, the *maximum* hourly wind speed of 89 km/h for Vancouver results in a considerably higher wind-induced pressure difference (about 217 Pa) for the windward wall. It is important to recognize that the *maximum* wind speed will not occur frequently. Typical wind pressures are more likely near the magnitude of that calculated using the *mean* wind speed. Therefore, it is likely that the stack effect will be the dominant driving force on cold winter days. On mild spring or fall days, the wind effect may dominate instead.

Few data are available regarding the magnitude of actual mechanically-induced pressure differences for combined fan and duct systems that serve corridors or suites in mid- and high-rise residential buildings. However, it is clear that stack-induced pressure differences across building elements can sometimes be significant in comparison to the typical safety factors used by some designers for corridor supply air systems (25 to 125 Pa). In particular, for buildings where the suite access doors are leaky compared to the envelope (as in many of the ten buildings tested in this project), the majority of the pressure difference between the corridor and outdoors will be across the envelope. Therefore, it is expected that the pressure differences across the envelope induced by stack effects sometimes will be near or exceed those that are induced by the corridor supply air system. If this occurs, then the winter stack effects can considerably reduce the outdoor airflows from the corridor supply air system into corridors that are located above the neutral pressure plane. At the same time, for suites located above the NPP, the winter stack effects can also assist the mechanically-induced flow of air from the corridor into the suites. For corridors and suites that are located below the neutral pressure plane, the reverse will be true. As a result, air can sometimes flow from windward suites below the NPP into leeward suites above the NPP. This occurs because the stack-effect drives airflows from corridors on lower stories into the corridors on upper stories, which are a source of air supply for the leeward suites above the NPP.

It is also likely that stack- and wind-induced pressure differences can sometimes significantly exceed the static pressure capabilities of in-suite exhaust systems. If this occurs, these naturally-induced pressure differences can reverse the intended direction of flows through these devices, particularly for suites located below the NPP.

For the hypothetical corner suite located above the NPP, the wind-induced pressurization of the windward exterior wall of the suite will tend to drive airflow into the suite from outdoors through this wall. Wind-induced suction on the leeward exterior wall of the suite will tend to drive airflow from the suite to outdoors through the leeward exterior wall of the suite. The stack effect, the operation of the corridor supply air system, and the operation of suite exhaust systems will tend to drive airflow from the corridor into the suite and will assist the tendency for air to flow from the suite to outdoors, but will counteract the tendency for air to flow from outdoors into the suite. At the same time, wind-induced suction on other leeward walls of the building will counteract the tendency for air to flow into the suite from the corridor and from the suite to outdoors, but will assist the tendency of air to flow into the suite from outdoors.

Combining Airflows

The total airflow through a leakage opening can be calculated using Equation 1, if leakage data and the combined pressure difference are known. Unlike the combined pressure difference, this airflow is not the algebraic addition of the airflows that would occur if each driving force acted separately, because there is a non-linear dependence of flow on pressure difference.

The non-linearity occurs as a result of turbulent flow through leakage openings. Most leakage openings in mid- and high-rise residential buildings have a flow exponent in the range of 0.5 to 0.7 (ASHRAE 1992). Larger openings such as grilles or suite access doors tend to have more turbulent flow and lower flow exponents (near 0.5); smaller openings such as unintentional openings in the building envelope tend to have less turbulent flow and larger flow exponents (near 0.7).

This non-linear dependence of airflow on pressure difference is important, because it means that the individual building airflows caused by each driving force cannot be determined simply by procedures such as turning the mechanical system on or off. Each system operating condition produces different pressure regimes, different NPP locations, and different flows.

2.4.5 Summary

Pressure Differences Caused by Stack Effect

Determining the magnitude and direction of the stack effect in a real building requires knowing the building geometry and the location of the NPP. In addition, to assess the impact of the stack effect on suite ventilation, indoor and outdoor temperatures must be measured continuously.

Even during a single day, the NPP location and indoor-outdoor temperature differences can vary due to occupant interactions such as opening interior or exterior doors or windows. However, the indoor temperatures and the location of the NPP are more likely to be stable at night when the occupants are sleeping. This trend indicates that stack effect calculations should be based on measurements carried out during the night.

Pressure Differences Caused by Wind Effect

Wind effects on suite ventilation are complex due to the natural variations of wind speed and direction and due to the impact of leakage area distributions. The magnitude and direction of the wind effect depend on several parameters. These include the surface pressure coefficient, interior pressure coefficient, outdoor temperature, barometric pressure, wind speed, and wind direction.

Field tests or wind tunnel tests to determine surface pressure coefficients are impossible or impractical for most building designs. As an alternative, these coefficients can be estimated using equations that correlate the coefficients with wind direction, with building orientation and geometry, and with suite location within the building.

The interior pressure coefficient is a first approximation for determining interior pressures. Multi-compartment analyses using computer programs such as CONTAM96 (Walton and Persily 1996) could be carried out to determine interior pressures, but the need for building-specific wall leakage data makes this latter approach impractical for designers.

Wind speed, wind direction, and outdoor temperature need to be measured continuously on-site (above the test building) to determine the impact of wind effects on suite ventilation. An averaging period of 5 to 20 minutes for the speed and direction data is sufficient for the purposes of demonstrating the effects of wind on suite ventilation.

Pressure Differences Caused by Mechanical Equipment

The performance of mechanical ventilation systems in mid-and high-rise residential buildings is dependent on uncontrolled leakage areas, static pressures, and occupant interactions within the building and its suites. As a result, the performance of these systems is uncontrolled.

In assessing suite ventilation, the lack of system control makes it is necessary to determine the performance of the mechanical ventilation systems under actual operating conditions. Important parameters are the pressure differences induced by operating these types of equipment, along with the resulting supply and exhaust flows, particularly for the corridor supply air system and the suite exhaust equipment.

Pressure Differences and Airflows Caused by Combined Driving Forces

Individual driving forces cause pressure differences that can be added algebraically. However, airflows caused by separate driving forces acting upon a single leakage opening cannot be added algebraically. Instead, these airflows must be determined using a non-linear relation that depends on leakage data and on the combined pressure difference across the leakage opening.

The stack- and wind-induced pressure differences can be significant driving forces for ventilation airflows. Mechanically-induced pressure differences are likely in the same order of magnitude as the pressure differences induced by natural forces.

Each of the driving forces can act in different directions. As a result, any particular force may assist or counteract other forces. Sometimes the mechanical forces might be exceeded by the natural forces. Reductions or reversal of intended flows can then occur. This means each driving force can have a positive or negative impact on ventilation flows.

2.5 Location and Quality of Possible Ventilation Air Sources

There are two possible sources for ventilation air entering a suite. One source is outdoors. Air from outdoors may or may not be conditioned (heated or cooled) and treated (humidified or filtered) as it enters the building and then the suite.

The second source is other spaces within the building, as described by the "multiple-spaces" method in Appendix H of ASHRAE Standard 62 (1990a). In the case described here, the recirculated air from other spaces referred to in the ASHRAE Standard does not first pass through a return air system. Instead, the air that moves directly between these spaces and the suite and is called transfer air. It is not typically conditioned or treated as it moves from one space to another space within the building. Of particular interest is the transfer air originating from other occupied suites, because the air in those suites can be significantly contaminated by occupant activities. These other suites are not necessarily adjacent to the suite of interest and may be located many stories below it or simply across the common corridor.

Sentence 6.2.3.11.(2) of the National Building Code of Canada (NBC 1990) specifically states that "air from one suite shall not be circulated to any other suite nor to a public corridor" in a residential mid- or high-rise building. This implies that air that has already passed through one suite cannot be used to ventilate a corridor or another suite. A design goal of mechanical ventilation systems in mid- and high-rise residential buildings is to prevent this transfer air from flowing from suites to corridors and from suite to suite.

Where there is a potential for transfer air to enter a suite, the relative quality of each ventilation air source becomes an important factor in determining the performance of suite ventilation. For example, the concentration of a contaminant in each air source and the contaminant transport rates from these sources to the suite of interest affect the concentration of the contaminant in the suite. Most contaminants in mid- and high-rise residential buildings are transported by ventilation airflows.

Two continuity equations govern contaminant transport by airflows. These equations represent the continuity of airflows and the contaminant mass balance. They are the basis for tracer gas techniques that have been used to determine ventilation rates in buildings (Harrje et al. 1982, Lagus and Persily 1985, Harrje et al. 1985, Persily and Axley 1990). The following describes the two continuity equations, along with an example to illustrate how these equations can be used to determine the relative fractions of inter-suite transfer air and outdoor air in the ventilation air that enters a suite.

2.5.1 Continuity of Airflows

The first continuity equation relates the ventilation airflows entering and leaving a suite in a mid- or high-rise residential building as follows:

$$\rho_o\, q_o + \rho_t\, q_t = \rho_s\, q_s \qquad \textit{(Equation 5)}$$

where

q_o = outdoor airflow rate into suite of interest, m^3/s,
ρ_o = outdoor air density, kg/m^3,
q_t = transfer airflow rate from other suites into suite of interest, m^3/s,
ρ_t = transfer air density, kg/m^3,
q_s = flow rate for air exiting suite of interest, m^3/s, and
ρ_s = exiting air density, kg/m^3,

Equation 5 states that the combined mass of outdoor and transfer air entering a suite is equal to the total mass of air exiting that suite, which is the ventilation rate for that suite. It assumes all air that enters the suite of interest from spaces within the building except from other suites is outdoor air. If the minimum ventilation rate along with the transfer *airflow rate* between occupied suites is known, then the maximum *flow rate* of outdoor air entering the suite can be determined using Equation 5. Alternatively, if the transfer air *fraction* of the minimum ventilation rate is known, then the maximum outdoor air *fraction* can be determined instead.

2.5.2 Contaminant Mass Balance

Based on Wadden and Scheff (1983) and ASHRAE (1990a), a second continuity equation can be developed to relate the time-varying contaminant amount within a suite to the contaminant generation and airflow rates (assuming no elimination or "sink effect" of the contaminant within the suite). This first-order differential equation is as follows:

$$\rho_s \cdot V_e \cdot \frac{dC_s}{d\tau} = \left[\left(10^6 \cdot \frac{M_{air}}{M_x} \cdot G\right) + \left(\rho_o \cdot q_o \cdot C_o + \rho_t \cdot q_t \cdot C_t\right)\right] - \left[\rho_s \cdot q_s \cdot C_s\right] \qquad \textit{(Equation 6)}$$

where

V_e = effective volume of suite of interest, m^3,
C_s = concentration of contaminant x within suite of interest, ppm by volume,
τ = time, s,
M_{air} = molecular weight of air, 28.97 g/mol,
M_x = molecular weight of contaminant x, g/mol,
G = generation rate of contaminant x within suite of interest, kg/s,
C_o = concentration of contaminant x in outdoor air, ppm by volume, and
C_t = average concentration of contaminant x in other suites that have transfer airflows into the suite of interest, ppm by volume.

Equation 6 shows that for steady state conditions ($dC_s/d\tau = 0$), the combined amount of the contaminant generated within the suite and the contaminant entering the suite from outside the suite is equal to the amount of the contaminant exiting the suite. In this case, the contaminant concentration in the suite of interest is at its equilibrium level. For unsteady conditions, the contaminant concentration in the suite will increase or decrease exponentially towards a new equilibrium. This change in equilibrium is due to imbalances caused by changes in generation rate, ventilation rates, or source concentrations.

2.5.3 Inter-Suite Transfer Air and Outdoor Air Fraction Example

Equations 5 and 6 can be combined to determine the minimum inter-suite transfer air fraction for a suite under steady-state conditions, as follows:

$$F_t = \frac{C_{eq} - C_o}{C_t - C_o} \qquad \textit{(Equation 7)}$$

where

F_t = minimum transfer air fraction for suite of interest, dimensionless, and
C_{eq} = equilibrium concentration in suite of interest, ppm by volume.

To illustrate the application of Equation 7, consider the use of carbon dioxide (CO_2) as an indicator of transfer airflows (Turiel and Rudy 1982, Persily and Dols 1990, Reardon et al. 1994). CO_2 is one of many common contaminants in suites of mid- and high-rise residential buildings. Apart from outdoor air, its source is most often the respiration process of occupants. The amount of CO_2 generated by this process depends primarily on the activity levels of the occupants.

During the day, occupants enter and exit the building and carry out many different tasks. As a result, the day-time generation rates and CO_2 concentrations in suites throughout the building will be changing.

At night, most occupants in the building are sleeping. As a result, the CO_2 generation rates in suites are expected to be stable for a significant period of time. Based on studies of post-occupancy CO_2 decay rates in office buildings (Persily and Dols 1990), CO_2 concentrations in the suites will likely achieve a stable equilibrium level sometime during the night (assuming all other parameters remain constant).

In addition to the magnitude and stability of the CO_2 generation rates, the new equilibrium level will also depend on the magnitude and stability of the CO_2 concentrations in the transfer air and outdoor air and on the magnitude and stability of the suite ventilation rates. In particular, the rate at which the equilibrium level is achieved will strongly depend on the magnitude of the suite ventilation rates. The magnitude and stability of the suite ventilation rates are determined by the nature of the leakage openings and by the nature of the three different driving forces, as discussed in other sections of this report.

Due to the presence of occupants, transfer air exiting other suites in the building may have been significantly contaminated by CO_2, even at night. For example, if the outdoor air exchange rate for a typical suite is near the 0.35 ach level recommended by ASHRAE Standard 62 (1990a) and there are two sleeping occupants in the suite, then it is expected that the suite will experience concentrations near 800 ppm at night. With this ventilation rate, the equilibrium CO_2 concentration will be reached in about 3 hours after the majority of people have fallen asleep.

Based on our experience, the concentration of CO_2 in the outdoor air is usually in the range of 350 to 400 ppm, which is significantly lower than the likely concentrations inside occupied suites. It is also likely that the outdoor concentration will usually be stable over the period of any one day. However, it may sometimes vary substantially over longer periods of time, because of atmospheric events such as the formation of inversion layers.

As an example calculation using Equation 7, consider the following hypothetical set of conditions: the CO_2 equilibrium concentration in an unoccupied suite of interest is 500 ppm, the flow-weighted average CO_2 concentration in all of the other occupied suites is 800 ppm, and the outdoor CO_2 concentration is 350 ppm. With these conditions, the minimum inter-suite transfer air fraction is 23% for the suite of interest.

An inter-suite transfer air fraction of 0% means that all of the air entering the suite of interest is at the outdoor CO_2 concentration. Therefore, the air entering the suite of interest can be considered to be uncontaminated by passing through any significant number of other suites that have CO_2 concentrations higher than the suite of interest.

When the inter-suite transfer air fraction is 100%, all of the air entering the suite of interest is at the flow-weighted average CO_2 concentration of the other suites that have direct or indirect flows into the suite of interest. In this case, all of the air entering the suite of interest can be considered to be transfer air that has been contaminated by passing through one or more other suites. The CO_2 concentrations in the other suites can be lower, the same, or higher than the CO_2 concentration in the suite of interest.

It is important to recognize that the inter-suite transfer air fraction based on CO_2 transfer only accounts for direct flows from occupied suites outside the suite of interest and for indirect flows from these suites through shafts and corridors into the suite of interest. It does not account for transfer air that did not pass through other occupied suites. Pollutants other than CO_2 may be contaminating some of this other transfer air.

Therefore, the calculated inter-suite transfer air fraction in our example means first of all that the mechanical ventilation system was unsuccessful in preventing the transfer of air between suites. At least 23% of the air entering the suite of interest is from occupied suites. Second, it means that at most 77% of the air entering the suite can be considered to be uncontaminated outdoor air.

The outdoor fraction could be lower than 77% if contaminants other than CO_2 are introduced into the suite's ventilation air by sources located elsewhere in the building, including inside the occupied suites.

2.5.4 Summary

Continuity equations are the basis for tracer gas techniques that have been used to determine ventilation rates. These equations can also be used to determine the minimum inter-suite transfer air fraction and the maximum outdoor air fraction for a suite at the time of the test. These fractions can be determined if we know that the tracer generation rates in the building are stable and if we know the contaminant concentrations of the outdoor and transfer air sources and in the suite. Therefore, it is important to determine the magnitude and stability of these parameters when assessing suite ventilation.

3.0 Procedures to Collect and Analyze Field Data

3.1 Introduction

As part of this project, we developed six sets of test procedures to collect and analyze field data. The results of these analyses are the key parameters that characterize suite ventilation. These parameters were discussed in Section 2. The following summarizes the six sets of field tests:

- **Test Set 1: Normal and External Driving Forces**

Locate leakage openings of the test suite and building. Measure the pressure differences across these openings with the suite operating normally. Together, the location and pressure difference data were used to assess the potential for outdoor air and transfer air to enter and exit the test suite during the test period (assuming a constant corridor air supply).

Above the building, measure the wind speed, wind direction, and outdoor temperature. These weather data were used to estimate the relative magnitudes of each external driving force (stack-, wind-, and mechanically-induced) for the test suite during the test period.

Test Set 2: Pressure and Airflow Capabilities of Suite Exhaust Devices

In the test suite, measure the pressure differences (test suite to outdoors and test suite to corridor) that are induced by operating the exhaust devices separately and in combination within the suite. These data were used to quantify the internal driving forces for the test suite at the time of the test.

Also, collect data that can be used to determine the airflow rate through each suite exhaust device while it is operating against a fixed indoor-outdoor pressure difference of 20 Pa. These airflow rates were used to quantify the "as installed" capacity of these devices.

- **Test Set 3: Corridor Supply Airflow Rates**

In the corridor adjoining the test suite, collect data that can be used to determine the corridor supply airflows for three different corridor leakage and winter weather combinations: normal nighttime operation, normal daytime operation, and increased leakage between the corridor and outdoors (during daytime operation). These airflows were used to determine the response of the building's corridor supply air system to the external driving forces and leakage at the time of the test.

- **Test Set 4: Leakage Characteristics of Suite Access Doors**

Collect data that can be used to determine the leakage characteristics of the test suite's access door. (Based on the theoretical examination in Section 2.3, this door is expected to be the primary leakage site between the corridor and suite). The door leakage area was used along with the pressure difference data from Test Set 1 to calculate the range of airflow rates through this doorway during the test period.

- **Test Set 5: Magnitudes and Uniformity of Suite Air Change Rates**

Carry out a tracer gas decay test overnight in the unoccupied test suite with simultaneous concentration measurements at four different locations in the suite. These data were used to quantify the magnitude and uniformity of air exchange within the test suite at the time of the test.

- **Test Set 6: Inter-Suite Transfer Air Fractions**

Measure the CO_2 concentration at a central location in the unoccupied test suite during an overnight decay of a CO_2 pulse, which was caused by a one-time injection of CO_2 into the suite. Also, measure the CO_2 concentrations outdoors, in the corridor, and in the vertical shafts adjoining the corridor. These data were used to quantify the fraction of inter-suite transfer air in the ventilation air that entered the suite at the time of the test.

Each set of tests was first piloted in two suites of a Vancouver high-rise residential building. They were then used in field tests of nine other mid- and high-rise residential buildings. The results of these tests are described in Section 4.

The next six Sections (3.2 through 3.7) describe each set of performance tests in more detail. Each Section discusses one set of tests and is subdivided into three parts. First, background issues that are relevant to our selection of a test method are discussed. These issues include a discussion of the advantages and disadvantages of the different measurement techniques that are currently available. Next, an overview of the measurements we carried out is presented. Details of the measurement procedures are located in Appendix B. Finally, the analyses required to translate the measured data into usable information are described.

3.2 Test Set 1: Normal and External Driving Forces

3.2.1 Background

As described in Section 2, the amounts of infiltration and exfiltration for a particular suite in a mid- or high-rise residential building depend on the size and location of leakage sites and on the magnitudes of the stack-, wind-, and mechanically-induced pressure differences. Stack- and wind-induced pressure differences, which are created by external driving forces, cause uncontrolled infiltration and exfiltration of outdoor and indoor air in suites. Pressure differences induced by operating mechanical ventilation systems outside the suite can assist or counteract these airflows.

Empirically determining all of the time-varying pressure differences and airflows for a test suite in a mid- or high-rise residential building is difficult, time consuming, and expensive. Alternatively, a detailed analysis can be carried out to simulate the multi-compartment pressure differences and airflows in a calibrated computer model of the building. However, this approach is limited by the need for a detailed knowledge of the building and mechanical system flow characteristics. These characteristics are often unavailable and obtaining them through field measurements is also difficult, time consuming, and expensive. Fortunately, it is unnecessary to determine every airflow and pressure difference in a building to understand how the test suite and building operate.

In combination with the other five sets of tests, leakage site location, airflow direction, and pressure difference data can be used to explain how air enters the suite under normal winter operating conditions. We expect that the broad patterns and trends within the building at the time of our tests will be representative of those for other days with similar weather conditions. An example of a broad pattern is: *"airflows at the time of the test are mostly from the stair shafts to the corridor on upper stories in the test building"*. An example of a broad trend is:

"corridor supply airflows tend to increase as corridor airtightness is reduced". Researchers can then anticipate when airflow directions will be reversed by changes in stack- and wind-induced forces, and how these changes will impact ventilation rates in suites.

Airflow patterns and trends can be determined using tracer gas methods (Shaw et al. 1991). However, the use of these methods for this purpose is time consuming and was beyond the scope of this project. As a simple alternative, a smoke tube can first be used to define the location of leakage sites and to determine "one time" airflow directions in the suite and in the remainder of the building. This test is a useful supplement to subsequent pressure difference measurements, because it adds the capability to qualitatively estimate the airflow rates between adjoining spaces (a pressure difference alone does not mean there is a flow between adjoining spaces).

A hand-held electronic pressure gauge with a thin copper tube as a probe can then be used to quickly and accurately measure the combined pressure differences at the leaks. These spot measurements can be used to characterize suite and building operation patterns and trends.

It is important to recognize that the combined pressure difference measurements include stack-, wind-, and mechanically-induced pressure differences. To determine the relative magnitudes of these three effects, the stack- and wind-induced pressure differences need to be separated from the combined pressure difference. After the driving forces are separated, the pressure difference data can then be used to characterize the individual effect of each external driving force on the airflow characteristics of the test suite.

An electronic data-logging weather station that measures wind speed, wind direction, and outdoor temperature on site was used during testing. The station measurements can be used along with the equations described in Section 2.4 to separately calculate the stack- and wind-induced pressure differences for the test suite. These measurements can also be used to verify the stability of stack- and wind-induced pressure differences during other tests (especially during the air change rate and transfer air fraction testing).

3.2.2 Measurements

The measurements in Test Set 1 were subdivided into four groups: general data collection, smoke tube tests, pressure difference tests, and weather data collection. The following describes each group of measurements.

General Data Collection

In Test Set 1, we first collected general data that characterize the test suite and building. These data were subdivided into two types: building data and mechanical equipment data. The building data were required in our analyses of ventilation system performance and included: test suite and building geometry (including location, floor area, and volume of the test suite), test suite and building orientation, and suite access door geometry. The mechanical equipment data were collected only for documentation purposes and included: ventilation system characteristics (equipment type and location) and plumbing penetration characteristics.

Smoke Tube Tests

After the general data collection was complete, we carried out tests using a smoke tube to identify leakage locations and to determine airflow directions in the test suite and building. The smoke tube tests were carried out with the test suite operating normally. Normal conditions were defined as the suite's doors and windows closed, the suite's interior doors open, the corridor supply air and central exhaust air systems operating (unless these systems could not be operated), and without the intermittent ventilation equipment in the test suite being operated. Occupant interactions inside other suites, such as opening a window or operating a local exhaust device, could not be controlled. To minimize the effects of these occupant-interactions, we carried out the smoke tube tests near midnight, when most occupants were expected to be sleeping.

Several leakage locations were tested with the smoke tube. For the storey containing the test suite, the primary locations to test were between the test suite and adjoining spaces. These adjoining spaces included outdoors, other suites, the corridor, and vertical shafts. Secondary locations on this storey included between the corridor and its adjoining spaces. The smoke tube tests were also carried out in corridors on other occupied stories during a walk-through of the remainder of the building. The other corridors included at least the top storey, bottom storey, and a storey near the anticipated mid-height NPP of the building.

Pressure Difference Tests

After the smoke tube tests were complete, we carried out spot measurements of combined static pressure differences throughout the building. The test conditions and measurement locations were the same as for the smoke tube tests.

A Modus Instruments digital manometer was used to measure the static pressure differences. This manometer has a useable range of -250 to +250 Pa with a resolution of 1 Pa. The manometer was calibrated using a Dwyer 115 inclined-block fluid manometer (rated accuracy of ± 0.6 Pa). The calibrated accuracy of the digital manometer is about ± 1 Pa. Prior to each set of pressure measurements, the manometer was zeroed in still air with both ports open to the same space.

For each pressure difference measurement, the manometer was placed on the same side of the flow separation as the tester, with its high pressure port open to this space. Its low pressure port was connected by tubing to the static pressure probe. We used thin copper tubing as a static pressure probe (ASHRAE 1992). The copper tube was easily bent to allow the probe to be inserted through flow separations and to be aligned with its inlet perpendicular to the opening in the flow separation. Care was taken to position the manometer so that the inlet for the high pressure port would not be exposed to velocity pressures during the measurement.

For example, to measure the pressure difference across a closed doorway, the probe was first bent 90 degrees. It was then inserted under the door and turned 90 degrees so its inlet was positioned pointing up, was located about 10 cm above the base of the door, and the tube inside the suite was against the suite side of the door. This position placed the inlet so it could sense static pressure rather than velocity pressure.

As another example, the indoor-outdoor pressure difference was sometimes measured at a window. In this case, the copper tubing was bent to conform to the geometry of the window frame (with the window open) so that the inlet of the tubing would be pointing down. The window was then closed onto the copper tubing to achieve a tight seal without crushing the copper tubing.

Weather Data Collection

Throughout Test Set 1 (and the other five Test Sets), we recorded the average on-site wind speed, wind direction, and outdoor air temperature every 5 minutes. These outdoor climate conditions were collected using a Davis Instruments Weather Wizard III weather station. This station has a datalogger, a cup anemometer, a wind vane, and a shielded temperature sensor. The three sensors were located on a portable 5 m tall mast that we attached to the roof of the test building. The resolution of the monitor and the accuracy of the sensors is rated as follows: wind speed (0.1 km/h resolution, ± 5% accuracy), wind direction (1° resolution, ± 7° accuracy), and temperature (0.1°C resolution, ± 0.5°C accuracy). The datalogger measured each weather parameter once every 5 seconds and recorded the average once every 5 minutes. The protocol for setting up the weather station is described in Section B.1 of Appendix B.

Air temperatures at a central location inside the test suite were measured once every 5 seconds throughout the tests by a digital thermometer attached to an electronic datalogger. The average air temperature at this location was recorded once every minute. Spot measurements of air temperatures in stair shafts and corridors were also carried on occupied stories during a walk-through of the remainder of the building. Spot measurement locations included at least the storey on which the test suite was located, the top storey, the bottom storey, and a storey near the middle of the building. A separate digital thermometer was used for the spot measurements. Both digital thermometers were calibrated and each had a rated accuracy of ± 0.5°C.

3.2.3 Data Conversion and Analyses

No conversions of the airflow direction data from smoke tube and pressure differential tests were required. These data were used directly to estimate the locations of neutral pressure planes in the building at the time of the test, when all three driving forces were present. The data were also used as an aid to characterize airflow patterns and trends in the building. These patterns and trends are discussed in Section 4.

Estimates of stack-induced pressure differences that the suite experienced at the time of the test were made using general principles regarding thermal buoyancy and using the indoor and outdoor temperature data, as outlined in Section 2.4.1. Specifically, we calculated the stack-induced static pressure differences using building height, measured indoor and outdoor temperatures, and assuming the NPP due to the stack effect alone was located at the mid-height of the building. Further research regarding whole-building leakage area distributions for mid- and high-rise residential buildings is required to validate this assumption. The smoke and pressure differential test data could not be used to determine the NPP location in the absence of wind- and mechanically-induced pressure differentials, because we could not eliminate these two effects.

As discussed in Section 2.4.1, a thermal draft coefficient of 0.8 was used, because carrying out field tests to determine this parameter was beyond the scope of this project. This value provides a conservative estimate of the stack-induced pressure differential.

The barometric pressure was not measured. Instead, we used the average barometric pressure for the city in which the building was located (CSA 1993). For the selected test sites, normal variations in barometric pressure are expected to have less than a 2% effect on the calculated stack pressure.

Calculations of wind-induced pressure differences on each exterior wall of the test suite were performed using the building geometry data, the on-site wind speed, wind direction, and outdoor temperature data, and using Swami and Chandra's wind pressure coefficient equations. These equations were described in Section 2.4.2. Wind speeds were interpolated from the anemometer height to the appropriate reference height, using the power-law relations described by ASHRAE (1997) for the wind boundary-layer. As Section 2.4.2 described, an interior pressure coefficient of -0.2 was assumed as a first approximation to demonstrate the impact of wind effects on suite ventilation. An averaging period of 10 minutes was selected in analyzing the wind speed and direction data. The barometric pressure that was used in the stack-effect analyses was used in these calculations.

The stack- and wind- induced pressure difference estimates were then added together to determine the combined natural driving force for each exterior wall of the test suite. We then compared the ratio of each separate stack- and wind-induced pressure difference to the combined stack- and wind-induced pressure difference to estimate the relative importance of each effect at the time of the test. These comparisons are described in Section 4, where this information is required to explain observed phenomena.

We also compared the calculated combined stack- and wind-induced pressure differences with the measured combined pressure difference data. The difference between the calculated and measured pressure differences is likely due to mechanical system operation (supply and exhaust systems). These comparisons cannot precisely determine the magnitude of the mechanically-induced pressure differences due to uncertainties in the estimates of stack- and wind-induced pressure differences. However, they do provide a sense of the relative magnitudes of the natural and mechanical driving forces at the time of the test. These comparisons are also described in Section 4, where this information is needed to explain observed phenomena.

3.3 Test Set 2: Pressure and Airflow Capabilities of Suite Exhaust Devices

3.3.1 Background

Since 1990, CSA Standard C260 (1990) has required that fan curves for residential mechanical ventilating equipment be provided as part of the manufacturer's available literature. However, these curves are not always available to designers.

When fan curves are available, a designer can use the curves along with estimates of suite leakage and common duct design calculations to properly size suite ventilation equipment. These data can then be used to estimate the static pressure differences and airflows between the suite, outdoors, and corridor when the exhaust devices are operating. Unfortunately, these analyses are not always carried out for mid- and high-rise residential buildings. As well, the pressure differences between suites, corridors, and outdoors are usually unknown and design exhaust flows are seldom achieved, except by accident.

There were two types of tests in Test Set 2. The first type of tests allowed us to determine the static pressure differences between the test suite, the corridor, and outdoors that are induced by operating exhaust devices within the suite. These data were collected to determine whether suites can be significantly depressurized by operating these devices.

The static pressure differences induced by operating each exhaust device separately and then all together can be simply measured using a hand-held digital manometer, as described in Test Set 1. The pressure difference attributable to operating each device or group of devices is the algebraic difference in pressure difference measurements with and without the device(s) operating.

The second type of test in Test Set 2 collected data that allowed us to determine the installed airflow capacities of the exhaust devices within the test suite. These airflow rates were then compared with design specifications and equipment ratings to determine whether there is any difference between these capacities. The installed airflow rates were also compared with various design guidelines where possible.

A conventional flow hood could be used to measure the actual flow rate through each exhaust device under normal operating conditions. However, this test has three disadvantages. First, the conventional flow hood would not determine the *capacity* of the exhaust device, unless a separate fan was also used to depressurize the suite relative to outdoors. Second, the flow resistance of a conventional flow hood may affect the flow through the exhaust device, unless the hood has an internal fan to compensate for this resistance. Third, to determine the total exhaust flow when several exhaust devices are operating simultaneously, each device must be measured separately. While this level of information can be useful, the time required to carry out individual measurements was beyond the scope of this project.

Instead of a conventional flow hood, we developed a new procedure that is based on the measurement procedure described in Appendix A1 of ASHRAE Standard 136 (1993b). The ASHRAE procedure describes the field use of a blower door to measure the airflow rates through installed exhaust devices. In essence, the envelope of the entire suite, in combination with the blower door, acts as a large fan-compensated flow hood. Our procedure was similar to the ASHRAE procedure, but differed in two ways.

First, we used a single suite depressurization of 20 Pa rather than using the various pressure differences that are induced by operating exhaust devices separately and in combination. This depressurization was selected to reduce the likelihood of wind-induced pressure interference in the measurement procedure and to standardize the results. It was also selected as a likely upper bound for the depressurization of a suite. Based on our experience, this depressurization can occur in a well-sealed suite with high capacity exhaust devices. Higher depressurizations are unlikely to occur, except in very rare cases. This depressurization is also based on the limit indicated by the National Building Code of Canada (NBC 1990) for suites without spillage-susceptible combustion appliances.

The depressurization of 20 Pa is slightly less than the rating requirement specified by CSA Standard C260 for exhaust devices with ducted outlets (25 Pa). However, if a device cannot meet the rated capacity at a 20 Pa depressurization, it will definitely be unable to do so at 25 Pa. Conversely, if a device operating at a 20 Pa depressurization meets or exceeds the design specification, then it will also do so for smaller depressurizations.

Second, our method required that we use the blower door to depressurize the suite to 20 Pa with respect to the corridor (with the corridor open to outdoors) with and without each exhaust device operating within the suite. The flow attributable to a particular device or group of devices is the algebraic difference in measured flows between the two cases.

It is important to recognize that our test does not explicitly address the issue of what the exhaust flows are at various suite depressurizations. A detailed study of exhaust device performance would require a multi-point depressurization test of the suite to get the installed characteristics at various pressure differences (CSA 1990). However, such testing probably is unnecessary, because we expect that our measurements at 20 Pa reflect actual operating flows within about 10%[2].

3.3.2 Measurements

The measurements in Test Set 2 were subdivided into two groups: pressure difference tests and airflow capacity tests. The following briefly describes each group of measurements in this set of tests. Details of the measurement procedures are described in Section B.2 of Appendix B.

The pressure difference tests were carried out at night when occupant interactions were less likely to disrupt building pressure regimes. However, the airflow capacity tests were carried out during the day to avoid disturbing building occupants with the noise generated by the blower door operation. Occupant interactions were not expected to be a significant factor in these latter tests.

Pressure Difference Tests

The measurements of pressure differences induced by operating suite exhaust devices were carried out in three stages.

First, we used the hand-held manometer described in Test Set 1 to measure pressure differences between the test suite, outdoors, and the corridor, with the test suite operating normally. Normal conditions were defined as the suite's exterior doors and windows closed, the suite's interior doors open, the corridor supply air and central exhaust air systems operating (unless these systems could not be operated), and without the intermittent ventilation equipment in the test suite being operated or sealed.

Next, the pressure difference measurements were repeated with each intermittent exhaust device operated separately and then all together.

Finally, if there were openings for continuous exhaust devices in the suite, the second step was repeated with each of these openings sealed separately and then with all of them sealed.

Airflow Capacity Tests

To generate the 20 Pa suite depressurization and to determine the airflows caused by operating the exhaust devices, we used a Retrotec Series 800 blower door with a detachable multi-hole (8 ranges) orifice plate mounted in the suite access doorway. The blower and orifice plate

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[2] During prototype trials of the FANalyzer fan test rig (Sikorski and Moffatt 1996), performance tests were carried out on residential exhaust fans similar to those found in the test suites. Relationships between flow and back pressure were developed. Based on those relationships and assuming a 50 Pa back pressure in the exhaust duct system with no suite depressurization, we expect 20 Pa of suite depressurization relative to outdoors will reduce exhaust flows by less than 10%.

assembly had been calibrated using procedures similar to those described in CGSB Standard 149.10 (1986). The calibrated flow range for the assembly allows the device to be used to measure flows from approximately 24 to 2160 L/s (50 to 4580 cfm). The assembly flow measuring accuracy is rated at ± 5% or better by the equipment manufacturer. The hand-held manometer described in Test Set 1 was used to measure pressure differences in these tests. Airflows were determined for each exhaust device operating case. These cases were described in the pressure difference tests of this Test Set.

3.3.3 Data Conversion and Analyses

No conversions of the induced pressure difference test data were necessary. However, the flow measurement data required conversion, because the blower door does not measure flows directly. Instead, it produces pressure difference data across the orifice plate. These data must be converted to airflow rates using flow versus pressure difference calibration data for the orifice plate. Therefore, for each flow measurement case, we calculated the airflow rate from the suite through the blower door. The calculations followed the procedures described in CGSB Standard 149.10 (1986). Measured air temperatures in the suite and corridor were used in this procedure to correct the flow rates to standard conditions (20°C, 101.325 kPa).

We also calculated the pressure differences and airflows induced by operating the exhaust devices within the suite. As stated in the background discussion (Section 3.3.1), the induced pressure difference or airflow for an exhaust device or group of devices is the algebraic difference between the measurements with and without the device(s) operating. These calculated parameters were then compared to equipment ratings, to design specifications, and where possible to design guidelines.

The results of these calculations are described in Comparison 2 (Section 4.4.2).

3.4 Test Set 3: Corridor Supply Airflow Rates

3.4.1 Background

An informal survey we conducted of 25 people that design mechanical ventilation systems for Canadian mid- and high-rise residential buildings indicated that mechanical air supply to these buildings typically involves supplying outdoor air to corridors for pressure control, with the intent of limiting the migration of contaminants between suites. Few designers intend these systems to ventilate the suites surrounding the corridor. However, in practice, these systems can often inadvertently ventilate the suites.

The amount of air delivered by the corridor supply air system into a corridor and then into adjoining spaces cannot be determined intuitively. The airflow rate is the result of a number of complex interacting parameters that include: the flow resistance and capacity of the supply system, the isolation of the corridor from other spaces within the building, the relative airtightness of the building envelope, and the interference of stack- and wind-induced pressure differences.

Designers specify the supply system characteristics. However, when designing the supply system, they typically have little or no information regarding the actual airtightness of the combined corridor wall and suite access door assemblies or of the airtightness of the building envelope. Furthermore, they seldom take into account the effects of stack- and wind-induced pressure differences. Consequently, the pressure in the corridor relative to the suites is unknown, the amount of air leaking from the corridor into the suites is unknown, and suite ventilation occurs more through accident than design.

The purpose of this test is to measure the amount of airflow being delivered by the mechanical supply system to the corridor under different operating conditions. We are specifically interested in the supply airflow into the corridor that adjoins the test suite. Once we know the airflow rate from the corridor supply air system and the number of suites on the same storey as the test suite, we can estimate the fraction of the flow that likely passes through the test suite's access door (as is typically done by the designer's we surveyed). This flow can then be compared to the range of actual flows through the suite access door that we measured during the test period. Based on the principles of flow continuity, it is expected that the measured flows through the suite access doors will be lower than their "design" flows, because there are other leakage openings in the corridor, such as elevator shaft, stair shaft, and garbage chute access doors.

3.4.2 Measurements

The measurements we carried out in Test Set 3 are briefly described below. Details of the measurement procedures are described in Section B.3 of Appendix B.

In Test Set 3, we measured the airflow rate at each outlet of the corridor supply air system on the same storey as the test suite. Our measurement procedure is based on the procedure described in Appendix A4 of ASHRAE Standard 136 (1993b). That Appendix describes the use of a calibrated continuously-variable orifice plate with a constant fan speed to create a zero pressure difference and to measure flow. This approach is attractive, because it removes the interference effect of the flow measurement device on the air flowing from the outlet.

Our procedure differed from the ASHRAE procedure in two respects. First, we used a calibrated orifice plate that has several discrete overlapping flow measurement ranges. Second, we varied the fan speed instead of the orifice size to create a zero pressure difference.

In our procedure, we used a custom-built neutral-pressure device. This device was fabricated by Sheltair and is based on the calibrated "door fan" flow element and blower that was described in Test Set 2. We expect the measurement accuracy for corridor supply airflow rates is ± 10%. The hand-held manometer described in Test Set 1 was used to measure pressure differences in these tests.

Three separate tests were carried out in the corridor adjoining the test suite. The first test was carried out at night under normal operating conditions just prior to the air exchange decay test.

Normal operating conditions were defined as all of the corridor doors and windows closed, the corridor supply air and central exhaust air systems operating (unless these systems could not be operated), and without the intermittent ventilation equipment in the test suite being operated. The windows and exterior doors in the test suite were also closed. Interior doors within the test suite were open. We could not control the operation of exhaust devices, windows, and doors within suites other than the test suite, because we did not have access to the other suites.

The other two tests were carried out during the following day after the decay tests (Sections 3.6 and 3.7), when the outdoor temperatures were typically warmer. The second test was carried out under the same normal operating conditions. The third test was carried out with significantly increased leakage between the corridor and outdoors. The intent of the latter two tests was to determine if there were noticeable differences in corridor supply airflow rates due to diurnal differences in stack- and wind-effects or due to changes in corridor leakage area. In particular, it is expected that if any flow differences are noted due to diurnal weather changes, then seasonal variations in weather could cause significant variations in flows.

3.4.3 Data Conversion and Analyses

As in Test Set 2, the flow measurement data required conversion, because our neutral-pressure device does not measure flows directly. Instead, it produces pressure difference data across the orifice plate. These data must be converted to airflow rates using flow versus pressure difference calibration data for the orifice plate. Therefore, for each flow measurement case, we calculated the airflow rate from the corridor supply air outlet through the blower door. The calculations followed the procedures described in CGSB Standard 149.10 (1986). Measured air temperatures in the supply air and corridor were used in this procedure to correct the flow rates to standard conditions (20°C, 101.325 kPa).

The corridor supply airflow data were then compared to design airflow specifications. Our intent in this comparison was to determine whether the mechanical supply air systems for the corridor were operating as intended.

The differences between the supply airflow rates from the night test and the first day test were used to characterize the susceptibility of the corridor supply air system to the combined impact of diurnal differences in stack- and wind-effects under normal operating conditions.

Differences in supply airflow rates between the second and third tests due to the increased corridor leakage were used to characterize the susceptibility of the corridor supply air systems to changes in corridor leakage area. For example, during some of the field tests, we found some corridor windows were open or stair shaft doors were propped open.

The results of these analyses are described in Comparison 1 (Section 4.4.1).

3.5 Test Set 4: Leakage Characteristics of Suite Access Doors

3.5.1 Background

As Section 2.3 described, the leakage area of suite access doors can vary significantly. These doors can be either be tight fitting and weather-stripped for noise and draft control or they can be undercut to allow for greater airflow to the suite.

The leakage characteristics of the suite access door are a major determinant of the supply airflow rate into a corridor and from the corridor to the adjoining suites. Unfortunately, mechanical designers rarely coordinate door leakage characteristics with architects. Consequently, their effect on the performance of corridor supply air systems is uncontrolled.

One reason that door leakage characteristics are not specified is that leakage data specifically for suite access doors are not available. As a first step in remedying this problem, we carried out tests that allow us to calculate the leakage characteristics of installed suite access doors.

Our tests did not address the leakage of suites as a whole or of other building elements within a suite. Limited amounts of these data types are already available to designers, as discussed in Section 2.3. While the existing data may not be directly applicable to the test suites, further tests to gather these types of data require considerable effort and control of adjoining suites.

Our test procedure is based on the procedure described in ASTM Standard E 783 (1984). That Standard describes a depressurization test to determine door air leakage using a chamber formed by sealing a sheet of material to the exterior side of the door frame. This procedure accounts for flows through all gaps between the door and its frame, and not just through the bottom gaps. Flows through top and side gaps can be significant fractions of the total leakage.

Our procedure differs from the ASTM procedure in three respects. First, rather than measuring the amount of extraneous leakage between the blower door frame and the suite access door frame, we eliminated this leakage by carefully sealing the corridor-side joint between the two frames with tape (including the joint between the blower door frame and floor or threshold). This difference in procedures is unlikely to have a significant effect on the accuracy of the test result, because the leakage of the taped joint was expected to be considerably less than the leakage between the suite access door and its frame. The integrity of the taped seal was then tested with a smoke tube while the seal was subjected to a 20 Pa depressurization. Any flow through the seal was rectified by further taping and retesting of the seal.

Second, the intent of our test was to determine the leakage area of the suite access door. While a single-point depressurization test as described by the ASTM procedure can be used to estimate the leakage area, better accuracy can be achieved by carrying out a multi-point depressurization test. Consequently, we carried out a multi-point test by incorporating the requirements of CGSB Standard 149.10 (1986) in our test procedure.

Third, our test created and measured pressure differences across suite access doors rather than across exterior doors. In our tests, these pressure differences were generated using a blower door attached to the frame of the suite access door.

3.5.2 Measurements

The measurements we carried out in Test Set 4 are briefly described below. Details of the measurement procedures are described in Section B.4 of Appendix B.

Our procedure required that the blower door assembly described in Test Set 2 be mounted on the corridor side of the suite access door frame, with the door closed. The blower door draws air from the suite, between the access door and its frame, and discharges to the corridor. Care was taken to ensure the orifice plate at the blower inlet was at least one or more orifice diameters (10 cm) away from the suite access door's surface. Care was also taken to fasten the sheet of the blower door tightly to the blower door frame, so that the sheet could not interfere with the flow through the gaps between the suite access door and its frame.

It was not possible to directly measure the pressure difference across the suite access door that was induced by the blower door. A direct measurement would require drilling holes in the corridor wall or passing tubing through a gap between the suite access door and its frame. For tightly weather-stripped doors, a tube might displace significant lengths of weather-stripping and increase the leakage of the suite access door.

As an alternative to a direct measurement, an exterior door or window in the suite, along with a door or window with outdoor access in the corridor, was opened for the duration of the test. All the doors in the suite that were between the suite access door and the suite's open exterior door or window were also opened. The purpose of opening these spaces to outdoors was to provide a reference pressure in the corridor that was based on the pressure in the suite. In this way, we could measure the pressure difference between the corridor and inter-door space and correlate it to the pressure difference between the test suite and corridor. To compensate for a constant offset caused by stack-, wind-, and mechanically-induced forces, we measured this pressure difference at the start and end of the test. This offset was then removed following CGSB Standard 149.10 (1986) procedures to determine the true pressure difference that was induced across the suite access door by the blower. The hand-held manometer described in Test Set 1 was used to measure pressure differences in these tests.

One disadvantage to this procedure is that the suite and corridor pressures are more susceptible to changes in wind-induced pressure differentials and to occupant interactions in other suites (such as turning exhaust devices on or off or opening or closing doors or windows within their suites). Unfortunately, it is seldom possible to wait for a period of low or constant wind. Furthermore, the time available for testing was limited, because the leakage tests were carried out during the day to avoid disturbing building occupants with the noise generated by the blower door operation. Changes in corridor and test suite pressures due to changes in wind, envelope leakage, or equipment operation can be resolved during statistical analyses of the test data.

Our test procedure ensures that the leakage area of the suite access door is much smaller than the leakage of the test suite and of the corridor envelope, when these two spaces are open to outdoors. As Section 2.3 described, it is not intuitively clear for a particular suite whether this is also true when the test suite and corridor are closed to outdoors. Therefore, it is important to recognize that if the test suite and corridor were not open to outdoors in our measurement procedure, pressures within these spaces could change as the flow through the blower door changed, because of pressure differences across suite and corridor leakage openings to outdoors. In particular, the test suite pressure would decrease and the corridor pressure would increase, as the flow through the blower from the suite to the corridor increased. It would be difficult to correlate the suite and corridor pressures in this case without knowing the leakage areas of the test suite and corridor.

3.5.3 Data Conversion and Analyses

As in Test Set 2, the flow measurement data required conversion, because the blower door does not measure flows directly. Instead, it produces pressure difference data across the orifice plate. These data must be converted to airflow rates using flow versus pressure difference calibration data for the orifice plate. Therefore, for each flow measurement case, we calculated the airflow rate from the suite through the blower door. The calculations followed the procedures described in CGSB Standard 149.10 (1986). Measured air temperatures in the suite and corridor were used in this procedure to correct the flow rates to standard conditions (20°C, 101.325 kPa).

Non-linear regression of the pressure difference data and calculated airflows were then used to calculate the equivalent leakage area of the suite access door (using procedures described in CGSB Standard 149.10 (1986)).

We also calculated the theoretical equivalent leakage area for the suite access door using measured door geometry and the Gross and Haberman method for flow through door gaps (ASHRAE 1992). This theoretical leakage area was then compared to the leakage area determined using our field measurements. The comparison is a useful check of the validity of both the field measurements and the theoretical procedure. Laboratory measurements of door leakage as outlined in ASTM Standard E283 (1984) would be another useful comparison, but these measurements were beyond the scope of this project.

The calculated leakage area of the suite access door (based on the blower door test) was then used with the pressure differences we measured under normal operating conditions in Test Set 1 to characterize the range of flows across this doorway during the test period. Finally, this range of airflows was compared to the corridor supply airflow transferred to the suite (assuming the total supply airflow was evenly distributed to all suites on the same storey, as is typically done by 25 designers we surveyed). As described in Section 3.4.1, it is expected that the measured flows through the suite access doors will be lower than their "design" flows, because there are other leakage openings in the corridor, such as elevator shaft, stair shaft, and garbage chute access doors.

3.6 Test Set 5: Magnitudes and Uniformity of Suite Air Change Rates

3.6.1 Background

The effectiveness of a ventilation system with regard to the magnitude and uniformity of air exchange is often defined by parameters such as "ventilation or air-exchange efficiency" and "ventilation or contaminant-removal effectiveness" (Persily 1986, Seppänen 1986, Säteri 1991). These parameters include normalizing factors that depend on spatial or temporal average concentrations. The normalizing factors include "local or mean age of air" or the "system average contaminant turnover time".

Currently, there is little agreement and often great controversy regarding the procedures for determining the above-mentioned performance parameters and their normalizing factors, especially for complex spaces such as suites in a mid- or high-rise residential building. These parameters and normalizing factors assume there are only readily-identifiable mechanically-induced supply and exhaust flows from a space, and that natural infiltration is negligible. However, natural infiltration is an intentional (albeit haphazard) characteristic of most mid- and high-rise residential buildings. As a result, there are typically no single readily-identifiable entry or exit flows that can be used to determine these parameters and normalizing factors for a suite (Persily and Grot 1985). Therefore, conventional definitions of effectiveness are inappropriate for suites.

For this project, we have used an alternative definition to describe the effectiveness of a suite ventilation system. In broad terms, a ventilation system is "effective" if it provides sufficient air change rates and distribution to maintain uniformly acceptable indoor air quality in all occupied zones of a suite. This definition focuses on the relation between air exchange and contaminant concentrations at various locations in the suite. The term "air change rate" refers to all external ventilation airflows that affect the contaminant concentrations in a suite. These airflows include direct air exchange between the suite and outdoors, as well as indirect air exchange through the transfer of air from other building spaces. The term "distribution" refers to the relative magnitudes of the internal ventilation airflows within the suite (air movement and circulation between and within each separate room).

The individual airflows entering and exiting a suite (other than through the suite access door or suite exhaust system) are difficult to measure directly or to predict analytically from leakage and pressure difference data. Even if these individual airflows could be determined, combining them to determine the air change rate and distribution for each room of a suite would be difficult due to the non-linear dependence of flow on pressure differences. To avoid the difficulties associated with measuring or calculating these airflow rates, tracer gas decay measurements can be used instead to quantify the effective air change rate for each room of a suite. ASTM Standard E 741 (1983) describes these measurements in detail.

In summary, the tracer gas decay test determines the average rate at which a pollutant would be removed from a particular point within a room over a brief period of time. A non-reactive tracer gas that is not normally present in the atmosphere is first injected into the room and then mixed. The tracer gas concentration is then measured over time, as the gas decays exponentially toward its equilibrium level. The effective air change rate is then calculated using non-linear regression of the decay data. The accuracy of this technique in determining the effective air change rate is estimated to be about ± 10% or better (ASTM 1983).

The decay method makes six very broad assumptions that include:

- the envelope of the space being tested is clearly defined,
- the airflow and pressure regimes around the suite are stable during the test,
- the tracer gas is thoroughly mixed in the room prior to measuring the decay,
- the tracer gas is decaying towards an equilibrium,
- there is no removal of the tracer gas from the room air via a sink effect, and
- there are no other tracer gas sources in spaces adjoining the room or, if there are other sources, then these other sources have constant generation rates.

The first five of these six assumptions can best be met by using a non-reactive tracer gas to test rooms of an unoccupied suite at night. During the night, occupants throughout the remainder of the building typically are asleep and are less likely to cause changes in building leakage or ventilation flow rates. Also, wind speeds also tend to be more stable at night than during the day. The validity of the sixth assumption is discussed below.

By using a multi-point tracer gas sampling system (one sensor in each room), the relative air change rates or air distribution pattern within the suite can be determined simultaneously. This pattern can then be used to assess whether air entering the suite is "short circuiting" to large envelope leaks (such as exhaust openings) and leaving most of the suite's "stale" air undisturbed.

It is important to recognize that the simultaneous multi-room decay test described above requires that there is no artificial mixing in the test suite during the decay. This requirement is necessary to avoid disturbing the natural distribution and circulation patterns inside the suite by additional mixing. As a result, when only a single tracer gas is used, there can be interzonal flows of the same tracer gas from room to room within the suite. The flows of the tracer gas into one room from a second room tend to lower the decay rate of the tracer gas in the first room. This means that air exchange rates based on these decay tests for any particular room can only be treated as minima. Therefore, the sixth assumption above is still true outside the test suite, but it is not necessarily met inside each room of the test suite. A tracer gas test using multiple tracer gases could be used to eliminate the interzonal interference problem (Lagus and Persily 1985, Enai et al. 1990, Harrje et al. 1990, Ohira et al. 1993), but this test was beyond the scope of this project.

3.6.2 Measurements

The measurements we carried out in Test Set 5 are briefly described below. Details of the measurement procedures are described in Section B.5 of Appendix B.

Our test procedure is based on ASTM Standard E 741 (1983). In our procedure, we used a single tracer gas and a portable four-sensor instrument (Halitec F01-P), which continuously collects sensor conductance data that can be used to determine the tracer gas concentrations. This instrument was custom designed for Sheltair Scientific Ltd. in 1991 and has been employed in several other CMHC projects since that time (including ventilation testing on low-rise buildings).

The Halitec tracer gas sensors are internally-heated tin dioxide semiconductors that are sensitive in the parts per million range. These sensors do not measure concentration directly. Instead, their output is conductance, which is dependent on the concentration to which they are exposed to changes. They respond to a step change in concentration by reaching 95% of their final conductance within two to three minutes. The sensors require a 2 to 3 hour warm-up period prior to use. This period allows the sensor internal temperatures and conductances to fully stabilize. Each tracer gas sensor is attached to a sensor box that has a 20 m long shielded cable to allow the location of sensors in different rooms of the suite.

The four Halitec sensors were calibrated at room temperature using a sealed aquarium and systematic injections of known amounts of tracer gas. Each sensor was found to operate differently. A calibration curve (third-order polynomial) was generated for each sensor to correlate the measured sensor conductance with tracer gas concentration. The calibrated range covered 0 to 1000 ppm of the tracer gas with an accuracy of ± 10 ppm.

The Halitec monitor includes a built-in data acquisition system that is able to auto-zero each tracer gas sensor during the decay test, store large amounts of data, and download data through an RS232 port. During our tests, the monitor was set to record the conductance of every sensor simultaneously once every minute. The monitor does not contain a time clock, so it was necessary to record the start and stop times for the first and last set of measurements. Recording these times allowed us to correlate the decay data with other data, such as weather and pressure measurements.

Appendix C shows the location of each of the four tracer gas sensors for each of the ten suites that were tested. The sampling sites were typically located in the kitchen, living room, master bedroom, and bathroom. Except in the kitchen, each sensor was located at approximately the middle of the occupied zone in each room. In the kitchen, the sensor was placed on an unused countertop to avoid damage, because the kitchen was often used as a work area.

The monitoring period started several hours prior to the injection of the tracer gas, which was carried out on or after midnight. The pre-injection period allowed us to determine background levels of contaminants that might interfere with the tracer gas tests. The monitoring period continued typically until 08:00 to 10:00 the next morning. The length of the decay monitoring period was selected to capture most or all of the period required for a tracer to decay to equilibrium, plus some of the post-decay background levels as well. For comparison, current standards such as ASHRAE Standard 62 (1990a) and CSA Standard F326 (1993) require that the outdoor air change rate in a suite be 0.3 ach or more. This translates into a decay period of about 3 hours, which is significantly shorter than our decay monitoring period.

During the decay period, the suite was unoccupied and the suite was operating normally. Normal conditions were defined as the suite's exterior doors and windows closed, the suite's interior doors open, the corridor supply air and central exhaust air systems operating (unless these systems could not be operated), and without the intermittent ventilation equipment in the test suite being operated.

The tracer gas was injected into each room using a perimeter-weighting strategy. This strategy assumes the volume of a room is proportional to its perimeter. As a result, the tracer gas was injected continuously at a constant flow rate as its container was carried around the perimeter of every room and space within the suite. The tracer gas was injected until the concentration in each room was similar and typically between 500 to 1000 ppm (about 75 to 150 L of tracer gas at standard temperature and pressure for an average-sized suite).

Immediately following the injection of the tracer gas, a blower was carried throughout the suite to mix the gas. A mixing time of about 5 minutes was used. Observations of the tracer gas concentrations in the pilot building indicated this period was sufficient to achieve good initial mixing in the small, open-plan suites that we tested (average volume of 149 m^3). The mixing blower was turned off during the subsequent decay period.

3.6.3 Data Conversion and Analyses

The tracer gas system measured the conductance of each of the four sensors once every minute and stored the set of four data as one record (identified by a sequential number that indicates the number of elapsed minutes from the start of monitoring). Specifically, record 1 is the set of conductance data measured one minute after the start of monitoring. We used the recorded start and stop times to convert the sequential record numbering to actual time of day. Then, the sensor calibration data was used to convert the conductance measurements to tracer gas concentrations.

To determine the effective air change rate for each room that was sampled, we first plotted the natural logarithm of the calculated tracer gas concentration (corrected for an average non-zero equilibrium level due to interzonal flows) against time in hours on a linear scale. Most of these offsets were near zero, which indicates interzonal flow interferences in these tests were relatively insignificant. Minor interferences were only apparent in the suites with low air exchange rates (0.70 ach or less).

On this above graph, the calculated concentrations were expected to form an approximately straight line during the decay period (once equilibrium was achieved in the room immediately following injection in the test suite). Next, we chose a sample of the calculated concentration data that appeared to be simultaneously linear for each room in the suite (minimum period of 2 hours). The samples were selected to start with the highest possible concentration in the linear region to minimize the effects of instabilities in ventilation rate and concentration.

Finally, non-linear regression techniques described by ASHRAE Guideline 2 (1990b) were used to fit the "best" straight line through each of the four data samples. The slope of each line is the effective air change rate for the sampled space during the decay period. The correlation coefficient from the regression analysis describes how well the data correspond to a straight line. The correlation coefficients in our regression analyses ranged from 0.970 to 0.999 with an average of 0.993. Comparison 7 (Section 4.4.7) describes the effective air change rates based on these analyses.

We did *not* calculate the actual ventilation flow rates that correspond to the air change rate in each room for two reasons. First, the boundaries of some rooms were not well defined, such as in combined open-plan kitchens, dining rooms, living rooms, and corridors. This would not be a problem if the concentration was uniform in the combined space. However, the test results described in Comparison 7 (Section 4.4.7) indicated that there were non-uniform concentrations within these open-plan spaces.

Second, even with well-defined boundaries, the volume of a specific room that was involved in the air exchange was unknown. This volume is commonly called the "effective" volume (Sterling et al. 1987). It can be significantly less than the actual volume of the room due to the effects of furniture, equipment, and stagnant regions within the room, such as corners. Determining the effective volume requires the use of constant-concentration tracer gas techniques, which were beyond the scope of this project. However, using the actual volume of the room would provide a conservative estimate of the minimum ventilation flow rates into these rooms, if the boundaries of each room could be defined.

3.7 Test Set 6: Inter-Suite Transfer Air Fractions

3.7.1 Background

A tracer gas decay test cannot distinguish between inter-suite transfer air and the direct supply of outdoor air to a suite. The purpose of this set of tests is to go one step further than the tracer gas decay test and determine what fraction of the air entering the test suite is transfer air from other suites.

Test Set 6 is based on the premise that elevated CO_2 concentrations in an occupied building are a good indicator that air in the test suite has been contaminated by inter-suite transfer air. For CO_2 to be a valid indicator of contamination from other suites, the sole source of CO_2 within the building must be from occupants in those suites. This is a reasonable assumption for mid- and high-rise residential buildings, except when there is an unlikely spillage of combustion gases from fossil-fuel-fired heating equipment.

Our approach in Test Set 6 was to conduct a second decay test using a release of CO_2 within the test suite. This second decay test was conducted at the same time as the tracer gas test described in Test Set 5. The reason this second test can be used is that the tracer gas concentration will always tend to decay towards zero. In contrast, the CO_2 concentration will always tend to decay towards a non-zero equilibrium level, which is determined by the outdoor level, the indoor levels, and the ventilation rates. If there is a difference in the simultaneous decay rates of the tracer gas and CO_2, the difference is assumed to be due to the presence of CO_2-laden transfer air from other suites.

The inter-suite transfer air fraction test is by far the most complicated test that we conducted as part of this research project. It may also be the most controversial, because it is a new technique. The least that can be discovered from our test is an indication that transfer air from other suites is present in the ventilation air of the test suite. The best is to be able to bracket the amount of inter-suite transfer air that is reaching the test suite with some degree of confidence.

Equation 7 in Section 2.5.3 can be used to calculate the inter-suite transfer air fraction. This equation indicates that the inter-suite transfer air fraction depends on the outdoor CO_2 concentration, on the equilibrium CO_2 concentration in the test suite, and on the average CO_2 concentration of the transfer air that is entering the test suite from other suites.

The CO_2 concentrations outdoors can be determined by direct measurements. However, the equilibrium CO_2 concentration in the test suite and the average CO_2 concentration of the inter-suite transfer air cannot be determined as simply.

The equilibrium CO_2 concentration in the test suite can be measured directly if ventilation rates are stable in the building. However, some fluctuations in ventilation airflows are likely due to changes in weather. Depending on the magnitude of these fluctuations, there could sometimes be sufficient variations in the CO_2 concentrations to make determining the equilibrium level difficult.

As a solution to this problem, a decay test that begins with high initial levels of CO_2 can be carried out in the test suite. The high concentrations of CO_2 in this test are intended to make the weather-induced variations in CO_2 concentrations insignificant. Consequently, our test provides better estimates of the equilibrium CO_2 concentration in the test suite. The equilibrium CO_2 concentration in the test suite can then be determined using non-linear regression of the CO_2 decay data.

This average CO_2 concentration of the inter-suite transfer air can be defined as: the sum (for all suites other than the test suite) of the CO_2 exiting each suite and entering the test suite, normalized by the total amount of air exiting all of these suites and entering the test suite. The amount of CO_2 exiting a suite is the concentration of CO_2 in the air exiting the suite multiplied by the amount of air exiting the suite.

It is practically impossible to measure all of the CO_2 concentrations in other suites and the inter-suite airflow rates. However, it is possible to estimate the average concentration for the other suites using Equations 5 and 6 in Section 2.5, several measured or calculated parameters, and two assumptions.

Specifically, the measured parameters were the CO_2 concentrations outdoors and in the corridor adjoining the test suite. The calculated parameters were the airflow rate through the suite access door of the test suite and the air change rate for the test suite. The first assumption is that each of the suites other than the test suite are occupied with two sleeping occupants, on average. The second assumption is that the behavior of these other suites is similar to that of the test suite.

We expect that the average CO_2 concentration in these other suites can be estimated within ± 100 ppm. This estimate of the average is only a first approximation and is not precise, particularly in a building where the ventilation rates depend significantly on weather parameters. However, it provides a conservative estimate of the inter-suite transfer air fraction. In particular, if there are fewer than two occupants in the other suites on average, then the actual inter-suite transfer fraction will be higher than the calculated fraction.

An uncertainty analysis following the procedures described in ASHRAE Guideline 2 (1990b) was conducted on the test method to assess the CO_2 measurement equipment needs, and to assess the accuracy required for estimating the average and equilibrium CO_2 concentrations. A summary of the results of this analysis follows:

- We arbitrarily set a goal of detecting transfer air when it was 10% or more of total ventilation air with an uncertainty of no more than ± 50% of the mean inter-suite transfer air fraction.
- The outdoor CO_2 concentrations and the time-varying CO_2 concentrations in the test suite need to be measured to within ± 10 ppm.
- Non-linear regression can be used to determine the equilibrium CO_2 concentration in the test suite with an accuracy of about ± 10 ppm. The accuracy of this technique is almost entirely dependent on the accuracy in measuring the initial CO_2 concentration in the test suite at the start of the decay period.
- The average CO_2 concentration of the inter-suite transfer air needs to be estimated within ± 100 ppm when the inter-suite transfer air fraction is 50% or less and the air change rate in the test suite is 1.5 ach or less. Higher transfer air fractions and higher air change rates require more accurate estimates, which are difficult to make. However, it is important to recognize that inter-suite transfer air fractions are less important at the higher air change rates, because the test suite is more likely to be receiving outdoor air directly.
- A sample of CO_2 concentrations for a period of approximately 2 hours within the decay period provides sufficient accuracy in determining the inter-suite transfer air fraction. Longer sample periods do not significantly improve the uncertainty in calculating this fraction.
- An order of magnitude improvement in the accuracy of the test equipment would not significantly improve the uncertainty of our inter-suite transfer air fraction calculation.

3.7.2 Measurements

The test procedures to inject and mix CO_2 in the test suite and then to measure the decay of CO_2 in this suite were based on the same procedures as in Test Set 5.

The simultaneous tracer gas and CO_2 decay test period was selected based on CO_2 measurements in office buildings by Persily and Dols (1990). Their data confirmed the need for nighttime measurements when the building is near steady-state conditions. Specifically, the CO_2 decay test was carried out between approximately midnight and 08:00 the next morning. It was assumed that the vast majority of occupants will be sleeping during this period. Consequently, CO_2 generation by occupants and building operating conditions are likely constant during this period (approximately "steady-state conditions).

During the CO_2 decay test, a single-point continuous sampling of the CO_2 concentration in the test suite was carried out. The sample point was located immediately adjacent to the tracer gas sample site in the living room. This decay followed a pulse injection of CO_2 throughout the suite that achieved a concentration of between 2000 and 3000 ppm of CO_2 in the living room. The CO_2 concentration was measured once every 5 seconds and the average of the 12 concentration measurements was recorded once every minute during the decay test.

A PP Systems Model EGM-1 CO_2 monitor with a range of 0 to 2000 ppm and an accuracy of $\pm$ 10 ppm was used to measure the CO_2 concentrations. This monitor uses a non-dispersive infra-red detector with an internal sampling pump. It automatically auto-zeros once every minute by rerouting its sample airflow through a built-in soda lime scrubber. As a result, it is one of the most precise instruments that is available. The monitor is also equipped with a built-in datalogger that is capable of storing large amounts of data and of downloading those data through an RS232 port. The monitor was calibrated prior to its use in each set of test suites (once in Vancouver, once in Toronto, once in Montreal, and once in Winnipeg).

In addition to the CO_2 concentrations within the test suite, we measured CO_2 concentrations outdoors for 15 minutes just prior to and just after the CO_2 decay test. Also, sequential spot measurements of CO_2 concentrations in several different indoor spaces were carried out over successive 5 minute periods just prior to the decay test. Specifically, we measured CO_2 concentrations in the corridor adjoining the test suite and in selected vertical shafts adjoining the corridor. A shaft was selected for sampling if the smoke tube tests in Test Set 1 indicated that airflow was into the corridor from the adjoining shaft.

3.7.3 Data Conversion and Analyses

No conversions of the CO_2 concentration measurements were necessary. However, analyses using the measured CO_2 concentrations were required to estimate the equilibrium and average CO_2 concentrations and to calculate the inter-suite transfer air fraction for the test suite.

To determine the equilibrium CO_2 concentration in the test suite during the decay period, we first plotted the natural logarithm of the CO_2 concentration (corrected using an initial estimate of the non-zero equilibrium level) against time in hours on a linear scale. On this graph, the calculated concentrations were expected to form an approximately straight line during the decay period (after equilibrium was achieved immediately following injection in the test suite). As for the tracer gas decay tests, the correlation coefficient from the regression analysis describes how well the data correspond to a straight line. The correlation coefficients in our regression analyses ranged from 0.986 to 1.000 with an average of 0.997.

Next, we chose a sample of the calculated concentration data that appeared to be linear (minimum period of 2 hours). The sample was selected to start with the highest possible concentration in the linear region to minimize the effects of instabilities in ventilation rate and concentration. This sample was also selected to coincide with the period selected for the tracer gas in Test Set 5.

Finally, non-linear regression of the CO_2 decay data, as described in ASHRAE Guideline 2 (1990b), was used to obtain a new estimate of the equilibrium CO_2 concentration in the test suite during the decay period. The new estimate was calculated using the following equation:

$$C_{eq} = C_i - e^b \qquad \textbf{\textit{(Equation 8)}}$$

where

- C_i = is the CO_2 concentration in the suite at the start of the decay period, ppm by volume, and
- b = is the regression line's intercept at the start of the decay period, ln (ppm by volume).

The entire analysis process was carried out iteratively until changes in the estimated equilibrium CO_2 concentration were below a specified tolerance (10^{-5} ppm).

To estimate the average CO_2 concentration in suites other than the test suite, Equations 5 and 6 of Section 2.5 were used to develop the following equation:

$$C_t = \frac{\left[(1-F_o)\cdot(\rho_s\cdot q_s - \rho_c\cdot q_c)\cdot C_o\right] + \left[\rho_c\cdot q_c\cdot C_c\right] + \left[0.6583\cdot 10^6\cdot G\right]}{\left[(1-F_o)\cdot \rho_s\cdot q_s - (F_o)\cdot\rho_c\cdot q_c\right]} \qquad \textbf{\textit{(Equation 9)}}$$

where

- C_t = average CO_2 concentration in suites other than the test suite that have transfer airflows into the test suite, ppm by volume,
- F_o = inter-suite direct transfer air fraction for each suite including the test suite (excludes indirect CO_2 transfer from the corridor), dimensionless,
- q_s = flow rate for air exiting each suite, including the test suite, m^3/s,
- q_c = flow rate for air entering each suite from the corridor, including the test suite, m^3/s,
- ρ_c = corridor air density, kg/m^3,
- C_o = outdoor CO_2 concentration, ppm by volume,
- C_c = CO_2 concentration within corridors adjoining suites, including the test suite, ppm by volume, and
- G = CO_2 generation rate within each suite other than the test suite, kg/s.

The direct inter-suite transfer air fraction represents the amount of ventilation air that is transferred directly from one suite to another, including from the test suite. Consequently, this fraction does not include CO_2 transport from the corridors into the suites. Instead, this transport from the corridor is explicitly accounted for in Equation 9.

It is important to recognize that the direct inter-suite transfer air fraction is different compared to the fraction defined in Equation 7 of Section 2.5.3. The latter fraction assumes the CO_2 in the corridors originated in other suites within the building. Consequently, the fraction in Equation 7 includes the direct transport of CO_2 between suites and the indirect transport of CO_2 from the corridor into the test suite.

With the above definition of the direct inter-suite transfer air fraction in mind, this fraction can be correlated with the estimated equilibrium CO_2 concentration in the test suite using the following equation:

$$F_o = \frac{[\rho_s \cdot q_s \cdot C_{eq}] - [\rho_c \cdot q_c \cdot C_c] - [(\rho_s \cdot q_s - \rho_c \cdot q_c) \cdot C_o]}{[(\rho_s \cdot q_s - \rho_c \cdot q_c) \cdot (C_s - C_o)]} \qquad \textit{(Equation 10)}$$

where

C_{eq} = equilibrium concentration in test suite, ppm by volume.

Equations 8 through 10 were solved iteratively beginning with an initial estimate of the direct inter-suite transfer air fraction. This process was carried out by refining the estimate of the direct inter-suite transfer air fraction until the difference between the estimated and calculated fractions were below a specified tolerance (10^{-5}).

In these analyses, the CO_2 generation rate for the two sleeping occupants in each suite other than the test suite was based on an assumed metabolic rate of 0.7 met (ASHRAE 1997). Appendix D in ASHRAE Standard 62 (1990a) indicates that CO_2 production is directly proportional to metabolic rate (0.3 L/min at 1.2 met and 0 L/min at 0 met). Therefore, for the combination of two sleeping occupants, we calculated the CO_2 generation rate would be 5.83 mL/s (0.35 L/min). This generation rate is equivalent to 1.05×10^{-5} kg/s (0.63 g/min).

Using the estimates of the equilibrium and average CO_2 concentrations and the arithmetic average of the measured outdoor concentrations, the inter-suite transfer air fraction for the test suite was calculated using Equation 7 from Section 2.5.3. As described in Section 2.5, the calculated fraction is the likely minimum value. The uncertainty associated with this value was determined using procedures described in ASHRAE Guideline 2 (1990b).

Comparison 9 (Section 4.4.9) describes the results of these analyses.

4.0 Results from Field Testing of Ten Suites

4.1 Introduction

To demonstrate how real suites are ventilated, we tested suites in a sample of ten mid- and high-rise residential buildings across Canada. The field tests followed the procedures that were described in Section 3. The results of these field tests are now described.

Section 4 is subdivided into four parts, each of which presents one of the following:

- our reasons for selecting weather conditions, buildings, and suites for the tests,
- an overview of the test building and suite characteristics,
- key findings based on our analyses of the field test data, and
- a discussion of problems with the building ventilation systems we tested.

4.2 Selection of Test Weather Conditions, Buildings, and Suites

The following describes our reasons for selecting buildings and suites for field testing. It also describes our reasons for selecting specific weather conditions for the tests.

As requested by CMHC, ten test buildings were selected to obtain a cross-section of the three Canadian climatic regions: maritime, western, and central. Specifically, the test buildings included: four in a maritime climate (Vancouver, British Columbia); three in a western climate (Winnipeg, Manitoba); and three in a central climate (two in Toronto, Ontario and one in Montreal, Quebec).

CMHC had requested that the buildings be tested during cold weather. We carried out the tests during late February and early March 1996. This specific period was selected, because daily temperature variations in most regions tend to be near the winter maximums at this time of the year (Environment Canada 1982b). As a result, the test buildings would likely be exposed to the largest variations in stack-induced pressure differences between night-time and day-time tests in Test Set 3 at this time of year. Table 1 describes the range of weather conditions during the test period for each suite.

In selecting the test buildings, we chose buildings to obtain a cross-section of different building heights and different suite exhaust system types (separate, central, intermittent, continuous, and combinations thereof). We also selected one building that used transfer ducts between the suites and adjoining corridors.

One suite in each selected building was tested, as requested by CMHC. We attempted to select a test suite that would be prone to poor or excessive ventilation at the time of testing. However, this criterion was constrained in practice by two factors.

One constraining factor was our difficulty in accessing suites. We first explained the tests and their purpose to occupants and offered them an honorarium to participate. However, many occupants were unable or unwilling to cooperate due to scheduling conflicts, security-related issues, or lack of interest. This restricted the number of suites available for testing.

Table 1: Test Period Weather Conditions

Building Number	Building Location	Outdoor Temperature [°C]			Wind Speed [km/h]		
		Min	Max	Avg	Min	Max	Avg
1	Vancouver	2	9	4	0	15	2
1	Vancouver	7	14	11	0	3	0
2	Vancouver	0	15	5	0	15	3
3	Vancouver	0	10	5	0	10	2
4	Vancouver	2	16	6	0	10	3
5	Toronto	-13	-3	-9	5	24	16
6	Toronto	-15	-4	-11	5	39	15
7	Montreal	-5	11	1	5	24	12
8	Winnipeg	1	6	2	11	37	25
9	Winnipeg	-10	-4	-7	6	31	16
10	Winnipeg	-13	7	-7	0	21	9

A second constraining factor in suite selection that we could not predict in advance was the weather conditions during our scheduled tests. Due to the dependency of suite ventilation on weather, a selected suite that had poor or excessive ventilation one day might experience acceptable ventilation on another day. This was particularly true if wind conditions changed suddenly. As a result, it was fortuitous if a suite experienced poor or excessive ventilation during our tests.

With the exception of one Vancouver building, a second suite in each building was not tested due to the above-mentioned constraints and due to budget limitations. During our test protocol development in Vancouver, a second suite was selected for testing in the tallest building. The intent of testing this second suite was to allow us to examine the effect of differences in stack-induced pressures that were caused by different suite locations with respect to the neutral pressure plane.

4.3 Characteristics of the Test Buildings and Suites - An Overview

Table 2 lists several general configuration characteristics of the ten buildings and eleven suites we tested. For confidentiality reasons, none of the buildings or suites are specifically identified by their address in this report. A floor plan of each test suite is shown in Appendix E.

The volume listed for each test suite in Table 2 is the total conditioned volume of the suite, including reductions in volume due to drop ceilings, but not including reductions due to cabinetry, appliances, or furnishings.

All of the test buildings were approximately fully-occupied, except one. In Building 1, the occupancy was only about 30% of its maximum.

Other characteristics of the test buildings and suites are discussed in the following eight brief summaries.

Table 2: General Characteristics of Test Buildings and Suites

Building					Test Suite			
Building Number	Building Tag	Test Floor	# of Stories	Suites/ Floor	Volume [m^3]	Floor Area [m^2]	Number of Bedrooms	Number of Bathrooms
1	BC 6	31	32	4	151	64	1	1
1	BC 6	11	32	4	151	64	1	1
2	BC 1	9	9	7	127	53	1	1
3	BC 2	9	9	4	119	49	1	1
4	BC 5	3	10	10	102	43	1	1
5	Ont 5	8	10	12	171	72	2	1
6	Ont 4	4	13	10	135	56	1	1
7	Que 4	6	8	15	135	56	1	1
8	Man 5	4	6	7	180	74	2	1
9	Man 1	6	6	6	231	98	2	2
10	Man 2	6	6	5	142	50	1	1

Building Classifications

Except for the three buildings we tested in Winnipeg, all of the test buildings were high-rise buildings (eight stories or more). All of the test buildings in Winnipeg were classified as mid-rise (six stories).

Building Shafts

Each test building had two stair shafts. These shafts connected every residential storey, except in Building 3. In that building, the stair shafts were not directly accessible on the top storey, which was the test floor. Instead, the stair shafts were indirectly accessible by crossing the open rooftop. The stair shafts in Building 3 only directly connected the stories below the test floor.

Every test building had at least one elevator shaft that connected every residential storey.

Each test building had a single garbage chute, except three of the Vancouver buildings (1, 3, and 4). These chutes connected every residential storey.

Outdoor Access Doors from Corridor

Only three of the ten test buildings had outdoor access doors in the corridors on the test floor. Buildings 2 and 3 each had two of these doors only in the corridor adjoining the test suite. Each of these doors opened onto the roof of the building. Building 4 had a single door to outdoors in the corridor adjoining the test suite. This door opened onto a terrace.

Suite Locations and Exterior Exposure

Three of the test suites were located below the neutral pressure plane (NPP). These suites were in Building 1 (Floor 11), Building 4, and Building 6. All of the other test suites were located above the NPP. Four of these other test suites were located on the top storey of the building.

All of the test suites were corner suites with two exterior walls, except Buildings 4, 6, and 7. Each of these three other test suites had only one exterior wall.

The test suites in Buildings 2, 3, 9, and 10 on the top storey of the building. As such, their ceilings were the roof of the building.

Suite Access Doors

Geometric characteristics of the suite access doors for the test suites are listed in Table 3. The gaps were located between the door and its frame. Gaps were measured from within the suite with the door closed and latched. The data for Building 1 apply to both Floors 11 and 31. Door to frame gap data were not collected for Buildings 1 and 2, because we did not recognize the importance of these data until our tests in the third building.

Table 3: Geometric Characteristics of Suite Access Doors

Building Number	Door Width [mm]	Door Height [mm]	Door to Frame Gaps [mm] Top	Bottom	Hinge Side	Latch Side
1	900	2060	<----- *No gap data collected* ----->			
2	860	2030	<----- *No gap data collected* ----->			
3	860	2010	10	5	3	6
4	910	2010	6	7	1	4
5	850	2060	2	6	3	4
6	850	2060	6	5	3	3
7	910	2010	4	18	3	2
8	890	2210	6	10	2	6
9	890	2000	5	19	2	6
10	910	2010	5	16	2	5

Four of the eleven test suites had fully weather-stripped suite access doors (two suites in Building 1, one in Building 3, and one in Building 8). The weather-stripping on the suite access doors for these four suites was often not completely in contact with some part of the door, threshold, or floor.

Two test suites had partially weather-stripped suite access doors. There was a spring-loaded sweep on the bottom of the suite access door in Building 4. However, this sweep did not contact the floor. It appeared that there had been weather-stripping along the top and sides of this door at one time, but there was no weather-stripping in these locations at the time of our tests. In Building 7, only about 67% of the latch side of the door was weather-stripped. There was no indication that the remainder of the door had been weather-stripped in the past.

There was no weather-stripping on the suite access doors of the other five test suites (Buildings 2, 5, 6, 9, and 10).

The suite access door in Building 9 fit poorly in its frame. This door could swing in and out at the latch side about 6 mm, even when the door was latched. This range of motion was due to a significantly oversized striker plate in the door frame. The access doors for the other test suites did not move significantly when latched.

Transfer Ducts

Only Building 8 had a transfer duct between the test suite and adjoining corridor. This duct was fitted with horizontal-louvered grilles on both ends. It was acoustically-lined and contained one 90° elbow and a fire damper. The ductwork provides a fixed and relatively large leakage area for flow between the corridor and suite. Its use is an indication that the corridor supply air system was intended to supply air to the suites in this building.

In the other nine buildings we tested, the lack of an intentional fixed leakage area between the corridor and suites is consistent with the usual primary design intent of the corridor supply air system: to pressurize the corridor relative to these suites, rather than to supply air to the suites adjoining the corridor.

Mechanical Supply and Exhaust Systems

Every test building had a rooftop corridor supply air system. Building 1 also had a second corridor supply air system on Floor 4, which served Floors 1 through 18. The rooftop system served Floors 19 through 32.

The corridor supply air systems operated continuously during the tests, except in Building 7. In this building, the corridor supply air system was out of service due to maintenance problems, which could not be rectified at the time of testing. Substantial smudging on the corridor ceilings indicated that this unit had been functioning in the past.

Buildings 8 and 9 used time clocks to control the operation of the corridor supply air system. The time clocks in these two buildings were set to manual override so the systems would run continuously for the duration of the test periods.

The test suite in Building 8 had a continuous exhaust system for the kitchen, bathroom, and an in-suite storage room. Building 10 also had a continuous exhaust system for the kitchen and bathroom in the test suite.

Building 7 had a continuous exhaust system for the bathroom in the test suite. The kitchen in this suite had a separate in-suite intermittent exhaust system that was also connected to a second continuous exhaust system that served several stacked suites.

The other seven test buildings had separate in-suite intermittent exhaust systems for the kitchen and bathroom(s) in each suite.

Every continuous exhaust system for the test suites had a vertical shaft that served each residential storey. Each of these shafts was connected to a central rooftop exhaust fan, except in Building 7. In this building, the kitchen and bathroom exhaust shafts were each connected to one of 15 down-blast rooftop exhaust fans instead.

At the time of testing, some of the rooftop fans for Building 7 were out of service. The reason they were inoperative is unknown. In particular, the rooftop fan serving the bathroom of the test suite (and of all suites above and below) was inoperative. However, the rooftop fan for the kitchen exhaust was operative.

All of the rooftop fans for the kitchen and bathroom exhausts in Building 7 were controlled by time clocks. The time clocks switched these rooftop fans on at 07:00 and off at 23:00. As a result, the bathroom and kitchen exhaust for the test suite in Building 7 was off during our tracer gas tests. Two rooftop exhaust fans that were connected to service rooms in the parkade operated continuously during our tracer gas tests.

In the other two buildings with continuous exhaust, the central exhaust fans were operating during our tracer gas tests.

Each of the intermittent in-suite exhaust systems for the test suites was ducted laterally to outdoors, except in Building 7. In that building, the kitchen range hood was ducted to a vertical exhaust shaft that was connected to all of the suites above and below the test suite. This vertical shaft had a rooftop exhaust fan, as stated above.

All of the intermittent exhaust fans in the test suites were off during our tracer gas tests.

Each high-rise test building had a smoke control system, except one in Toronto (Building 5). None of these systems operated during the tests. The three mid-rise test buildings in Winnipeg did not have smoke control systems.

Suite Fan-Coil Units

Two of the test suites had vertical fan-coil units (Building 6 in Ontario and Building 9 in Manitoba). There was no outdoor air intake for either fan-coil unit.

In the Ontario suite, the fan-coil unit was apparently intended to supply heating and cooling to the suite. The unit was located in a wall between the living room and bedroom. This unit supplied recirculated air from within the suite directly to these two rooms through supply outlets on the walls. Return air was drawn into the unit through a grille in the living room wall. All of the interior doors in this suite were significantly undercut (about 30 mm) to provide a path for return air (and transfer air to the bathroom). The fan-coil unit cycled on and off during the decay test (to maintain the temperature in the suite at 20°C as defined by the thermostat heating setpoint). This operation may have affected the distribution of air in the suite during the test. Due to time limitations, tests with the unit off were not carried out to quantify the impact of the fan-coil unit on air distribution within the suite. Noise from this unit did not seem to be excessive.

In the Manitoba suite, the fan-coil unit was located in a bedroom closet adjacent to the central hallway of the suite. This unit supplied recirculated air from within the suite directly to the kitchen, to the living room, and to both bedrooms through supply outlets on the walls. Return air was drawn into the unit through a grille in the hallway wall. The kitchen and living room were open to the hallway. The bedroom doors were undercut about 20 mm to provide a path for return air.

Baseboard heaters were present in the Manitoba suite to supply heat during the winter. The intent of the fan-coil unit was to provide cooling during other periods of the year (direct-expansion cooling coil in unit with condensing unit on roof). This unit could also be used to circulate air in the suite throughout the entire year. However, the noise from the fan and at the supply grilles seemed to be excessive when the unit was operating. The noise could cause occupants to avoid using the unit except when cooling was necessary. As a result, this suite was tested with the fan-coil unit off during our decay tests. However, we used this fan-coil unit for mixing within the test suite prior to our decay test.

4.4 Key Findings

Our key findings are based on analyses of the field data that we collected in the ten test buildings. The presentation of these findings is in the form of nine groups of comparisons, as follows:

1. design versus measured corridor supply airflows for the ten test buildings,
2. design and measured corridor supply airflows versus design and measured suite exhaust airflows for the ten test buildings,
3. design and measured corridor supply airflows versus minimum outdoor air capacity requirements of ASHRAE Standard 62 (1990a) and CSA Standard F326 (1993) for the ten test buildings,
4. design and measured suite exhaust airflows versus minimum exhaust capacity requirements of ASHRAE Standard 62 (1990a) and CSA Standard F326 (1993) for the ten test buildings,
5. measured versus theoretical leakage areas of the suite access doors for the ten test buildings (not including the test suite below the NPP in Building 1),
6. range of airflows across the suite access door during our tests versus measured corridor supply airflows for the ten test buildings,
7. measured room air exchange rates in two test suites of Building 1 (with the interior doors open and then closed in one suite located above the NPP, and with the interior doors open in the other suite located below the NPP),
8. measured room air exchange rates in the ten test suites with the interior doors open (not including the test suite below the NPP in Building 1), and
9. measured inter-suite transfer air fractions for the ten test suites.

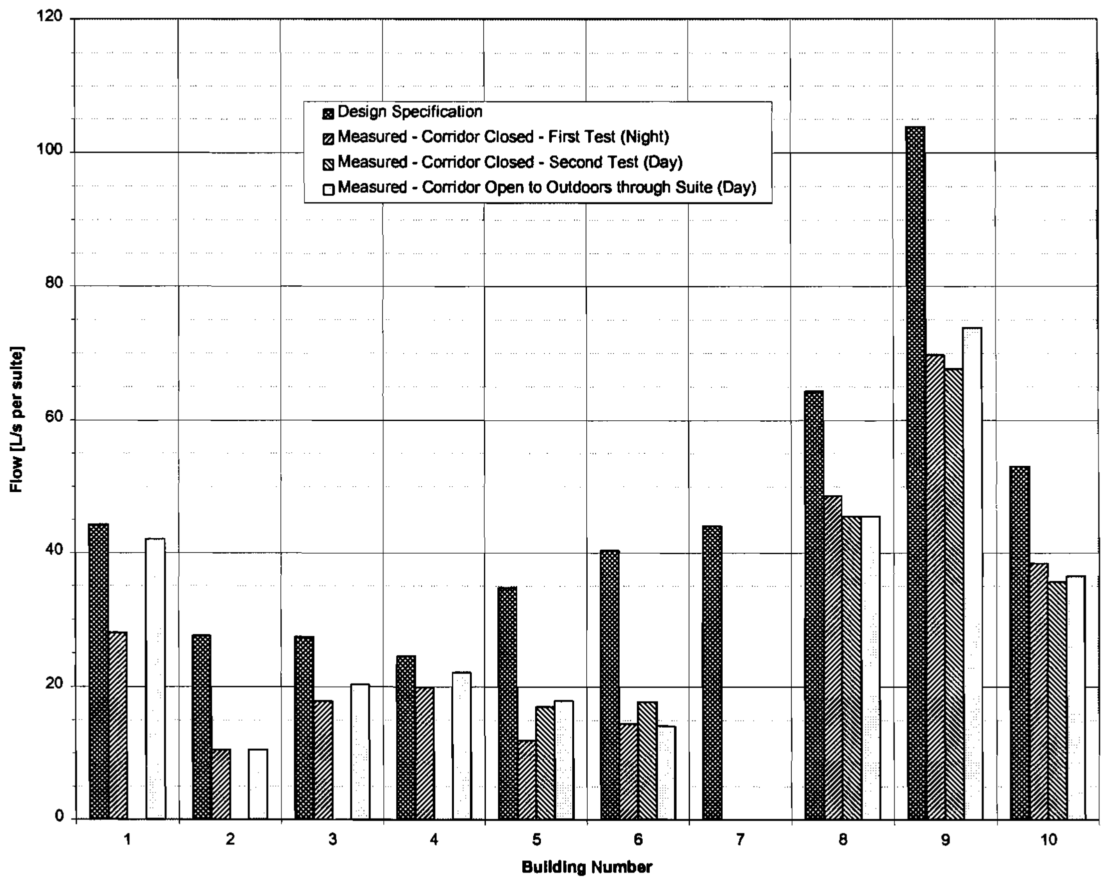
For each of these nine groups, a comparison graph or table is first presented. Next, an explanation of the types and sources of results in the graph or table is provided. Finally, our key findings are presented in point form with explanatory comments as required to support these statements.

4.4.1 Comparison 1: Corridor Supply Airflows (Design vs. Measured)

Introduction

Figure 5 shows a comparison of the design and measured corridor supply airflows for the ten test buildings. These airflows are presented on a per suite basis.

Figure 5: Comparison of Corridor Supply Airflows (Design vs. Measured)



The design airflows in Figure 5 are derived from a review we conducted of drawings and specification documents for the ten test buildings.

The measured airflows in Figure 5 are based on our analyses of the field data that we collected using Test Set 3. This set of tests was described in Section 3. The corridor supply airflow in Building 1 was only measured outside the upper test suite (Floor 31).

Three groups of measured airflows are presented: first test (night), second test (day), and third test (day with corridor open to outdoors).

The first test was conducted at night, whereas the second test was conducted during the following day (about 12 hours later). Both of these tests were carried out with the corridor adjoining the test suite closed to outdoors. The intent of the second test was to examine the effect of diurnal variations in stack- and wind-induced pressure differences on these airflows. Second tests were not carried out in the Vancouver buildings (1 through 4), because the additional benefit of the second test was not recognized during these tests. No corridor supply airflow tests were carried out in Building 7, because this system was out of service.

The third group of airflows was measured with the corridor open to outdoors immediately after the second test. Our intent in carrying out the third test was to examine the effect of changes in corridor leakage (and back pressures) on these airflows.

The corridor supply airflow per suite was calculated by dividing the total corridor supply airflow equally among all suites adjoining the corridor. In this analysis, we used the design assumption that leakage areas of the suite access doors are similar. This assumption is not always true, because the door characteristics sometimes may vary from suite to suite.

Furthermore, we did not account for door leakage between the corridor, stair shafts, elevator shafts, service rooms, or outdoors, because designers specify airflow rates based only on the number of suites or on the capacity of installed exhaust devices. Even if designers did include these other doors, they do not consider the effects of the neutral pressure plane location on flow directions through these doors.

Key Findings:

- **There is a wide variation in the design specifications for corridor supply airflows.**

  The design specifications for the corridor supply airflows of the test floors ranged from 25 to 64 L/s per suite, excluding one building (104 L/s per suite for Building 9). Excluding this large airflow, the average design flow was 40 L/s per suite. Based on the total volume of the test suites, these airflows correspond to suite air exchange rates in the range of 0.73 to 1.35 ach, with an average of 1.0 ach (excluding the largest airflow). The 104 L/s per suite flow corresponds to a suite air exchange rate of 1.62 ach.

  Reasons for the variations in design specifications of the corridor supply airflows are discussed in Comparison 2 (Section 4.4.2).

- **Measured corridor supply airflows are significantly lower than the design flows.**

  Qualitatively, there were strong corridor supply airflows to the test stories in most buildings when the mechanical ventilation systems were operating. However, some corridor supply airflows were weak and appeared to be nowhere near the likely design flows.

  In several buildings, some corridor supply air outlets had been partly closed by internal balancing dampers. Other outlets had been partly or completely closed by externally adjustable louvers. The airflows from these outlets were significantly reduced compared to the other corridor supply airflows in the building. Odors were often apparent on stories where outlets had been partly closed, but usually no odors were apparent on stories where the outlets were open. Tampering with louvers on corridor supply air outlets by building occupants possibly indicates occupant dissatisfaction with mechanical system operation. The reasons for this dissatisfaction are unknown. Possible reasons include: noise, adverse effects on thermal comfort (drafts from cool supply air), or excess air velocity. None of the external louvers were closed on the test floors.

Based on the first test (night with the corridor closed to outdoors), the measured corridor supply airflows on the test floors ranged from 34 to 81% of the design flows, with an average of 59%. The measured flows during the second test (day) exhibited a similar tendency.

As discussed in Section 2, corridor supply airflows can also be significantly influenced by other factors, such as high stack pressures on upper stories and/or low corridor leakage areas. The following two points discuss these issues further.

- **There can be substantial variations in actual corridor supply airflows over the course of a day in some buildings.**

  In two of the test buildings (5 and 6), there was a substantial change in the corridor supply airflow from the first test to the second test, based on the differences in airflows between these two tests.

  We could not eliminate the possibility of confounding factors during these tests (such as changes in building envelope leakage due to occupants opening windows in their suites and operation of scheduled equipment). An example of scheduled equipment is the operation of parking garage exhaust fans during hours when the number of vehicles entering or exiting the garage is expected to be high. The cold weather at the time of the tests makes window opening less likely to be significant than changes in weather conditions and changes in equipment operation.

  It is important to keep in mind that our tests were only a snapshot of the building while it operated under limited variations in weather conditions. Further tests at different times of the year or multi-compartment computer simulations are needed to more precisely analyze the effects of annual variations in temperature and wind on airflows.

  For Building 5, the corridor supply airflow increased from the first test to the second test by about 42%. For Building 6, this airflow increased from the first test to the second test by about 22%. There was no significant change in the wind- or stack-induced pressure differences for the test floor in both buildings. The reasons for the large variations in airflow are unknown.

  There was no significant change in corridor supply airflows for the three other buildings that had two tests (Buildings 8, 9, and 10). This was particularly notable for Building 9, which was exposed to a substantial change in wind conditions from the first test to the second test.

  For Building 9, there was no significant change in stack effect, but the wind-induced pressure difference for the test floor increased from about 11 Pa to about 15 Pa on the leeward side. In this case, the average measured wind speed above the building increased from about 14 to 29 km/h. The wind direction also changed between these two tests (about a 90° clockwise shift). In the first test, the wind direction caused the supply air intake to be on the leeward side of the rooftop unit. In the second test, the intake was perpendicular to the wind.

- **The airtightness of the building envelope and suite access door affects the corridor supply airflows.**

  By opening the corridor on the test floor to outdoors through the test suite in the third test, we significantly increased the leakage area of the corridor on the test floor. This also virtually eliminated the leakage-induced back pressure on the corridor supply air outlet for this storey. The change in corridor airtightness that we achieved cannot be quantified, because we did not determine the airtightness of the corridors or building envelopes in our tests.

The differences between the corridor supply airflows we measured in the second and third tests were significant for two reasons. First, even with an open corridor, the measured airflows were still significantly less than the design airflows. In this case, the measured flows ranged from 35 to 95% of the design flows with an average of 66%.

Second, compared to the measured corridor supply airflows in the second test with the corridor closed, the flows with the corridor open were usually significantly greater (100 to 150% of the flows in the first test with an average of 111%). One building did not follow this trend.

In Building 6, the windward test suite was located below the NPP of the building when the corridor and test suite were closed to outdoors. In this case, the corridor supply air outlet was shielded from direct stack- and wind-induced pressurization by the combined flow resistance of the building envelope and suite access doors. Opening the corridor and test suite to outdoors caused the NPP to shift downward toward the test suite and directly exposed the corridor supply air outlet on the test storey to pressurization by stack and wind effects. This shift in NPP location, along with the increased leakage area of the test storey, caused flows from outdoors into the corridor to increase. In turn, the increased flows and exposure to exterior pressure regimes increased the back pressure on the supply air outlet (rooftop intake for corridor supply air was under suction due to the wind). As a result, the corridor supply airflow on the test storey was reduced by opening the test corridor to the outdoors through the windward test suite.

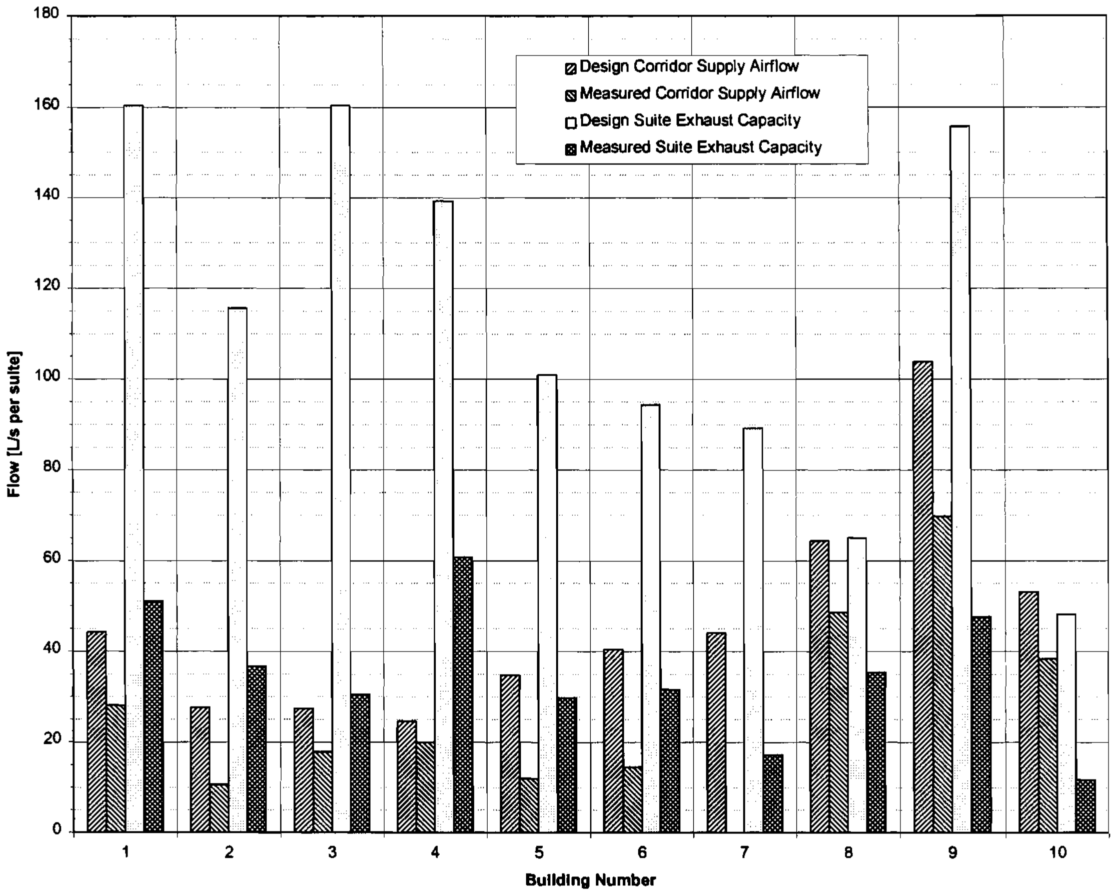
It is important to recognize that opening a single corridor to outdoors does not eliminate the stack-induced back pressures in corridors on other stories. As a result, the corridor supply airflows on the storey with the open corridor may still be indirectly affected by stack effects applied through the system fan by back pressures at the corridor supply air outlets on other stories.

4.4.2 Comparison 2: Corridor Supply Airflows and Suite Exhaust Capacities (Design vs. Measured)

Introduction

Figure 6 shows a comparison of the design specifications for the corridor supply airflows and suite exhaust airflows for the ten test buildings. It also shows the measured airflows for these buildings. These airflows are presented on a per suite basis.

Figure 6: Comparison of Corridor Supply Airflows and Suite Exhaust Capacities (Design vs. Measured)



The design supply airflows and exhaust capacities in Figure 6 are based on information that was derived from our review of drawings and specification documents for the ten test buildings.

The measured supply airflows in Figure 6 are based on our analyses of the field data that we collected using Test Set 3. The measured supply airflow for each building is the same as the first test presented in Comparison 1 (Section 4.4.1). No corridor supply airflow tests were carried out in Building 7, because this system was out of service.

As discussed in Comparison 1, the corridor supply airflow per suite was calculated assuming the total corridor supply airflow was equally divided among all suites adjoining the corridor.

The measured exhaust capacity per suite for each building is the total exhaust capacity for the test suite with all exhaust devices in the suite operating. These capacities were determined from data we collected using Test Set 2 while the test suite was depressurized to 20 Pa with respect to outdoors. As described in Section 3.3.1, we expect that these capacities are within 10% of the actual flows through the suite exhaust devices under normal operating conditions.

Key Findings:

- **There is a wide variation in the design specifications for total suite exhaust capacities.**

  The design specifications for total suite exhaust capacities of the test suites ranged from 48 to 160 L/s per suite with an average of 113 L/s per suite. Based on the total volume of the test suites, these exhaust capacities correspond to suite air exchange rates in the range of 1.22 to 4.91 ach, with an average of 2.88 ach.

  The reasons for the wide range of exhaust capacities are not clear. However, it appears unlikely that the variations are related to exhaust capacity requirements, as discussed in Comparison 4 (Section 4.4.4).

- **Measured exhaust capacities were always considerably lower than the design exhaust capacities.**

  The installed capacities of suite exhaust devices were only a small fraction of the exhaust capacities specified by the designers. Specifically, the measured total exhaust capacities for the test suites ranged from 19 to 54% of the design capacities with an average of 32%.

  These low fractions were expected to some extent, because designers tend to deliberately oversize suite exhaust devices. Typically, the total design exhaust capacities are in the range of 120 to 400% of the total suite exhaust capacities required by ASHRAE Standard 62 (1990a) and CSA Standard F326 (1993). The relations between the design and measured exhaust capacities and the exhaust capacity requirements for the test suites is discussed in Comparison 4 (Section 4.4.4).

  Other reasons for the low fractions are described in the final two points of this comparison.

  No correlation was possible between the installed versus design exhaust capacity fractions, the suite access door leakage, and suite depressurization, because of the nature of our test procedure. Our procedure used a blower door in the suite access door opening to determine the exhaust capacities at a constant suite depressurization of 20 Pa. This procedure caused the suite access door leakage to be eliminated from the leakage area of the test suite during the exhaust device tests.

  Also, no correlation could be made between the installed versus design exhaust capacity fractions, the ductwork flow resistances for the exhaust devices, or the building envelope leakage. The latter two parameters were not determined in our tests.

- **Design corridor supply airflows are usually much lower than the design suite exhaust capacities.**

  Based on the review we conducted of drawings and specification documents for the ten test buildings, the supply sizing factors used across Canada vary widely. These factors are typically in the range of 20 to 80% of the total intermittent suite exhaust capacity and 40 to 120% of the total continuous suite exhaust capacity. The design supply airflow depends on the type of suite exhaust system (intermittent or continuous) and on the designer's estimate for a suite exhaust diversity factor for intermittent exhaust systems.

In the two Ontario buildings (5 and 6), there were only intermittent suite exhaust systems in the test suites. The design corridor supply airflows for these buildings were 34 and 43% respectively of the design suite exhaust capacities. These fractions are significantly below the bottom of the range used by Ontario designers for these systems (60 to 80%).

- **Measured corridor supply airflows and suite exhaust capacities were usually slightly closer together than the design airflows and capacities.**

  With the exception of the three Winnipeg buildings (8 through 10), the measured corridor supply airflows were still usually much lower than the measured suite exhaust capacities.

  For three of the test buildings (1, 3 and 4), there were significantly smaller differences between the measured supply airflows and exhaust capacities compared to those between the design airflows and capacities. These reduced differences were largely due to the substantial differences between the design and measured suite exhaust capacities for these three buildings.

  In Buildings 4 through 6, there were also smaller differences between the measured supply airflows and exhaust capacities. However, the reductions in these differences were not as significant for these three buildings compared to the reductions for Buildings 1, 3, and 4. Although there were also substantial differences between the design and measured suite exhaust capacities for Buildings 4 through 6, the measured corridor supply airflows for these two buildings were also significantly reduced compared to the design supply flows.

  In the three Winnipeg buildings, the differences between the measured supply airflows and exhaust capacities increased considerably. This was particularly noticeable for Building 10. In this building, the design sizing factor for supply airflow was about 110%, but the factor based on measured flows was 328%. The increased differences for these three buildings were largely due again to the substantial differences between the design and measured suite exhaust capacities.

  Two of the three Winnipeg buildings (8 and 10) had continuous suite exhaust systems. The design sizing factors for the supply airflows in these two buildings were 99 and 110% respectively. These factors indicate the designers intended that the suite ventilation systems have equal or slightly excess mechanical supply flows compared to exhaust capacities under design conditions. Our measurements of these flows and capacities indicated there were large reductions in installed exhaust capacity without a corresponding reduction in corridor supply airflow. This means that these suite exhaust systems were definitely not "balanced" and there were considerable excess supply airflows to the test corridors in these two buildings.

- **Designer's did not ensure there is always sufficient leakage between the corridor and suite for the transfer of makeup air that includes the corridor supply air.**

  A simple comparison of measured corridor supply airflows with measured suite exhaust capacity cannot indicate whether a suite exhaust system is "balanced" under actual operating conditions, unless the actual operating conditions are near the capacity conditions for the suite exhaust devices. However, "one-time" pressure difference measurements between the suite and the corridor can indicate by themselves whether the system is "balanced" under normal operating conditions.

  In particular, a "balanced" system means that switching on an exhaust device within a suite will have no effect on pressure differences between the suite and corridor. It also means that the airtightness of the suite or the operation of other exhaust devices will not affect the exhaust flows of this exhaust device. For current suite ventilation systems, this can only occur when there is sufficient leakage area between the corridor and suite or between the suite and outdoors for the transfer of makeup air into the suite. Some (but not necessarily all) of this makeup air is corridor supply air.

  Based on data we collected in Test 2, operating even only one of two or more exhaust devices within the suite increased corridor to suite pressure differences by 1 to 5 Pa compared to the case with no suite exhaust. With all of the exhaust devices operating within a suite, these pressure differences increased by 1 to 10 Pa compared to the case with no suite exhaust. Therefore, it is clear that suite exhaust systems are not "balanced".

  The higher depressurizations tended to occur in the suites with relatively high capacity exhaust devices and tight suite access doors. Currently, suite access doors are the predominant leakage area between the corridor and suite. The leakage of these doors is quantified in Comparison 5 (Section 4.4.5).

  Consequently, the pressure difference changes that occur when suite exhaust systems operate are largely a result of designer's not ensuring there is always sufficient leakage between the corridor and suite for the transfer of makeup air from the corridor into the suite.

- **Designer's did not ensure that additional makeup air for exhaust can always be provided by infiltration from outdoors.**

  The finding discussed in the point above is significant, because it means that additional makeup air for suite exhaust devices must be provided by another source: uncontrolled infiltration through the building envelope. As a result, current suite exhaust systems can still be "balanced" if there is sufficient leakage directly or indirectly between the suite and outdoors for the infiltration of makeup air into the suite from outdoors.

  One possible source of this infiltration is outdoor air flowing directly into the suite through unintentional or intentional leakage openings in the suite's exterior surfaces. During cold weather, this practice is undesirable, unless the makeup air is heated prior to entering the suite. Also, outdoor air infiltration is not reliable in location, quantity, and quality.

  A second possible but even more undesirable source of infiltration is transfer airflows from adjoining suites and shafts. As discussed in Section 2.5, the ultimate source of these transfer airflows is outdoor air flowing into other areas of the building through leakage openings in the building envelope. However, these airflows can sometimes be significantly contaminated. Furthermore, as described in Section 2.5 of this report, inter-suite airflows are specifically prohibited by Sentence 6.2.3.11 (2) of the National Building Code of Canada (NBC 1990).

Our tests did not quantify the magnitudes of makeup airflows from each of these sources when the exhaust devices were operating under normal conditions, except in the two test suites with continuous exhaust and no intermittent exhaust (Buildings 8 and 10). Comparison 9 (Section 4.4.9) discusses our key findings regarding inter-suite transfer air fractions.

Based on data we collected in Test 2, operating even only one of two or more exhaust devices within the suite usually increased suite to outdoor pressure differences by 1 to 6 Pa compared to the case with no suite exhaust. With all of the exhaust devices operating within a suite, these pressure differences increased by 1 to 11 Pa compared to the case with no suite exhaust. Therefore, these data support our finding that suite exhaust systems are not "balanced".

The higher depressurizations tended to occur in the suites with relatively high capacity exhaust devices and small exterior window and door areas. Currently, the intentional and unintentional gaps within and around exterior windows and doors are probably the predominant leakage areas between the suite and outdoors, excluding the exhaust device openings themselves (Shaw 1980a). We did not measure the leakage areas of the exterior surfaces.

Consequently, the pressure difference changes that occur when suite exhaust systems operate are also partly a result of designer's not ensuring there is always sufficient leakage between the suite and outdoors for the transfer of makeup air from the outdoors into the suite.

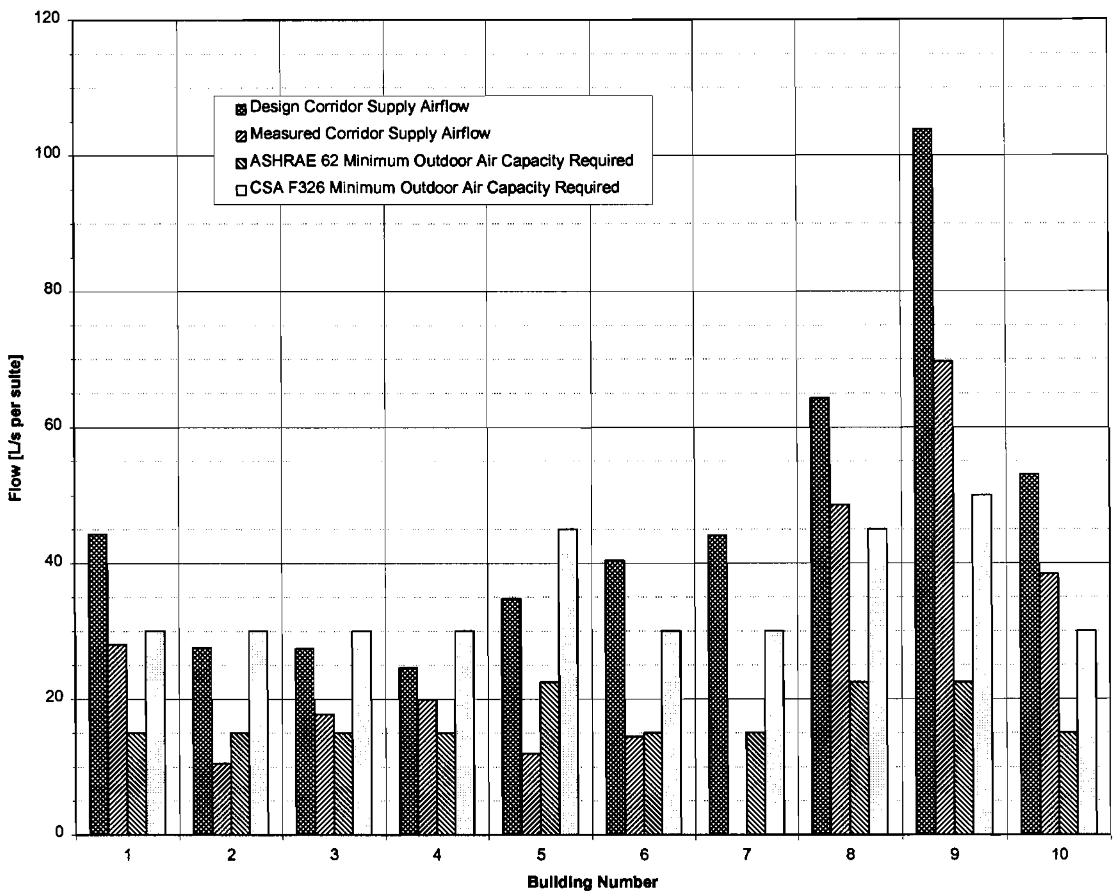
4.4.3 Comparison 3: Design and Measured Corridor Supply Airflows vs. ASHRAE and CSA Minimum Requirements for Outdoor Air Capacity

Introduction

Figure 7 shows a comparison of the design and measured corridor supply airflows for the ten test buildings. It also shows the minimum outdoor air capacity requirements for each test suite, based on ASHRAE Standard 62 (1990a) and CSA Standard F326 (1993).

The airflows in Figure 7 are presented on a per suite basis. As discussed in Comparison 1 (Section 4.4.1), the flows attributable to each suite were calculated assuming the corridor supply airflow was equally divided among all suites adjoining the test corridor.

Figure 7: Comparison of Design and Measured Corridor Supply Airflows vs. ASHRAE and CSA Minimum Requirements for Outdoor Air Capacity



The design airflows in Figure 7 are based on information derived from our review of drawings and specification documents for the ten test buildings.

The measured airflows in Figure 7 are based on our analyses of the field data that we collected using Test Set 3. The measured supply airflow for each building is the same as the first test presented in Comparison 1. No corridor supply airflow tests were carried out in Building 7, because this system was out of service.

The ASHRAE Standard 62 outdoor air capacities are based on a required outdoor airflow of 7.5 L/s per person in the test suite and on the room occupancy assumptions in this Standard. These capacities are similar in magnitude to those based on the ASHRAE Standard's minimum requirement of 0.35 ach.

The CSA Standard F326 outdoor air capacities are based on the required outdoor airflows to each occupied room. These capacities are about a factor of two greater compared to those based on the CSA Standard's minimum requirement of 0.30 ach.

In making the comparison of design and measured airflows with the requirements of the ASHRAE and CSA Standards, it is important to recognize that the primary intent of the corridor supply air system is usually to pressurize the corridor rather than to supply outdoor air for ventilating adjoining suites. A secondary intent of these systems is to provide exhaust makeup air for the suites. Furthermore, when the test buildings were designed and constructed, there was no specific requirement for compliance with these two Standards, except for an indirect reference to the ASHRAE Standard as "good practice" for ventilation systems designed according to Part 6 of the National Building Code of Canada (NBC 1990). As a result, it is expected that any agreement or excess of design or measured supply flows compared with required flows may be fortuitous. However, both Standards are now directly or indirectly codified as "good practice". The ASHRAE Standard is explicitly referred to in the 1995 version of the National Building Code of Canada (NBC 1995). Also, the ventilation requirements of Subsection 9.32.2 of the NBC 1995 are similar to those of the CSA Standard. Therefore, a comparison of design and measured airflows with the requirements of these two Standards is warranted.

Key Findings:

- **Design corridor supply airflows on a per suite basis usually significantly exceed ASHRAE minimum outdoor air capacity requirements.**

  The design corridor supply airflows on a per suite basis were 154 to 461% of the minimum outdoor air capacity requirements of ASHRAE Standard 62, with an average of 264%.

  Air supplied by these systems to the corridor is intended to be 100% outdoor air. However, it is important to recognize that the corridors can sometimes be contaminated by pollutant sources within the building. As a result, the corridor supply air transferred to suites from the corridors is not necessarily 100% outdoor air. Comparison 9 (Section 4.4.9) discusses the impact of corridor contamination on inter-suite transfer air fractions.

- **Measured corridor supply airflows on a per suite basis often were closer to ASHRAE minimum outdoor air capacity requirements.**

  The measured corridor supply airflows on a per suite basis were 53 to 310% of the minimum outdoor air capacity requirements of ASHRAE Standard 62 for the test suites, with an average of 160%.

  For most of the test suites, the measured corridor supply airflows on a per suite basis still significantly exceeded the requirements of ASHRAE Standard 62. However, for three test suites (Buildings 2, 5, and 6), the measured supply flows on a per suite basis were the same or significantly less than the ASHRAE Standard's requirements (70, 53, and 97% respectively). Building 7 was clearly a problem, because the corridor supply system was inoperative.

To examine the issue of corridor contamination and its impact on outdoor air delivery by the corridor supply system to adjoining suites, we measured "one-time" CO_2 concentrations in the corridors on the test floor for seven of the ten buildings. Three of these corridors (Buildings 3, 4, and 10) had CO_2 concentrations that were similar to outdoors. The other four corridors (Buildings 2, 5, 8 and 9) had elevated CO_2 concentrations compared to outdoors (29, 121, 6, and 12 ppm). The differences in the latter two buildings were not particularly significant. However the differences for Buildings 2 and 5 were troublesome, because the corridor supply systems in these buildings already delivered insufficient amounts of uncontaminated outdoor air to the suites on the test floor (located well above the NPP). Our CO_2 measurements did not quantify the outdoor air fraction in these corridors.

Corridor CO_2 measurements were not made in Buildings 1, 6, and 7. Due to the low building occupancy in Building 1 (about 30%), measuring a low corridor CO_2 concentration would not necessarily indicate that there were no flows into the corridor from suites that were unoccupied at the time. In Buildings 6 and 7, the airflows were from the test suite into the corridor. As a result, a corridor CO_2 measurement for these latter two buildings was unnecessary to indicate that the corridors could be contaminated.

- **Design corridor supply airflows on a per suite basis often significantly exceed CSA minimum outdoor air capacity requirements.**

  Even though the minimum outdoor air capacity requirements of CSA Standard F326 are about a factor of two greater than those requirements of ASHRAE Standard 62, the design corridor supply airflows on a per suite basis still often exceeded the CSA Standard's requirements. The design corridor supply airflows on a per suite basis ranged from 77 to 208% of the CSA Standard's requirements, with an average of 130%.

  However, four of the ten buildings (2 through 5) had design supply flows on a per suite basis that were near or slightly less than the CSA Standard's requirements. These flows ranged from 77 to 92% of the CSA Standard's requirements.

- **Measured corridor supply airflows on a per suite basis were often significantly less than CSA minimum outdoor air capacity requirements.**

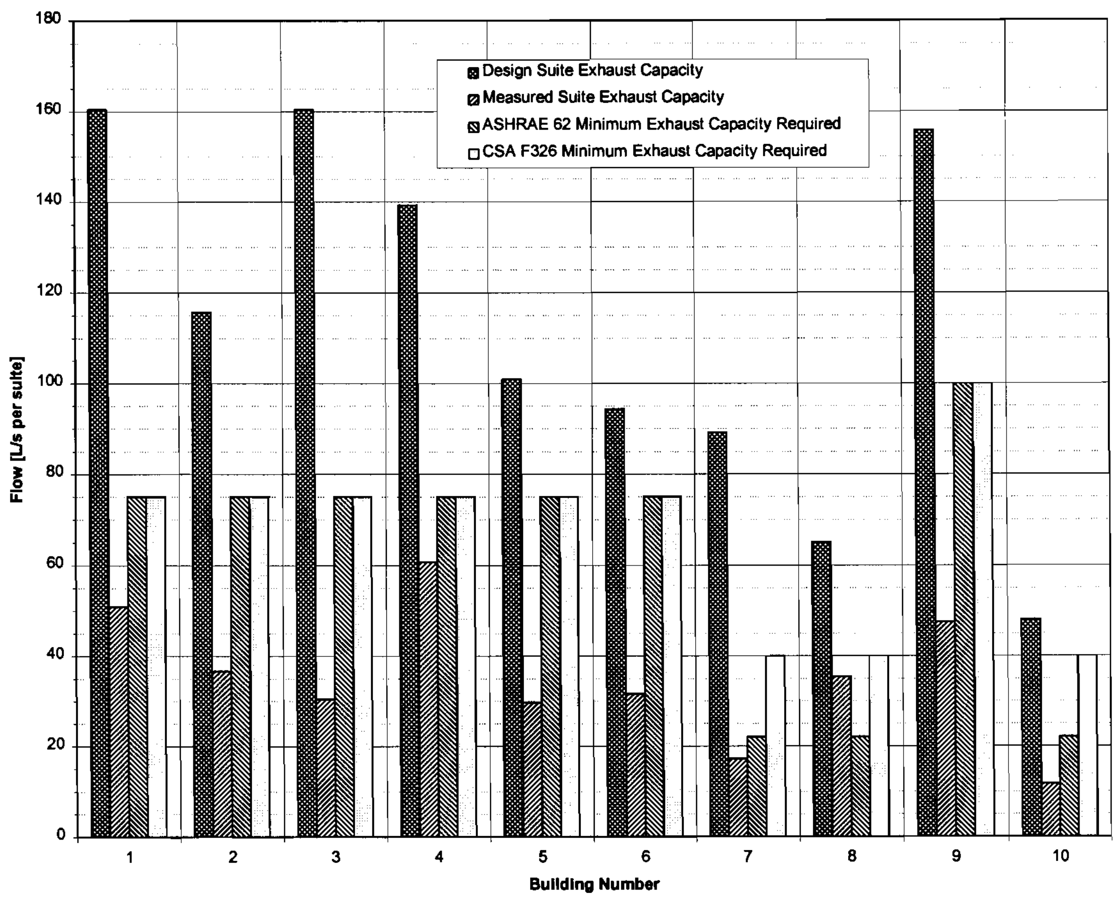
  The measured corridor supply airflows on a per suite basis were 27 to 139% of the minimum outdoor air capacity requirements of CSA Standard F326, with an average of 78%. Only the three Winnipeg buildings (8 through 10) had measured supply flows on a per suite basis in excess of the CSA Standard's requirements.

4.4.4 Comparison 4: Design and Measured Suite Exhaust Capacities vs. ASHRAE and CSA Minimum Requirements for Exhaust Capacity

Introduction

Figure 8 shows a comparison of the design and measured suite exhaust capacities for the test suites in the ten test buildings. It also shows the minimum exhaust capacity requirements for each test suite, based on ASHRAE Standard 62 (1990a) and CSA Standard F326 (1993). The airflows are presented on a per suite basis.

Figure 8: Comparison of Design and Measured Suite Exhaust Capacities vs. ASHRAE and CSA Minimum Requirements for Exhaust Capacity



The design exhaust capacities in Figure 8 are based on information that was derived from our review of drawings and specification documents for the ten test buildings.

The measured exhaust capacity per suite for each building is the total exhaust capacity for the test suite with all exhaust devices in the suite operating. These capacities were determined from data we collected using Test Set 2 while the test suite was depressurized to 20 Pa with respect to outdoors. As described in Section 3.3.1, we expect that these capacities are within 10% of the actual flows through the suite exhaust devices under normal operating conditions.

The minimum suite exhaust capacity requirements in Figure 8 are based on the total intermittent and continuous exhaust requirements (as the case applies) of ASHRAE Standard 62 and CSA Standard F326 for kitchens and bathrooms in the test suites.

Both the ASHRAE and CSA Standards have identical exhaust capacity requirements, except for continuous exhaust from kitchens. The CSA Standard requires a continuous exhaust capacity of 30 L/s for each kitchen rather than the 12 L/s required by the ASHRAE Standard.

Reasons for comparing the design and measured capacities with the requirements of these two Standards are discussed in the Introduction to Comparison 3 (Section 4.4.3).

Key Findings:

- **Design suite exhaust capacities always exceed ASHRAE and CSA minimum exhaust requirements.**

  Excluding Building 7, the design suite exhaust capacities were 126 to 295% of the minimum outdoor air capacity requirements of ASHRAE Standard 62 on a per suite basis, with an average of 189%. For Building 7, the ratio of design capacity versus ASHRAE Standard 62 required capacity was considerably larger (405%).

  For each of the test suites without continuous exhaust systems, the ratio between the design capacities versus the capacities required by CSA Standard F326 was the same as the ratio based on ASHRAE Standard 62. However, for the suites with continuous exhaust systems (Buildings 7, 8, and 10), the CSA-based ratios were almost half of the ASHRAE-based ratios. The difference was due entirely to the different continuous kitchen exhaust requirements in the two Standards.

- **Measured suite exhaust capacities usually were significantly lower than ASHRAE and CSA minimum requirements.**

  Unlike the design suite exhaust capacities, the measured exhaust capacities usually were significantly lower than the exhaust capacity requirements of ASHRAE Standard 62 and CSA Standard F326.

  Only the test suite in Building 7 had a measured exhaust capacity that exceeded the requirement of the ASHRAE Standard (even though the bathroom exhaust was inoperative). For this suite, the ratio between measured and ASHRAE-required capacity was 161%. However, the measured capacity in this suite did not exceed the requirement of CSA Standard F326. The CSA-based capacity ratio in this case was 88%. It is likely the measured exhaust capacity would have been greater if the bathroom exhaust had been operating. However, we cannot determine whether the measured exhaust capacity would have met or exceeded the CSA-based capacity requirement in that case.

  For the other nine test buildings, the ratios between measured and ASHRAE-required capacities ranged from 39 to 81%, with an average of 55%. The differences between the ASHRAE- and CSA-based capacity ratios followed the same pattern as discussed in the point above.

If the over-sizing of suite exhaust systems by designers is intended to produce suite exhaust systems that meet or exceed the exhaust capacity requirements of ASHRAE Standard 62 or CSA Standard F326, then the current over-sizing factors are inadequate in most cases.

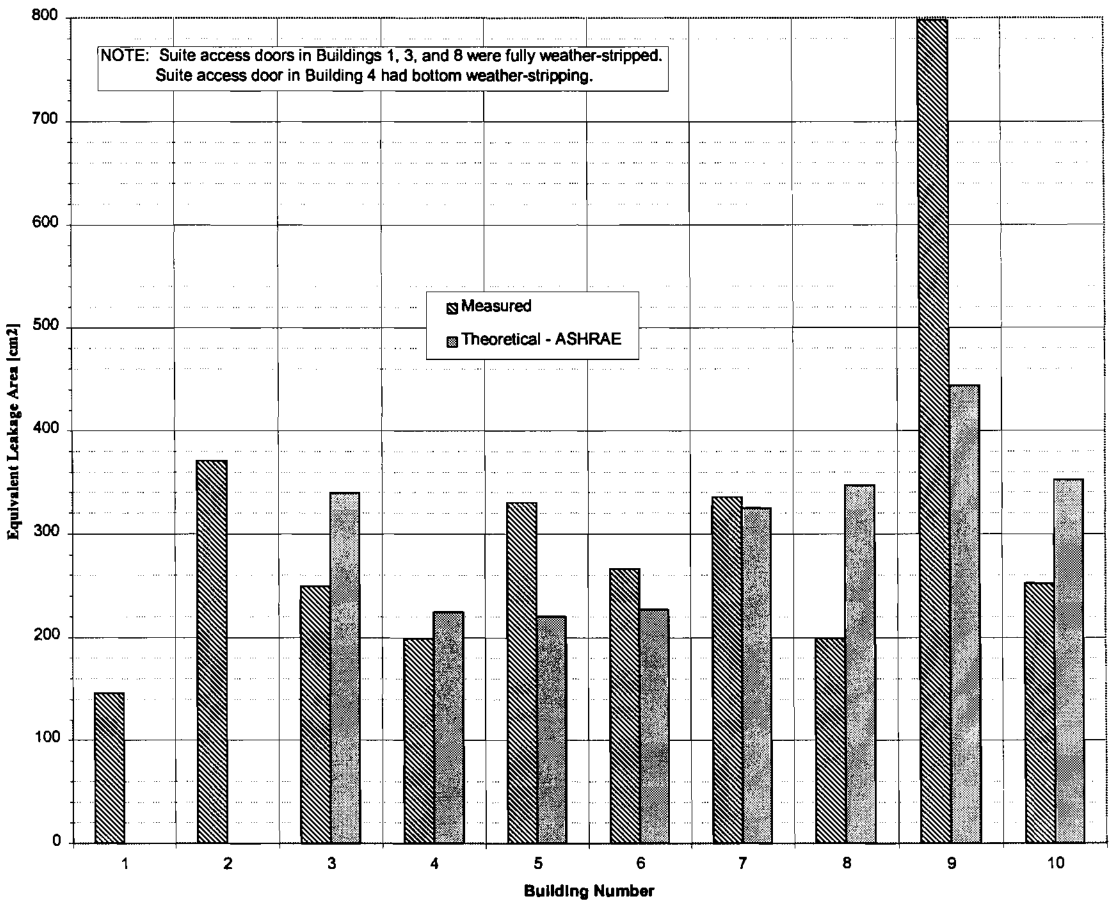
Of particular note is that the measured suite exhaust capacities usually were closer to the ASHRAE requirements than to the CSA requirements. This finding is consistent with the results of our informal survey of 25 mechanical system designers: they attempt to size suite exhaust systems to meet ASHRAE requirements.

4.4.5 Comparison 5: Leakage Areas of Suite Access Doors (Measured vs. Theoretical)

Introduction

Figure 9 shows a comparison of the measured and theoretical leakage areas of the suite access doors for the test suites. The values shown represent equivalent leakage area at a reference pressure difference of 10 Pa and a reference discharge coefficient of 0.611.

Figure 9: Comparison of Leakage Areas of Suite Access Doors (Measured vs. Theoretical)



The measured leakage areas were determined using data we collected using Test Set 4. These leakage areas include the leakage between the door and its frame, the leakage of the door itself, and the effects of weather-stripping.

Only one suite access door was tested in Building 1 (Floor 31). The other suite access door (Floor 11) was not tested.

The theoretical leakage areas for the suite access doors were determined using the method of Gross and Haberman, as described by ASHRAE (1992). This method was discussed in Section 2.3. Unlike the measured leakage areas, the theoretical leakage areas only include door-frame gap leakage and exclude the effects of weather-stripping. The leakage area of the door itself is not expected to be significant in comparison to the gap leakage.

Theoretical leakage areas were not calculated for the suite access doors of Buildings 1 and 2, because door-frame gap data were not collected for these two buildings.

Key Findings:

- **Measured leakage areas of suite access doors are large and highly variable.**

  The magnitude of suite access door leakage areas are highly dependent on the fit between the door and its frame (particularly at latch side), on the size of the door undercut, and on the presence and fit of weather-stripping between the door and its frame. As indicated in Table 3 and the discussion of suite access door characteristics for the test suites, all of these factors are highly variable.

  All of the measured leakage areas of the suite access doors are large. Excluding one very leaky door (Building 9), the measured equivalent leakage areas (ELA) of the suite access doors are in the range of 146 to 371 cm^2 with an average of 261 cm^2. The suite access door for the test suite in Building 9 has a considerably larger measured ELA (798 cm^2).

  Compared to all of the other suite access doors we tested, the tightest door (Building 1) was well weather-stripped, including the bottom of the door. However, we found that the bottom weather-stripping for this door was intentionally misaligned to accommodate the slight slope of the floor inside the test suite.

  The leakiest suite access door (Building 9) is unlike the other doors we tested. It has a very poor latch fit (with significant light transmission at this side of the door), large gaps between the door and frame (except on the hinge side), and a large undercut (19 mm). In this building, occupants had expressed complaints of drafts and excessive air velocity near suite access doors. In particular, the building manager reported that there were instances when pamphlets left under these doors were being blown along hallways within the suites. The large undercut for this suite access door may be an indication that the corridor supply air system was intended to supply ventilation air to the suites in this building.

  With the exception of the leakiest door, the measured leakage areas are all within the ranges reported by Tamura and Shaw (1976a) for similarly configured stair doors (140 to 374 cm^2) and by Colliver et al. (1994) for residential doors without weather-stripping (79 to 326 cm^2). Section 2.3 described these two ranges in more detail.

- **The measured leakage areas of the suite access doors were usually within allowable NFPA limits for fire doors, but always exceeded allowable NBC limits for fire doors, and always exceeded allowable NFPA limits for smoke-control doors.**

  NFPA Standard 80 (1992) specifies maximum allowable clearances between a "swinging fire door with builders hardware", its frame, the floor, and the door sill (if any). This type of door includes suite access doors. We converted the maximum allowable clearances to equivalent leakage areas using the theoretical method of Gross and Haberman. Excluding the leakiest door, all of the measured leakage areas were within the corresponding ELA limit based on the NFPA Standard 80 clearances (470 cm^2). The leakiest door considerably exceeded this limit. All of the doors had one or more clearances in excess of the fire door requirements (3 mm top and sides, 6 mm bottom) contained in Sentence 3.1.8.10 (3) of the National Building Code of Canada (NBC 1990).

NFPA Standard 105 (1985) specifies allowable air leakage rates for smoke-control doors. This Standard recommends that air leakage through doors between rooms and corridors should not exceed 5 L/s per m^2 of door opening. Although the Standard does not specify a flow exponent for the gaps around these doors, assuming a flow exponent of 0.5 is reasonable, based on the range of flow exponents we determined from our door leakage tests (average of 0.53). Therefore, the air leakage rate recommendation of NFPA Standard 105 corresponds to an ELA of 13 cm^2 for an average-sized suite access door (1.81 m^2). Consequently, this means that all of the suite access doors cannot be considered as smoke-control doors, based on this Standard. Alternatively, it also means that the leakage area of suite access doors need to be considerably reduced to meet this recommendation.

- **Weather-stripping modifications by occupants can affect leakage areas of suite access doors.**

  Unfortunately, in the sample of suite access doors we tested, there are no pairs of similar doors with and without weather-stripping. As a result, we cannot quantify the effect of weather-stripping on the leakage of these doors. However, most of the smaller leakage areas shown in Figure 9 correspond to either fully weather-stripped suite access doors (Buildings 1, 3, and 8) or to suite access doors with bottom weather-stripping (Building 4). Building 7 is not included in this group, because it has only partial weather-stripping along the latch side of the door. The larger leakage areas always correspond to doors without weather-stripping.

  Therefore, if an occupant was to modify the door weather-stripping (i.e. install as in Building 7), it is likely the suite access door leakage could change significantly. Possible reasons for an occupant to modify the weather-stripping include: perceived reductions in energy consumption, reductions in drafts (attempts to improve thermal comfort), and attempts to reduce noise, odors, and/or light transmission from the corridor. Occupants can also interfere with the door leakage area by placing a mat at the base of the door.

  Consequently, the leakage areas of suite access doors are uncontrolled and should not be relied on as a means of transferring ventilation air from the corridor to adjoining suites.

- **There are significant differences between theoretical and measured door leakage areas in some buildings.**

  The theoretical door leakage areas were also large and generally followed a similar pattern compared to the measured leakage areas. For Building 7, there was excellent agreement between the theoretical and measured leakage areas. However, the theoretical leakage areas sometimes differed significantly from the measured leakage areas for the other buildings. In particular, the theoretical leakage areas ranged from 56 to 174% of the measured leakage areas, with an average of 108%. The deviations occurred as a result of several factors.

  The suite access doors in Buildings 3, 4, and 8 had weather-stripping, which was not accounted for in the theoretical method. In Building 9, the suite access door had a poor latch fit, which also was not accounted for by the theoretical method. The reasons for the discrepancies in Buildings 5, 6, and 10 are unknown.

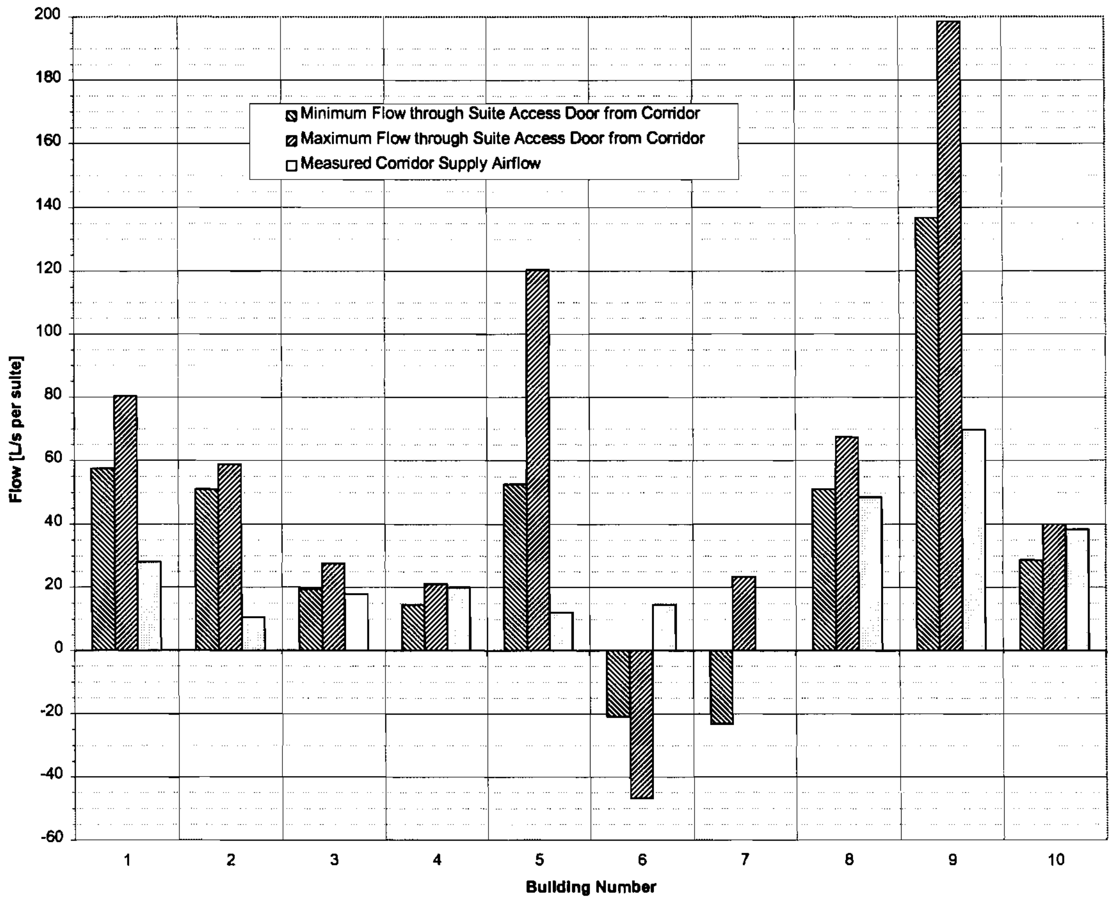
Based on the differences observed, it appears that theoretical calculations are no substitute for measuring the leakage areas of suite access doors.

4.4.6 Comparison 6: Range of Airflows through Suite Access Doors During Tests vs. Measured Corridor Supply Airflows

Introduction

Figure 10 shows the range of "measured" airflows through the suite access doors in the ten test buildings during our tests. A comparison of these airflows with the measured corridor supply airflows is also included. The airflows are presented on a per suite basis. Positive airflows represent flows from the corridor to the test suite. Negative airflows represent reverse flows.

Figure 10: Range of Airflows through Suite Access Doors During Tests vs. Measured Corridor Supply Airflows



We did not directly measure the "measured" airflows through the suite access doors during our tests. Instead, we calculated these "measured" flows by using Equation 1 (Section 2.1) to combine the measured leakage areas of the suite access door with the minimum and maximum measured pressure differences between the test suite and adjoining corridor at the time of the tests.

The pressure differences we used in the calculations were spot measurements that we made during the various tests while the test suite was operating normally. Normal operating conditions were defined as all of the corridor doors and windows closed, the corridor supply air and central exhaust air systems operating (unless these systems could not be operated), and without the intermittent ventilation equipment in the test suite being operated. The windows and exterior doors in the test suite were also closed. Interior doors within the test suite were open.

The "measured" door and corridor supply airflows for the test suite in Building 1 are only for the upper suite (Floor 31). As discussed in Comparison 5 (Section 4.4.5), we did not determine the leakage area of the door for the lower suite (Floor 11).

The "measured" airflow through the suite access door for Building 8 also includes our estimates of the flows through the transfer duct. This duct connects the test suite and adjoining corridor in parallel with the suite access door. The leakage area of the transfer duct was not measured. Instead, we estimated the leakage area using manufacturer's flow versus pressure drop data for the grilles and standard duct design procedures (ASHRAE 1997). Measured pressure differences between the test suite and corridor were then used to estimated the airflows through this transfer duct. We estimated the duct airflows were in the range of 19 to 25 L/s, based on the measured corridor pressurization of 4 to 7 Pa relative to the test suite.

The measured corridor supply airflows in Figure 10 are based on our analyses of the field data that we collected using Test Set 3. The measured supply airflow for each building is the same as the first test presented in Comparison 1 (Section 4.4.1). No corridor supply airflow tests were carried out in Building 7, because this system was out of service.

As discussed in Comparison 1, the corridor supply airflow attributable to each suite was calculated assuming the total corridor supply airflow was equally divided among all suites adjoining the corridor.

Key Findings:

- **Wide variation from building to building in "measured" airflows from corridor through test suite access doors.**

  The "measured" airflows through the test suite access doors varied by almost an order of magnitude from building to building. Including the transfer duct in Building 8, but excluding the unusually large flow in Building 9, these airflows ranged from 14 to 120 L/s, with an average of 45 L/s. For the test suite in Building 9, the range of airflows through the suite access door was 137 to 199 L/s. Based on the total volume of the test suites, these airflows correspond to suite air exchange rates in the range of 0.51 to 2.53 ach, with an average of 1.10 ach (excluding Building 9). For Building 9, the airflows correspond to suite air exchange rates of 2.13 to 3.10 ach.

  The variations in "measured" airflows can be attributed to the variations in leakage area of the suite access doors and the variations in pressure differences across these doors. The variations in door leakage area were discussed in Comparison 5 (Section 4.4.5). Pressure differences varied from a low of 1 Pa (Buildings 3, 4, 6, and 7) to a high of 49 Pa (Building 1).

  The low pressure differences were associated with leaky doors, whereas the high pressure differences were associated with tight doors. These combinations reduced the suite to suite variability of the airflows that would be expected if only the variability of the pressure differences was considered.

- **For some test suites, measured corridor supply airflows on a per suite basis are significantly lower than "measured" airflows from the corridor through the suite access doors.**

  We did not measure the pressure difference across the suite access doors at the time of the corridor supply airflow tests in Test Set 3. However, it appears that the "measured" airflows across the suite access doors at the time of these supply flow tests were likely in the range shown in Figure 10 (based on the lack of the variability of the stack- and wind-effects determined using data collected in Test Set 1).

  The measured corridor supply airflows on a per suite basis were always less than or approximately equal to the corresponding greater airflow "measured" across the suite access door. This was true even for suites located below the neutral pressure plane (Buildings 4 and 6). Only two test suites had supply flows on a per suite basis in excess of the corresponding smaller "measured" door flow (Buildings 4 and 10).

  In some suites, the differences between the supply and door flows were significant. Compared to the corresponding greater door flows, the measured supply flows ranged from 10 to 96% of these flows, with an average of 44% (excluding Building 7). This indicates that a significant fraction of the airflow through the suite access door for some suites is attributable to transfer airflows from the remainder of the building.

- **Airflows were reversed into the corridor for some suites.**

  As Figure 10 shows, the airflows through the suite access doors during our tests were generally from the corridor to the adjoining test suite. These airflow directions are based on pressure difference measurements we carried out in Test Set 1.

  Our pressure difference measurements were only spot checks. As such, they did not indicate long-term average airflow directions through the suite access doors. However, in all of the buildings except the four in BC (1 through 4), dust deposits on the frames of the suite access doors indicated a long-term average airflow direction. Based on these deposits, most door flows were usually from the corridor to the suite.

  The dust tracks on the door frame for Building 10 indicated that there had been flows into and out of the test suite at different times (approximately equal lengths of time based on the similarity of the deposits). This pattern was consistent with the time clock operation of the corridor supply air and central exhaust systems in this building, as described in Section 4.3. During our tests, we had set this time clock so that these systems operated continuously.

  In the test buildings, combinations of various driving forces usually were sufficient to overcome any wind-induced pressurization of an exterior wall that would tend to reverse airflows through the suite access door. These forces included mechanical pressurization of the corridor by the corridor supply air system, mechanical depressurization of the suite by continuous suite exhaust, natural pressurization of the corridor by stack effects (for suites located above the neutral pressure plane), and natural depressurization of the suite by wind-induced suction on another exterior wall of the suite. However, in two buildings, the airflows through the suite access door were reversed due to combined stack and wind effects

(Building 6) and due to continuous exhaust outside the test suite and an absence of a corridor supply airflow (Building 7).

The reversal of flows in Building 6 warrants further discussion. Our analyses of the stack and wind effects indicate the exterior wall of the test suite was pressurized from outside primarily (about 80%) by the stack effect. This pressurization occurred, because the suite was located below the neutral pressure plane. Wind effects also contributed to the pressurization of this wall from outside. The pressure differences across this wall ranged from 8 to 15 Pa. As a result, air tended to flow into the suite from outdoors. Without mechanical exhaust operating in the suite, the continuity of airflows required that this air then exit the suite into the corridor through the suite access door.

- **Using the leaks around suite access doors to supply ventilation air to suites is not a reliable system.**

  Even for a particular suite access door, there were wide variations in the airflows through the doorway, due to fluctuations in pressure differences between the corridor and suite. Excluding Building 7, the maximum flow ranged from 115 to 229% of the minimum flow, with an average of 157%. For Building 7, the flows reversed during the tests. The reverse flow was equal but opposite in magnitude to the other flow.

  The variations in pressure differences across these doors usually were not large. Excluding Buildings 1 and 5, the variations in pressure difference ranged from 1 to 5 Pa, with an average of 2 Pa. In Buildings 1 and 5, the variations were considerably larger (24 and 13 Pa respectively). There was no correlation between these variations and the leakage areas of the suite access doors.

  Due to the large leakage areas of suite access doors, airflows through leakage openings around these doors are very sensitive to small changes in pressure difference across the door. This was particularly true for the test suite in Building 9, which had a very leaky door and relatively large pressure difference variations (5 Pa). Consequently, using the leaks around suite access doors to supply ventilation air to suites is not a reliable system.

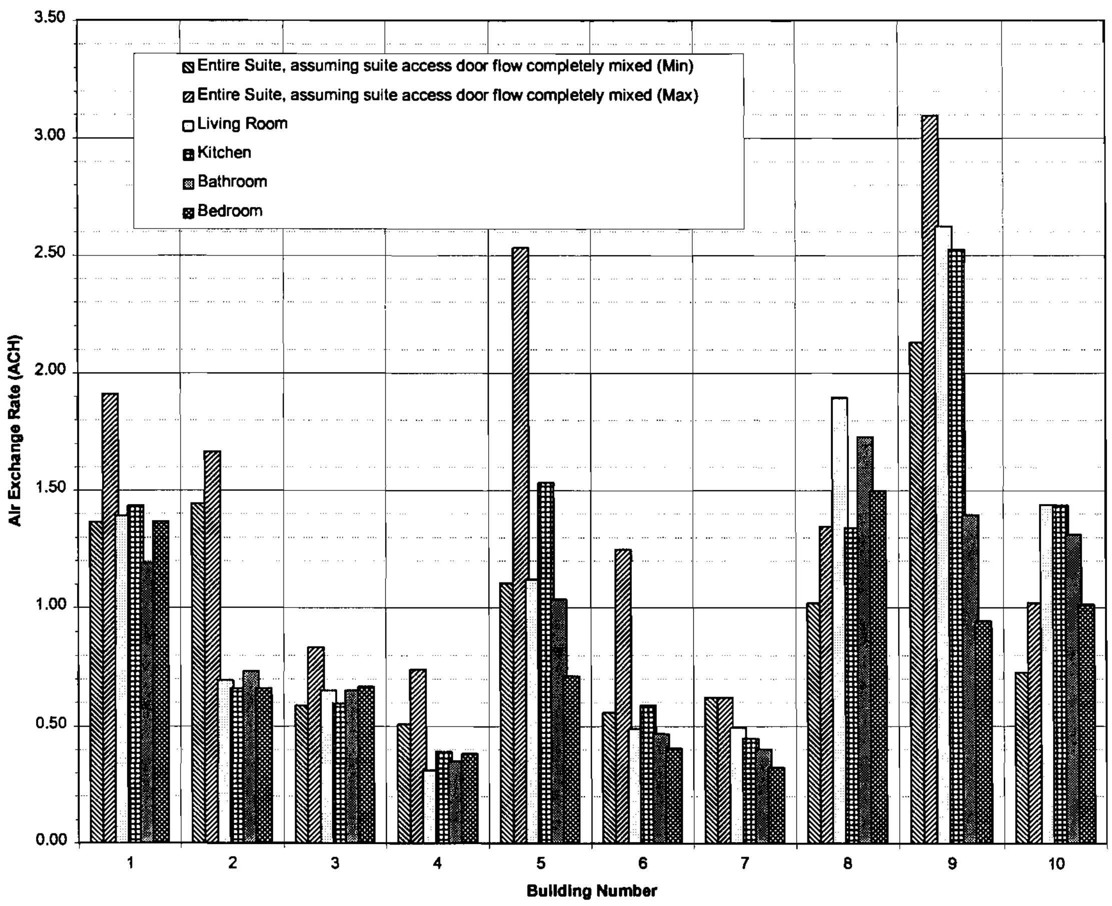
4.4.7 Comparison 7: Air Exchange Rates for Test Suites and Their Rooms (Interior Doors Open)

Introduction

Figure 11 shows the range of measured air exchange rates for the various rooms we sampled in the test suites using Test Set 5. These rates were measured with all of the interior doors open in the test suites. The effect of closing interior doors is described in Comparison 8 (Section 4.4.8).

Figure 11 also includes a comparison of these measured rates with rates we calculated using the range of "measured" airflows through the suite access doors (including the transfer duct for Building 8). These "measured" door flows were discussed in Comparison 6 (Section 4.4.6). For simplicity of comparison, only the magnitudes of the door flows were used in determining these rates.

Figure 11: Comparison of Air Exchange Rates for Test Suites and Their Rooms (Interior Doors Open)



Each pair of door-flow-based air exchange rates in Figure 11 was determined by dividing the minimum and maximum "measured" door flows by the total volume of the test suite. An implicit assumption of this method is that the door flows are completely mixed with all of the air in the suite. This assumption is not necessarily true, but it serves as a first approximation for comparison purposes.

All of the air exchange rates shown in Figure 11 for Building 1 are for the upper suite only (Floor 31). Air exchange rates for the lower suite (Floor 11) are described in Comparison 8.

It is important to recognize that the measured air exchange rates represent minimum effective air change rates, because of the potential interference from interzonal transfers of tracer gas between rooms within the test suite. Actual air exchange rates could be greater.

It should also be kept in mind that the air exchange rates do not necessarily represent outdoor air exchange. Instead, they represent the total amount of air entering or leaving a room. Some or all of this air may be transfer air from other spaces in the building. Comparison 9 (Section 4.4.9) discusses the issue of inter-suite transfer air fractions.

Key Findings:

- **Compared to existing ventilation standards, most rooms of the test suites are well-ventilated, but some are marginal or under-ventilated.**

  The measured room air exchange rates were higher than we expected. All of the rooms meet or exceed the ASHRAE Standard 62 requirement for 0.35 ach (1990a) and CSA Standard F326 requirement for 0.30 ach (1993). However, most rooms did not meet the more stringent requirements when compared to the occupancy- or room-based air exchange rates of these Standards.

  We were unable to calculate the air exchange rates for each room of a test suite based on these latter requirements. We also could not calculate an average air exchange rate for the entire suite based on a weighted average of the measured room air exchange rates. In both cases, poorly defined boundaries of rooms prohibited these calculations.

  However, we did calculate the required rate for the entire suite. The required rate for the entire suite can then be compared to each measured room rate. If the measured rate for every room in the suite meets or exceeds the required entire-suite-based rate, then the average rate for the entire suite will also meet or exceed the required rate for the entire suite (although still failing on a room by room basis).

  None of the rooms in the test suite of Building 4 appeared to meet either of the more stringent occupancy- or room-based requirements of ASHRAE Standard 62 or CSA Standard F326 (0.53 ach based on ASHRAE and 1.06 ach based on CSA). In particular, the air exchange rates in these rooms were only about one third of the CSA Standard's requirement.

  All of the rooms in the test suites of Buildings 2, 3, 6, and 7 appeared to meet or slightly exceed the more stringent requirements of ASHRAE Standard 62, but failed to meet the more stringent requirements of CSA Standard F326 by about a factor of two.

- **Large suite to suite variation in room air exchange rates.**

  The measured air exchange rates for each room varied considerably from suite to suite. These rates ranged from 0.31 to 2.62 ach for living rooms, from 0.39 to 2.53 for kitchens, from 0.35 to 1.73 ach for bathrooms, and from 0.32 to 1.50 for bedrooms. The variations between living room rates were the largest. These rates varied by a factor of about eight.

Reasons for the variations in the measured air exchange rates are discussed in the following two points.

- **Airflows from the corridor through the suite access doors appear to be primarily responsible for the air exchange in most of the test suites.**

  With the exception of Buildings 6 and 7, air flowed into each test suite from the adjoining corridor during the decay tests. Comparing the air exchange rates based on these door flows with the measured room air exchange rates shown in Figure 11, it appears that these door flows are primarily responsible for the air exchange in most of the test suites.

  This comparison is incomplete without a knowledge of the other flows into the test suites. While we did not measure these other flows, pressure difference data collected in Test Set 1 along with a knowledge of the probable leakage distribution in the suite can be used to indicate whether there can be flows into the test suites from sources other than the corridor.

  Except for Buildings 8 and 10, six of the eight buildings with flows from the corridor were also pressurized relative to outdoors. This means that air would flow from the suite to outdoors. In each of these six buildings, the adjoining suites or shafts were pressurized relative to the suite. The pressurizations of these spaces relative to the test suite were of the same order of magnitude or smaller compared that of the corridor. However, the leakage areas of the separations between the test suite and these spaces were probably considerably smaller compared to the large leakage area of the suite access door. This was particularly true for the shafts, which typically had concrete walls. As a result, it is likely the airflows through the suite access doors were the primary or sole reason for the air exchange in these suites.

  Buildings 8 and 10 had complex flows, including flows directly from outdoors into the test suite. These flows are discussed in the following point. It is not clear what fraction of the air exchange in these suites was attributable to the airflow through the suite access door.

- **Distribution of air varies in suites, but usually room air exchange rates are fairly uniform.**

  Usually there was only a small variation in measured room air exchange rates, based on a room to room comparison for each test suite. The average variation excluding Buildings 5 and 9 was about 0.23 ach. Some variations were less than 0.1 ach (Buildings 2, 3, and 4). Compared to the lowest rate in each of these eight suites, the highest corresponding rate varied from 111 to 152% with an average of 131%. The larger variations occurred in four buildings (5 and 8, 9, and 10).

  In Buildings 5, 9, and 10, the air exchange rates in the living room/dining room/kitchen region were significantly greater compared to the air exchange rate in the bedroom (with its door open). Specifically, the bedrooms in these suites had air exchange rates that were 46, 36, and 70% respectively of the highest rate elsewhere in the suite. Based on the findings presented in Comparison 8 (Section 4.4.8), the differences are expected to be much higher with the bedroom door shut.

The following is a general explanation of why the air exchange rates varied in the test suites. More specific explanations for Buildings 5, 8, and 10 follow this general explanation.

Much of the variations in living rooms and kitchens can be attributed to the variations in airflows through the suite access doors. These rooms tend to be well-connected with each other and typically are located adjacent to the suite access door.

Reasons for the variations in the bathrooms and bedrooms are more complex, because these rooms are typically farther away from the suite access door. In some cases, the pathway to these other rooms is convoluted (such as in Building 9) and flows can short circuit to outdoors before reaching these rooms. As a result, air exchange rates in these suites are less uniform. In addition, the exterior leakage areas for the bedrooms are probably always lower than elsewhere in the suite, because the window areas in the bedrooms tend to be smaller than in other rooms and the bathroom is typically equipped with a large leakage site (exhaust duct).

Building 5

In Building 5, the kitchen air exchange rates were significantly higher than other rooms, including the living room. The variation was primarily due to the complex geometry of the test suite and the exterior leakage area distribution. In this suite, the kitchen was immediately adjacent to the suite access door, but the remainder of the suite was accessed through a convoluted hallway.

The test suite in Building 5 had flows in from the corridor through the suite access door, flows to outdoors through the intermittent exhaust device openings in the kitchen and bathroom, and flows to outdoors through the exterior walls in the living room, bathroom, and bedroom. It is expected that the airflows to outdoors were significantly smaller in the bedrooms compared to those in the living room and bathroom. Both bedrooms had small window areas, which would result in less exterior leakage area in these rooms compared to the leakage area associated with the large window areas in the living room and with the two exhaust device openings in the kitchen and bathroom. Some of the ventilation air entering the kitchen from the corridor would short circuit to outdoors through the kitchen exhaust and would never reach the remainder of the suite. This flow pattern was confirmed using a smoke tube. As a result, the kitchen was better ventilated than the rest of the suite, especially compared to the bedroom.

Building 8

The air exchange patterns in Building 8 were unique and complex due to wind effects at the time of the decay tests. Our analyses of the stack- and wind-induced pressure differences during these tests indicate the exterior wall in common with the bedrooms and living room was pressurized from outside by strong winds. At the same time, the adjacent exterior wall in common with the living room and kitchen was depressurized outside by the same winds. The wind effect also pressurized the adjoining upwind suite relative to the test suite. Finally, the corridor was pressurized relative to the suite by the corridor supply air system. The continuous suite exhaust system contributed to the depressurization of the test suite relative to the corridor and outdoors.

Based on the window areas of each exterior wall in the test suite of Building 8, it is likely the wall in common with the kitchen and living room had significantly less leakage than the adjacent exterior wall. Furthermore, the leakage area of this adjacent exterior wall in the master bedroom was probably significantly greater than the leakage area of the partition wall separating the test suite and adjoining suite (due to the lack of windows and doors in the partition wall).

As a result of the above pressure differences and leakage openings, air flowed into the test suite of Building 8 from the corridor through the suite access door and transfer duct. Some of this air never reached the rest of the test suite, because it short circuited to outdoors through the continuous exhaust openings near the entrances to the bathroom and kitchen. Figure 11 shows that the flow from the corridor through the door and transfer duct was insufficient to explain all of the suite air exchange.

Air also flowed into this suite through the windward exterior wall that was in common with the bedrooms and living room and through the wall separating the master bedroom from the adjoining suite. Air flowed from the bedrooms into the living room through the connecting hallway. During this transfer, some of the air from the master bedroom short circuited to outdoors through the continuous exhaust opening in the storage room that was adjacent to the hallway. Air then flowed from the living room into the kitchen and then to outdoors through the leakage openings around the small leeward kitchen window and through the continuous exhaust opening near the entrance to the kitchen.

The combined airflows from the corridor and outdoors created a converging pattern in the living room and bypassed much of the kitchen. As a result, the kitchen was not as well ventilated as the remainder of the suite. These flow patterns were confirmed using a smoke tube.

It is very difficult to determine the fraction of air exchange caused by the suite access door and transfer duct airflows for this suite under these conditions.

Building 10

Building 10 also experienced flows from outdoors into the test suite through the exterior wall. These exterior wall flows were induced by wind that pressurized the wall from outdoors. They were also induced by the continuous suite exhaust system that depressurized the suite relative to outdoors. Stack effects tended to counteract both these influences, but the net effect was that the exterior wall was pressurized from outdoors. The pressure difference across the exterior wall and suite access door were similar in magnitude.

The leakage area of the exterior wall was likely similar to or less than that of the suite access door, because the window areas in this wall were small. Therefore, based on the magnitudes of the pressure differences and leakage areas, it is likely that 50% or more of the air exchange in the test suite of Building 10 was due to airflows through the suite access door.

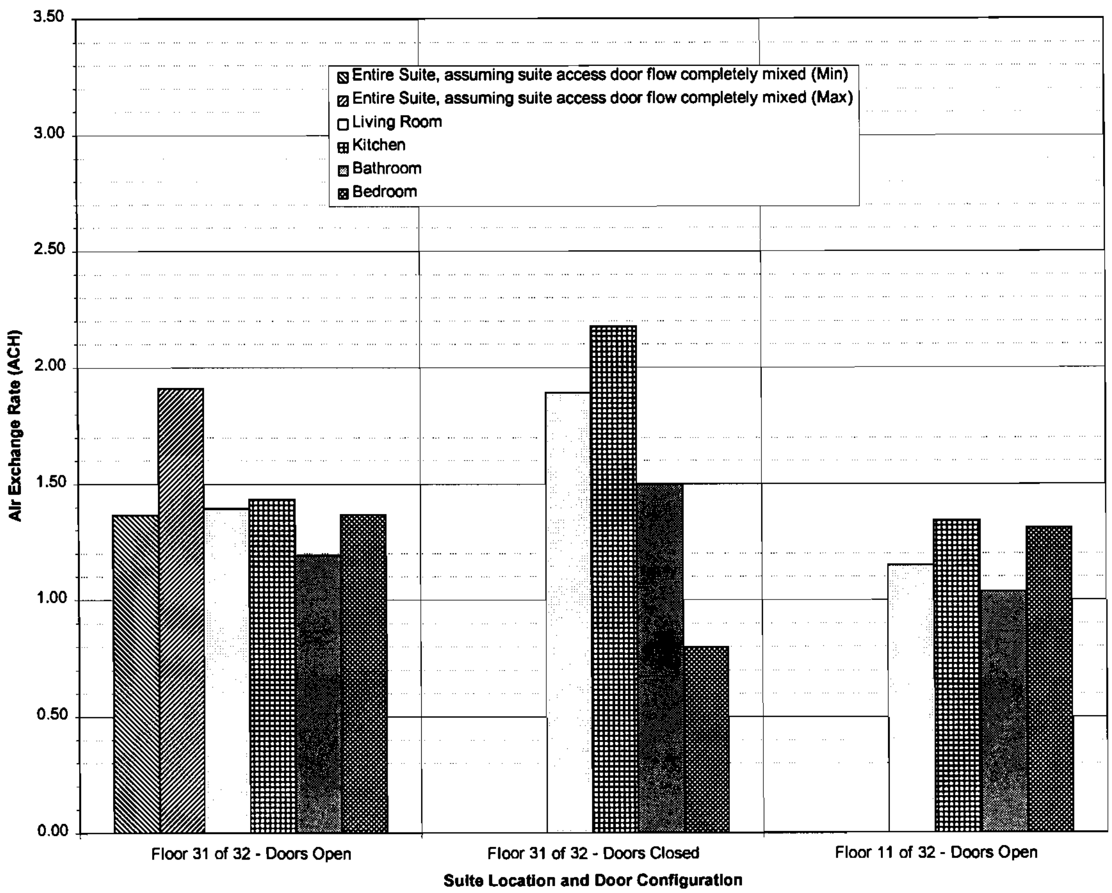
4.4.8 Comparison 8: Air Exchange Rates for Two Suites and Their Rooms (Building 1)

Introduction

Figure 12 shows the range of measured air exchange rates for the various rooms we sampled in the two test suites of Building 1. These rates were measured in the upper suite (Floor 31) with all of the interior doors open in one case and then with all of these doors closed in another case. They were also measured in the lower suite (Floor 11) with all of the interior doors open.

A comparison of these measured rates with the rates based on the range of "measured" airflows through the suite access door of the upper test suite is also included in Figure 12. These door flows were discussed in Comparison 6 (Section 4.4.6). For simplicity of comparison, only the magnitudes of the door flows were used in determining these rates. The method of determining these door-flow-based rates was discussed in Comparison 7 (Section 4.4.7).

Figure 12: Comparison of Air Exchange Rates for Two Suites and Their Rooms (Building 1, Interior Doors Open vs Closed, Suite Above vs Below Neutral Pressure Plane)



Suite access door flows were not determined for the latter two cases shown in Figure 12 for two reasons. First, although the leakage area of the suite access door for the upper test suite was measured, we did not measure the pressure differences across this door when the interior doors were closed. However, it is likely these pressure differences would be greater with the doors closed. The reason is that closing the interior doors increased the series flow resistance to outdoors through the test suite. In addition, there were no significant changes in stack- and wind-induced pressure differences between the tests with the doors open and closed.

Second, as discussed in Comparison 5 (Section 4.4.5), we did not determine the leakage area of the suite access door for the lower test suite. The magnitude of the airflow through the lower suite's door is discussed in the final point of this comparison.

As stated in Comparison 7, the measured air exchange rates represent minimum effective rates. Actual air exchange rates could be greater.

Key Findings:

- **Closing interior doors within the test suite can have complex effects, including reducing the suite volume that is directly open to flows from the suite access door and increasing the airtightness of these open volumes.**

  Closing interior doors within a suite can have very complex effects on room air exchange rates. One effect is caused by changing the volume of the suite that is open to the ventilation flows through the suite access door.

  Suites tend to be significantly smaller than single-family dwellings. Specifically, test suite volumes are in range of 102 to 231 m^3 with an average of 149 m^3. These smaller volumes mean that contaminant concentrations will tend to be higher and change more rapidly in suites than in houses given the same ventilation rate, airtightness, and pollutant source strengths. This is particularly true for individual rooms of a suite that are separated from the remainder of the suite by closed doors.

  By closing interior doors within the test suite, another flow resistance is placed in series for the flow path between the suite access door and the building envelope through the closed room. As a result, the airtightness of the open areas of the test suite can be increased. Unless the building envelope is very tight and the interior doors have a significant undercut, the increase in flow resistance will be significant and airflows through the suite access door are likely to decrease. For a tight building envelope, closing the interior doors will have less impact on the airtightness of the open volumes, because the dominant resistance will be that of the building envelope. In this latter case, the volumes open to the suite access door will still be reduced, but airflows out of these volumes will not be significantly affected.

- **Air exchange rate for the open living room and kitchen increased due to the reduced open volume of the suite.**

  By closing the interior doors in the test suite, the volume of the suite open to the suite access door was reduced by about 30% (from 151 m^3 to 105 m^3). The corresponding change in airtightness cannot be quantified, because we did not measure the leakage area of the suite in either case. The reduced open volume of the suite caused the air change rates in the open living room and kitchen to increase compared to the case with open interior doors. Specifically, the living room air exchange rate increased by 35%, while the kitchen rate increased by 52%.

The increases in air exchange rate for these rooms implies that the reduction in volume was the governing factor compared to changes in their airtightness. Consequently, the leakage areas of the building envelope in the closed rooms is probably significantly smaller than the leakage areas of the interior doors. We did not measure the leakage areas of these doors. However, their leakage areas are probably significantly greater than the weather-stripped suite access door.

- **Bathroom air exchange rate increased when its door was closed, possibly due to changes in the mixing patterns within this room.**

  The air exchange rate in the bathroom also increased when the interior doors in the test suite were closed compared to the case with open interior doors. Specifically, the bathroom air exchange rate increased by 26%. The reason for this increase in air exchange rate is not known.

  One possible explanation is the probable differences in flow patterns for this room when its door is open compared to when it is closed. A parallel process may be that increased amounts of ventilation air are available to the bathroom, because the exterior leaks in the nearby bedroom are less exposed. The following discussion examines the former reason in more detail, because of its complexity.

  When the bathroom door is open, low-velocity air from the adjoining hallway can enter the bathroom and short circuit quickly through the exhaust opening in the ceiling. Mixing within the room will be limited by the low-velocity airflow into the room. As a result, there can be significant stagnant regions within the lower parts of the bathroom, especially toward the wall opposite the door. It is possible that the tracer gas sensor, which was located toward this wall, was within a stagnant region.

  In contrast, when the bathroom door is closed, most of the air entering the room will have to pass into the room at a lower elevation through the gap under the bathroom door. The entry velocity into the bathroom will be greater, which will promote more mixing in the room. The size of the stagnant regions will also drop due to the increased length of the path from the door to the exhaust opening in the ceiling. Smoke tube tests confirmed both flow patterns.

- **Bedroom air exchange rate decreased when its door was closed due to increased flow resistance between open areas of suite and outdoors through bedroom.**

  As expected, Figure 12 shows that the bedroom air exchange rate decreased when its door was closed compared to the case with open interior doors. Specifically, with its door closed, the bedroom air exchange rate was only about 58% of the rate with the door open.

  Although we did not measure the flows into and out of this room directly, the difference in air change rates is most likely due to reduced flows into the room from the remainder of the suite. These flows were reduced by the increased flow resistance in the path between the suite access door and outdoors when the door was closed. Flows into the room through the door and out of the room to outdoors through the exterior wall on the opposite side of the room would be correspondingly reduced. Regardless of whether the door was open or not, these airflows would have to pass by the tracer gas sensor. It is less likely that the sensor in the bedroom was located in a stagnant region (compared to the bathroom).

- **The similarity of air exchange patterns and rates above and below the neutral pressure plane for this building may be fortuitous.**

  In Building 1, the room air exchange patterns and rates were similar for the test suites above and below the neutral pressure plane. This similarity may be fortuitous for two reasons.

  First, based on our analyses of the stack- and wind-induced pressure differences for these two suites, the calculated stack-induced pressure difference for the upper suite was about 27 Pa just before the decay test. For the lower suite, it was about –8 Pa. Wind-induced pressure differences were minimal for both these suites (less than 1 Pa). This means that the stack effect for the upper suite was tending to drive indoor air out of the suite toward outdoors, whereas it was tending to drive outdoor air into the lower suite through the building envelope.

  The substantial difference in calculated stack effect (35 Pa) is consistent with the difference in pressure drops we measured across the suite access doors and exterior walls of the two test suites just before the decay test (40 Pa). There was a 49 Pa pressure drop from the corridor through the suite access door to the upper test suite and a 10 Pa pressure drop from the suite through the exterior wall to outdoors (total drop of 59 Pa). For the lower suite, these pressure drops were 13 Pa and 6 Pa respectively (total drop of 19 Pa). That is, for both suites, air flowed from the corridor through the suite access door into the suite, and from the suite through the exterior wall to outdoors.

  The calculated stack effects, the measured pressure drops, and Equation 4 suggest that the mechanical ventilation system was a substantial driving force for airflows entering and exiting both suites. However, stack-driven airflows were also significant. Specifically, it appears that 27 Pa of the 59 Pa pressure drop from the corridor through the upper suite to outdoors was due to stack effect. The remainder (32 Pa) of the 59 Pa pressure drop was due to the corridor supply air system. For the lower suite, it appears that the contribution of the mechanical ventilation system was partially *offset* by the stack effect. Specifically, it appears that the 19 Pa pressure drop from the corridor through the lower suite to outdoors was comprised of the 8 Pa inward stack effect from outdoors and 27 Pa toward outdoors contributed by the corridor supply air system. The impact of the stack effect is important, because it means ventilation flows through the suite access door are susceptible to weather variations and location of the suite within the building.

  Second, Comparison 7 (Section 4.4.7) indicated it is likely that suite access door airflows were the primary or sole reason for air exchange in these test suites. This means the airflow rates through the test suite access doors were probably similar. We did not measure the leakage area of the suite access door for the lower suite. However, the measured pressure difference across this door was about a quarter of that across the upper suite's door. Therefore, using Equation 1 and assuming a flow exponent of 0.5 for the door leakage opening (which is characteristic of the doors we tested), it appears the leakage area of the suite access door for the lower suite was about twice that of the upper suite. This difference in leakage area is important, because it confirms that door leakage is not a reliable means of ventilating a suite. If the lower suite had had the same door leakage area as the upper suite, it likely would have received substantially less ventilation air than the upper suite.

4.4.9 Comparison 9: Inter-Suite Transfer Air Fractions

Introduction

Table 4 presents the mean values for the inter-suite transfer air fractions. These fractions were determined using the procedures we outlined in Test Set 6. The uncertainties associated with these measured fractions are listed as well.

Also shown in Table 4 are the CO_2 concentrations we measured or determined for use in Equation 7 (Section 2.5.3), which was used to calculate the transfer fractions. These data are useful in explaining some of the observed phenomena regarding inter-suite transfer airflows.

Table 4: Comparison of Inter-Suite Transfer Air Fractions

	CO2 Concentrations			Inter-Suite Transfer Air Fraction	
Building Number	Average Outdoors [±10 ppm]	Test Suite Equilibrium [±10 ppm]	Average for Other Suites [±100 ppm]	Mean	Uncertainty
1	375	375	475	0%	14%
2	398	415	657	6%	6%
3	400	446	710	15%	6%
4	374	374	1038	0%	2%
5	370	405	609	14%	8%
6	373	450	767	20%	6%
7	392	649	963	45%	8%
8	374	382	444	12%	27%
9	380	402	436	40%	75%
10	394	446	549	33%	23%

The CO_2 concentrations and transfer air fractions shown in Table 4 were consistent with smoke tube tests in terms of flow direction. All of these data and results for Building 1 are for the upper suite only (Floor 31). The data and results for the lower test suite (Floor 11) were similar.

As described in Test Set 6, the measured inter-suite transfer air fractions represent the amount of indirect and direct transfer of air from occupied suites within the test building compared to the total amount of air entering the test suite. It is important to recognize that the inter-suite transfer air fraction based on CO_2 transfer only accounts for direct flows from occupied suites outside the test suite and for indirect flows from these suites through shafts and corridors into the test suite. It does not account for transfer air that did not pass through occupied suites. Some of this other transfer air could be contaminated by pollutants other than CO_2.

Key Findings:

- **Most of the test suites had some transfer air flowing into them from other suites.**

  Only two suites of the ten suites we tested had a zero inter-suite transfer air fraction. This means that the other eight test suites had transfer air flowing into them directly or indirectly from occupied suites elsewhere in the building. This finding is significant, because Sentence

6.2.3.11.(2) of the National Building Code of Canada (NBC 1990) prohibits inter-suite transfer airflows, as discussed in Section 2.5.

Due to the low occupancy rate in Building 1 (about 30%), the inter-suite transfer air fraction for this building does not indicate that the test suite was not exposed to transfer air from other suites. Different results might be obtained when the building is fully occupied.

- **Large variation in inter-suite transfer air fractions.**

  The inter-suite transfer air fractions varied from 0 to 45% with an average of 19%. Building 7 had the highest transfer fraction. One reason was that this building did not have an operative corridor supply air system. Another reason was that the continuous bathroom exhaust system for the test suite was inoperative in this building. This allowed the bathroom exhaust shaft to act as a large leak between the test suite and suites below. Air flowed weakly from this shaft into the test suite and sometimes reversed.

  There was no significant pressure difference between the test suite and the suite immediately below it. For the suites farther below, we did not measure the inter-suite pressure differences. However, when the flow was from the exhaust shaft into the test suite, CO_2 from occupied suites located below the neutral pressure plane could readily enter the test suite. Measurements of the CO_2 concentration in this shaft could not be made to confirm this theory, because of the reversing flow pattern.

  The uncertainty associated with the calculated fractions ranged from 2 to 75% with an average of 18%. The highest uncertainty occurred in Building 9, where the air change rate in the suite was unusually high (2.62 ach in the living room compared to an average for all other test suites of 0.94 ach). The effect of the high air change rate can be explained as follows.

  Based on the CO_2 concentrations listed in Table 4 for Building 9, there was a relatively small but uncertain difference (56 ppm) between the concentrations outdoors and in the suites other than the test suite, because the suites were very-well ventilated. Most of the uncertainty in this difference was due to uncertainty associated with the average concentrations in the other suites (± 100 ppm). At the same time, there was also a significant difference (22 ppm) between the equilibrium concentration in the test suite and the outdoor concentration. As the equilibrium concentration in the test suite approaches the average concentration in other suites, the uncertainty in the transfer fraction increases, because its uncertainty becomes more dependent on the uncertainty associated with the larger concentration.

  A low uncertainty in the transfer fraction occurs when the suite ventilation rates are low, the concentrations in the test suite are near those outdoors, and the concentrations in other suites are relatively high.

- **Corridor supply air systems do not always meet their primary design intent, because they are incapable of always preventing inter-suite transfer airflows.**

  Based on an informal survey we conducted of 25 mechanical ventilation system designers, the primary design intent of the corridor supply air systems in mid- and high-rise residential buildings is to prevent inter-suite transfer airflows. In most of the test buildings, these systems were able to pressurize the corridors on every storey at the time of our tests. Consequently, the corridor supply air systems in these buildings prevented air from flowing from the suites into the corridors. These buildings tended to have similar CO_2 concentrations outdoors, in the corridors, and in the vertical shafts. However, it is important to recognize that these systems by their nature cannot prevent direct transfer airflows through partition walls, floors, and ceilings between adjoining suites.

In four buildings (4, 5, 6, and 8), smoke tube and pressure difference tests showed that the corridor supply air systems failed to prevent transfer airflows from suites to the corridors on lower stories, or from windward suites to the corridors. In two of these four buildings (5 and 8), the test storey was located above the neutral pressure plane. Flows in these two buildings were upward in the stair and elevator shafts from the lower stories toward the test storey. Flows were also from the stair and elevator shafts into the corridors on the upper stories, including the test storey in Building 5, but not the test storey in Building 8.

Consequently, the CO_2 concentrations in the vertical shafts and in the corridor of the test floor in Building 5 were elevated compared to outdoors. In particular, the CO_2 concentrations in the vertical shafts and in the corridor of the test storey in Building 5 were about 125 ppm greater than outdoors. The CO_2 concentration in the corridor of the test floor in Building 8 was only about 8 ppm greater than outdoors. This latter difference is within the measurement uncertainty of the CO_2 monitor (± 10 ppm).

4.5 Problems Due to the Operation of Mechanical Ventilation Systems

Two issues regarding the operation of the mechanical ventilation systems became apparent during our field tests. These issues included:

- the shutdown of mechanical ventilation systems by time clocks, and
- the reentrainment of contaminated air from the building.

The following is a general discussion of the above two issues.

4.5.1 Shutdown of Mechanical Ventilation Systems by Time Clocks

Three buildings had corridor supply air systems and/or central exhaust systems that were operated by time clocks (Building 7 in Quebec and Buildings 9 and 10 in Manitoba). The rationale for the use of the time clocks was not clear. Possible reasons for time clock use include attempts to reduce noise and to conserve energy. Our interviews with several designers indicated that the latter was their primary motivation.

The settings of the time clocks resulted in the absence of mechanical air supply and exhaust throughout these buildings during some periods of the day (typically at night). During cold weather, opening windows for natural ventilation is often impractical as an alternative due to the uncomfortable drafts caused by the entry of cold outdoor air.

It is important to note that Section 5.4 of ASHRAE Standard 62 (1990a) states that "When the supply of air is reduced during times the space is occupied, provision shall be made to maintain acceptable indoor air quality throughout the occupied zone". As stated above, it is unreasonable to use openable windows in a cold climate for this purpose. Therefore, the use of time clocks on supply and/or exhaust systems could contravene the ASHRAE Standard's requirement if these systems are intended to provide ventilation to the suites and if contaminant levels became elevated in the occupied suites.

The lack of corridor supply air in Building 7 resulted in complete building depressurization relative to outdoors when the roof-top exhaust fans were running. This exhaust mode also depressurized the building with respect to the parkade (even with the parkade exhaust fan running). Smoke tube and pressure difference tests showed that air was drawn from the parkade into a stair shaft and was distributed to suites on upper stories by stack-induced flows within the building.

This mode of operation is potentially hazardous if carbon monoxide (CO) concentrations in the parkade are elevated. In particular, this airflow scenario is specifically forbidden by Sentences 6.2.2.3 (3) and 6.2.2.4 (2) of the National Building Code of Canada (NBC 1990). This airflow pattern demonstrates the need for safety interlocks so that exhaust fans do not run when corridor supply air systems are inoperative. These safety interlocks are required for dwelling units by Sentence 9.32.3.8 (3) of the 1995 version of the National Building Code (NBC 1995), but were not required by the 1990 version. Furthermore, this problem also indicates a need for independent supply air systems for parkade vestibules, which were not always seen in the designs that we reviewed.

In Building 9, the time clock controlled only the corridor supply air system. This clock resulted in the building operating without corridor supply air from 22:00 to 08:00. During this period, it is unlikely occupants will use the individual suite exhaust systems during the period when the corridor supply system is switched off. Therefore, an interlock with the corridor supply system probably is unnecessary for these circumstances. However, this 10 hour period includes a significant fraction of the time when occupants are normally expected to be in the building and require ventilation air supply.

In Building 10, the time clock resulted in the corridor supply air system and central exhaust system operating only from 06:00 to 09:30 and from 15:30 to 22:00. During all other periods of day (seven days of the week), this building operated without mechanical supply to the corridors and without mechanical exhaust from the suites.

4.5.2 Reentrainment of Contaminated Air from the Building

The reentrainment of exhaust, combustion, and plumbing vent gases is apparently not well understood by designers and building owners. Specifically, the location of intakes, exhausts, combustion stacks, and plumbing vents appears to be governed more by building configuration than by a need to avoid reentrainment. This issue may be addressed by current research proposed by ASHRAE Technical Committee 4.3 "Ventilation Requirements and Infiltration", which will study the effect of intake and exhaust locations on reentrainment.

In one building in Manitoba, occupants had expressed their concerns of seeing "smoke" in hallways. The building owner thought that reentrainment of combustion exhaust from the stack of the natural-gas-fired supply air heater on the roof into its nearby air intake was responsible for the "smoke". He was considering extending the stack to reduce the potential for reentrainment. The "smoke" in this building did not occur during our testing. Although the source of this "smoke" was not clear, it is unlikely that it was from the natural-gas-fired equipment on the roof. This type of equipment does not normally produce smoke.

In general, combustion exhaust stacks discharged near the corridor supply air intakes of all test buildings, except in Ontario (Buildings 5 and 6). The location of these stacks is partly a result of using packaged equipment that includes the air intake and stack on a single unit.

A few of the test buildings had plumbing vents that were located near or even immediately under the air intakes for the corridor supply air system. However, Building 5 had extension pipes on the vents near the air intake so the vents discharged above the makeup air unit. The plumbing vents are a potential source of contamination for the building supply air if gases vented from the plumbing system are drawn into the air intakes.

5.0 Conclusions

The field performance tests showed suite ventilation to be highly influenced by weather, suite location within the building, and treatment of both interior and corridor access doors.

Ventilation within a suite at any given time is very difficult to predict. The test results showed there are substantial amounts of transfer air entering the test suites.

To ensure suite ventilation is both controlled and adequate under normal operating conditions, the building industry will need to develop and follow a strict set of ventilation design practices.

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APPENDIX A: GLOSSARY OF VENTILATION TERMINOLOGY

To maintain a consistent terminology and to facilitate the understanding of ventilation issues discussed in this report, the following list of definitions is presented. The definitions are in alphabetic order and are generally consistent with ventilation terminology used by ASHRAE (1990a, 1991, 1993b) and in Canadian standards and codes (CGSB 1986; CSA 1990, 1993; NBC 1990, 1995).

Air Change Rate

The ratio of the volumetric flow rate of air entering or leaving a space to the *conditioned volume* of the space (typically expressed in units of air changes per hour). The same volume units are used for the airflow rate and *conditioned volume.*

Combustion Air

The air required for the combustion of gas or other fossil fuel. This includes *supply air* for the combustion zone in excess of the air theoretically required for complete combustion.

Conditioned Volume

The total interior volume of the space that is subject to heating, cooling, humidification, dehumidification, or *ventilation.*

Dilution Flow

Movement of air with a lower concentration of contaminants into a space to reduce the concentration of contaminants in that space. Contaminants are also removed from the space by the air flowing out of that space.

Effective Air Change Rate

The constant *air change rate* that would result in the average contaminant concentration over a period of time when the actual concentration is varying over time.

Envelope

The surfaces formed by the walls, floors, and ceiling that enclose the *conditioned volume* of the space. These surfaces separate the space from other spaces, the outdoors, or the soil.

Equivalent Leakage Area

The equivalent amount of open area in a flow separation that would allow the same airflow rate to occur across the separation if all the airflows through individual leakage openings in that separation were combined. A reference pressure differential of 10 Pa is used.

Exfiltration

The movement of air out of a space through unintentional leakage openings in the *envelope*, through intentional openings around doors and windows, or through open doors and open windows. Other leakage openings that can be operated by the occupants are not included.

Exhaust Air

The movement of air from a space through intentional leakage openings in the *envelope*, not including intentional openings around doors and windows or open doors and open windows. This air is not intended to be supplied again to that space or to other spaces as part of the *supply air*.

High-Rise Residential Building

A building used for residential occupancy that is seven or more storeys in building height with any building area.

Infiltration

The movement of air into a space through unintentional leakage openings in the *envelope*, through intentional openings around doors and windows, or through open doors and open windows. Other leakage openings that can be operated by the occupants are not included.

Low-Rise Residential Building

A building used for residential occupancy that is three storeys or less in building height with a building area not exceeding 600 m^2. Most single-family detached dwellings are of this building type.

Makeup Air

Air flowing into a space to relieve a pressure decrease caused by greater *exhaust air* and *exfiltration* airflows from a space than *supply air* and *infiltration* airflows into that space.

Mechanical Ventilation

The *ventilation* of a space by air movement through powered airflow devices. Powered airflow devices include mechanical devices such as fans and blowers or combustion appliances, but exclude wind-driven devices such as turbines.

Mid-Rise Residential Building

A building used for residential occupancy that is four to six storeys in building height with any building area <u>or</u> that is three storeys or less in building height with a building area exceeding 600 m^2.

Natural Ventilation

The *ventilation* of a space by air movement through intentional openings that can be operated by the occupants (including doors or windows), by air movement through non-powered airflow devices, or by *infiltration* and *exfiltration*.

Neutral Pressure Plane

The set of locations in a space where there is a transition from positive to negative pressure differential (neutral pressure) at the separations between the space and its surrounding environment.

In single compartment buildings, this set of locations defines the edges of a plane that intersects the vertical surfaces of the *envelope*. The plane is not necessarily horizontal.

For multi-compartment buildings, this set of locations may define the edges of a plane or of a series of discontinuous surfaces that intersect the vertical surfaces of the *envelope*. Regardless of whether the *envelope* is open or not at the transition locations, there is no flow across the *envelope* at these locations.

Occupied Zone

The region within a space that is bounded by horizontal planes located at 75 and 1800 mm above the floor and by vertical planes located at 600 mm from fixed vertical surfaces.

Outdoor Air

Air from outside the building and that has not been previously circulated through the building. This air sometimes contains contaminants in unacceptable concentrations.

Plug Flow

Air movement through a space in predominantly one direction. Contaminants are transported out of the space with the flow.

Relief Air

Air flowing into a space to relieve a pressure increase caused by greater *supply air* and *infiltration* airflows into a space than *exhaust air* and *exfiltration* airflows from that space.

Return Air

Air removed from a space as *exhaust air* or as *recirculated air.*

Recirculated Air

Air removed from a space and that is intended to be supplied again to that space or other spaces as part of the *supply air*.

Static Pressure

The pressure that tends to burst (positive sign) or collapse (negative sign) the *envelope* of a space. If there is an airflow within the space, this pressure is measured perpendicular to the airflow.

Suite

An enclosed space that is composed of one or more rooms in close proximity to one another. These rooms are intended for occupancy and control by a single tenancy (rental or ownership tenure). The rooms have access to each other directly through doorways or indirectly through corridors or vestibules that are located within the same enclosed space.

Supply Air

The movement of air into a space through intentional leakage openings in the *envelope*, not including intentional openings around doors and windows or open doors and open windows.

Total Pressure

The algebraic sum of the *static pressure* and *velocity pressure*. It is measured by a probe aligned with the airflow. In a flow element, total pressure decreases in the direction of flow due to energy losses caused by friction and turbulence effects.

Transfer Air

Air that has moved between spaces within a building. This flow is not necessarily unidirectional. When the *neutral pressure plane* is located between the top and bottom of a tall opening connecting two spaces, there can be a bi-directional airflow through the opening.

Velocity Pressure

The pressure required to accelerate air from zero velocity to a specific velocity (or vice-versa). This pressure is proportional to the kinetic energy of the airflow. It tends to vary across an airflow element such as a duct due to changes in velocity across the flow element.

Ventilation

The process of supplying or removing *ventilation air* by natural or mechanical means to and from a space for control of temperature, humidity, or contaminants. This process does not necessarily include the addition or removal of heat or moisture from the air by mechanical equipment.

Ventilation Air

Air supplied or removed by the *ventilation system*. This air includes *outdoor air* and *recirculated air* that may or may not have been conditioned and treated, as shown in Figure 1 of ASHRAE Standard 62 (1990a). If the air is treated, the treatment process removes some of the contaminants or converts some of them to less objectionable forms.

Ventilation System

A set of powered or non-powered devices with or without ducts or vents that is installed in a building for *ventilation* of one or more spaces within the building.

APPENDIX B: FIELD TEST PROTOCOLS

B.1 Test Set 1: Normal and External Driving Forces

Protocol to continuously measure outdoor temperature, wind speed, and wind direction using a weather station at a building site.

1. Unpack the weather station components (monitor, five ABS mast sections, ratcheting tie-down straps, anemometer, gear clamps, outdoor temperature sensor and shield, shield cover, sensor cables, chain wrenches, extension cord).
2. Select a location at the top of the building to install the mast. This location should provide as much open access to the wind from all directions as possible. Locations such as a building column, a railing, or a ladder that leads to the roof of a mechanical penthouse are desirable for ease of installation. To avoid vibration and thermal plumes, do not attach the mast to a vent, a chimney, or to mechanical equipment.
3. Assemble the five mast sections by screwing them tightly together (total mast length is 5 m).
4. Attach the anemometer arm with wind speed and direction sensors to the upper end of the mast using two gear clamps. The anemometer arm should be oriented perpendicular to the mast so the rotation axes of the sensors will be vertical when the mast is installed. The wind direction sensor should be above the wind speed sensor. Confirm that the sensors rotate freely.
5. Determine the direction of magnetic north using a compass (stand as far away as possible from metal objects and check the direction from various regions of the rooftop to confirm the correct direction). Correct the magnetic north direction to true north if the local declination is known (BC).
6. Install the mast on the building using at least two ratcheting tie-down straps. Orient the mast vertically with the anemometer arm pointing toward north (true north in BC, magnetic north in other locations). Use engineering judgment in determining the length of the mast that is unsupported above the building (exposure to wind is desirable, but safety is paramount to prevent the mast from coming loose in high winds). Securely tighten the straps with ratchets and use the excess strap length to further secure the mast. If the straps cannot be used, use at least three existing screw holes on the building exterior and screw the mast to the side of the building. (Replace the screws in their original holes at the end of testing once the mast is removed).
7. Attach the outdoor temperature sensor and its radiation shield to the side of the mast (about midway along the length of the mast and on the side facing away from the building, preferably facing north). Orient the radiation shield so its long axis is vertical. Attach the shield cover plate to the mast about 3 cm above the top of the shield to allow air to circulate through the shield, but to prevent rain or snow from entering the shield.
8. Locate the weather monitor (screen and datalogger) indoors near a grounded AC power supply. Typically, this location is inside a mechanical room or at the top of a stair shaft. Choose a location that is unlikely to be accessed by building occupants to prevent tampering with the equipment.

9. Attach the wind and temperature sensor cables to the sensors on the mast and to the monitor. Use cable ties or tape to secure the cables to the side of the mast (to prevent wind damage to cables). Route the cables outdoors along the rooftop so they are not a tripping hazard. Keep the cables away from electrical devices. If the cables need to be joined for additional length, protect the cable connections from moisture and tampering using sealed boxes around the connections. Protect the cables from damage at the entrance to indoors (pass cables through the gap between the door or window and its frame). Secure the cables to the wall or floor so they are not a tripping hazard.

10. Connect the monitor to the AC power supply. Use the extension cord as required. Route and secure the power so it is not a tripping hazard. Install the backup battery in the monitor only after the AC power is connected.

11. Turn on the monitor and set it to local time.

12. Confirm that the monitor screen is reporting indoor temperature, outdoor temperature, wind speed, and wind direction. Spin the anemometer components manually in the absence of wind to create variations at the sensors.

13. Set the datalogger in the monitor to run continuously and to average wind and temperature data using a 5 minute period. Consequently, peak and average data for each period will be recorded once every 5 minutes (data are sampled once every 5 seconds). Start the datalogger.

14. Leave the weather station installed and the monitor running until all other testing in the building is complete. Periodically during the test period, check the weather station to ensure it is still operating and that the mast is secure.

15. The weather station is the last piece of test equipment to be dismantled and packed up at the end of testing. Prior to dismantling the station, stop the datalogger and download the recorded weather data to a laptop computer. Turn off, dismantle, and pack up the weather station. Use the chain wrenches to unscrew the mast sections. After dismantling the mast, replace any screws that were removed from existing holes in the building (if screws were used to fasten the mast to the building exterior).

16. At ground level, determine the orientation of the building with respect to north (magnetic or true as appropriate) using a compass. Record this datum, which is required to correct the measured wind angles to the orientation of the building.

B.2 Test Set 2: Pressure and Airflow Capabilities of Suite Exhaust Devices

Protocol to measure pressure differences induced by operating exhaust devices within a suite and to collect data for determining the airflow capacities of these devices.

1. In the corridor on the same storey as the test suite, unpack the blower door measurement components (blower door frame and sheet, blower with orifice plate, plugs for orifice plate, blower supports, blower cover, speed controller, extension cord, two pressure tubes, manometer, thermometer, tape).
2. Assemble the blower door frame. Place this frame against the door stop on the corridor side of the suite access door frame. Adjust the size of the blower door frame to tightly match the perimeter of the suite access door frame.
3. Remove the blower door frame and attach its sheet. Use tape to secure this sheet to the blower door frame so the sheet is taut.
4. Securely attach the suite pressure tap and tube to the corridor side of the blower door sheet.
5. Reinstall the blower door frame with its attached sheet in the suite access door frame.
6. Turn off all intermittent exhaust devices inside the test suite. Leave all continuous exhaust devices inside the suite open. Close all exterior windows and doors in the suite. Ensure that all interior doors in the suite are open, including the suite access door (access to this door and the suite is through the blower port in the installed sheet).
7. Measure and record the temperature of the air in the suite.
8. Estimate the leakage area of the suite that is to be tested. Plug the appropriate holes of the orifice plate on the blower to achieve the appropriate flow measuring range. Record this flow range setting.
9. Mount the blower on its support blocks and attach it to the blower door sheet. Orient the blower to blow into the corridor.
10. Attach the other pressure tube to the appropriate "flow pressure" port on top of the blower.
11. Open the corridor to outdoors using an exterior window or door.
12. Locate the manometer away from the airflow exiting the blower. Connect the manometer's low pressure port to the pressure tube from the blower door sheet. Leave the high pressure port of the manometer open to the corridor.
13. Connect the blower to the speed controller and plug the speed controller into a nearby AC power outlet. Use the extension cord to reach the power outlet as required.
14. Install the blower cover over the corridor side of the blower to finish sealing the blower door assembly.
15. With the blower sealed, measure and record the pressure difference between the suite and the corridor. A positive pressure means the suite is depressurized relative to the corridor.
16. Unseal the blower by removing its cover.

17. Using the speed controller, start the blower and adjust the blower speed to achieve a pressure difference of 20 Pa between the suite and corridor (suite depressurization as measured using the manometer). Record the starting time of the test.
18. Connect the "flow pressure" tube to the high pressure port of the manometer. Using the manometer, measure and record the static pressure difference across the orifice plate of the blower. This is the "flow pressure". Turn off the blower and repeat steps 8, 9, 14 through 18 if the "flow pressure" is out of range.
19. Disconnect the "flow pressure" tube from the manometer and repeat steps 17 and 18 with each intermittent exhaust device in the test suite operating separately, all together, and then all off again. There is no need to turn off and remove the blower if a second person inside the suite is used to change exhaust device operating modes (using two-way radio communication with the blower operator to verify operating modes).
20. Seal each continuous exhaust device opening into the suite separately and repeat steps 17 through 19. Only one opening at a time is sealed in this step. The second person inside the suite is used to seal/unseal the openings.
21. Seal all of the continuous exhaust device openings into the suite and repeat steps 17 through 19. The second person inside the suite is used to seal/unseal the openings.
22. Unseal all openings for continuous exhaust devices. Turn off the blower. Reinstall the blower cover over the corridor side of the blower to seal the blower door assembly.
23. With the blower sealed, again measure and record the pressure difference between the suite and the corridor.
24. Record the ending time of the test.
25. Dismantle and pack up the blower door components at the end of the test.
26. Close the suite access door. From inside the suite, record the pressure difference across the exterior wall and suite access door.
27. Turn on one intermittent exhaust device in the suite. Record the pressure difference across the exterior wall and suite access door. Turn off the device.
28. Repeat step 27 for each of the other intermittent exhaust devices in the suite.
29. Repeat step 27 with all intermittent exhaust devices operating at the same time.
30. Repeat steps 27 through 29 with each continuous exhaust device opening sealed separately and then with all of these openings sealed.
31. Unseal all openings and turn off all intermittent exhaust devices.

B.3 Test Set 3: Corridor Supply Airflow Rates

Protocol to collect data for determining the airflow rate through a corridor supply air outlet using a fan-compensated flow hood with an orifice plate.

1. In the corridor on the same storey as the test suite, unpack the flow measurement components (flow hood, flow hood support rods, blower with orifice plate, plugs for orifice plate, speed controller, extension cord, tripod, two pressure tap tubes, manometer, thermometer).
2. Assemble the rectangular flow hood. Ensure that the hood's spring-loaded support rods are seated in the appropriate recesses inside the hood end plates to avoid misalignment or collapse during testing.
3. Attach the flow hood to the blower. The flow hood is attached by clips to the inlet side of the blower. Ensure all four taps of the hood's perimeter static pressure manifold are correctly seated in the hood sides.
4. Attach one tube to the outlet port of the pressure manifold. This outlet is located at the bottom of the flow hood. Attach the other tube to the appropriate "flow pressure" port on top of the blower.
5. Mount the assembly (blower and hood) securely on top of the tripod.
6. Connect the blower to its speed controller and plug the speed controller into an AC power outlet. Use the extension cord to reach the power outlet as required.
7. Turn off all intermittent exhaust devices inside the test suite. Leave all continuous exhaust devices inside the suite open. Close all exterior windows and doors in the suite and ensure that all interior doors in the suite are open. Close all doors and windows in the corridor to be tested.
8. Measure and record the temperature of air flowing out of the corridor supply air outlet and of the air in the corridor. Also record the starting time of the test.
9. Estimate the flow rate from the corridor supply air outlet to be tested. Plug the appropriate holes of the orifice plate on the blower to achieve the appropriate flow measuring range (to achieve a flow pressure within the calibrated range). Record this flow range setting.
10. Move the assembly on the tripod into contact with the wall containing the corridor supply air outlet. Ensure all of the foam gasket on the end plate of the flow hood is close to or in contact with the wall (pressure differences between the corridor and the interior of the flow hood during measurement are near zero, so a perfect seal is not required). The center of the flow hood should be approximately aligned with the center of the corridor supply air outlet. At this time, the blower's fan blades will be freewheeling due to airflow through the hood/blower assembly. The flow hood's nylon sides will be displaced slightly outwards due to pressurization of the hood by airflow from the corridor supply air outlet and resistance of the blower orifice plate.
11. Locate the manometer away from the airflow exiting the blower. Connect the manometer's low pressure port to the tube from the flow hood manifold. Leave the high pressure port of the manometer open to the corridor.

12. Using the speed controller, start the blower and adjust the blower speed to achieve a zero static pressure difference between the flow hood and corridor (as measured using the manometer). With the zero pressure difference, the sides of the flow hood will be neutral (not distorted in or out by pressure).
13. Connect the "flow pressure" tube to the high pressure port of the manometer. Using the manometer, measure and record the static pressure difference across the orifice plate of the blower. Repeat steps 9 through 13 if the flow pressure is out of range. Record the ending time of the test.
14. If there are other corridor supply air outlets for the same corridor, move the measurement equipment to each of the other outlets in sequence and repeat test steps 7 through 13. Record the location of each outlet. Dismantle and pack up the components at the end of the tests.

B.4 Test Set 4: Leakage Characteristics of Suite Access Doors

Protocol to collect data for determining the equivalent leakage area of a suite access door.

1. In the corridor on the same storey as the test suite, unpack the blower door measurement components (blower door frame and sheet, blower with orifice plate, plugs for orifice plate, blower supports, blower cover, speed controller, extension cord, two pressure tubes, manometer, thermometer, tape).
2. Assemble the blower door frame. Place this frame against the door stop on the corridor side of the suite access door frame. Adjust the size of the blower door frame to tightly match the perimeter of this suite access door frame.
3. Remove the blower door frame and attach its sheet. Use tape to secure this sheet to the blower door frame so the sheet is taut.
4. Securely attach the inter-door space pressure tap and tube to the corridor side of the blower door sheet.
5. Reinstall the blower door frame with its attached sheet in the suite access door frame. Carefully tape the entire perimeter of the blower door frame and sheet to the suite access door frame and to the floor. Extend the tape on the carpet at least 15 cm away from the blower door to increase the resistance to flow through the carpet (if present).
6. Open one exterior window or door in the suite and ensure that all interior doors between the suite access door and the exterior window are open. Close and latch the suite access door (access to this door and the suite is through the blower port in the installed sheet).
7. Estimate the leakage area of the suite access door that is to be tested. Plug the appropriate holes of the orifice plate on the blower to achieve the appropriate flow measuring range. Record this flow range setting.
8. Mount the blower on its support blocks and attach it to the blower door sheet. Orient the blower to blow into the corridor. In the installed position, the suite access door surface should be located at least 10 to 15 cm upstream of the blower's orifice plate inlet.
9. Attach the other pressure tube to the appropriate "flow pressure" port on top of the blower.
10. Open the corridor to outdoors using an exterior window or door.
11. Locate the manometer away from the airflow exiting the blower. Connect the manometer's low pressure port to the pressure tube from the blower door sheet. Leave the high pressure port of the manometer open to the corridor.
12. Connect the blower to the speed controller and plug the speed controller into a nearby AC power outlet. Use the extension cord to reach the power outlet as required.
13. Using the speed controller, start the blower and adjust the blower speed to achieve a pressure difference of 20 Pa between the inter-door space and corridor (as measured using the manometer).
14. Use a smoke tube to check the seal between the blower door and the suite access door frame. Seal any leaks that are found with tape and repeat this step. Turn off the blower.

15. Install the blower cover over the corridor side of the blower to finish sealing the blower door assembly.
16. With the blower sealed, measure and record the pressure difference between the inter-door space and the corridor. A positive pressure means the inter-door space is depressurized relative to the corridor.
17. Unseal the blower by removing its cover.
18. Using the speed controller, start the blower and adjust the blower speed to achieve a pressure difference of 50 Pa between the inter-door space and corridor (as measured using the manometer).
19. Measure and record the temperature of the air in the inter-door space that is flowing out of the blower and of the air in the corridor. Also record the starting time of the test.
20. Connect the "flow pressure" tube to the high pressure port of the manometer. Using the manometer, measure and record the static pressure difference across the orifice plate of the blower. This is the "flow pressure". Turn off the blower and repeat steps 7, 8, 18, and 19 if the "flow pressure" is out of range.
21. Disconnect the "flow pressure" tube from the manometer and repeat steps 11, 18, and 20 for pressure differences between the inter-door space and corridor of 45, 40, 35, 30, 25, and 20 Pa.
22. Turn off the blower and reinstall the blower cover over the corridor side of the blower to seal the blower door assembly.
23. With the blower sealed, again measure and record the pressure difference between the inter-door space and the corridor.
24. Record the ending time of the test.
25. Dismantle and pack up the blower door components at the end of the test.
26. Close the exterior doors and windows that were opened in the corridor and suite for the test.

B.5 Test Set 5: Magnitudes and Uniformity of Suite Air Change Rates

Protocol to inject and mix a single tracer gas in a suite and then to measure the decay in concentration of the tracer gas in that suite using a multi-point continuous sampling system.

1. Check the tracer gas cylinder valve to ensure it is tightly closed prior to entering the building.
2. Prepare the suite for testing by checking that suite exterior doors and windows are all closed and latched. Check that operable ventilation equipment (e.g. exhaust fans, circulating fans, dryers) are off. Check that all room doors in the suite are fully open. Set the thermostat to 21°C.
3. Unpack the components of the multi-point tracer gas sampling system (monitor, four tracer gas sensors, four sensor boxes with attached cables, tripods, clamps).
4. Position the four sensor boxes in the test suite as follows: one in the living room, one in the kitchen, one in the master bedroom, and one in the bathroom. Except in the kitchen, each sensor box is located near the center of the room and is clamped to the top of a tripod, which is set to an elevation of approximately 4 feet above the room's floor. In the kitchen, the sensor box is taped approximately centrally along the kitchen counter top (near the outward edge of the counter top). The sensor boxes are oriented so that the sensor socket faces upward.
5. Install a tracer gas sensor on each sensor box. Ensure each sensor is correctly matched to its corresponding box. This step is critical to match the resistance pairings of the individual semiconductor sensors and boxes that were used during calibration of the tracer gas system. Record the locations of the sensor boxes and sensors.
6. Locate the monitor in a central location of the suite. Run cables from the sensor boxes to the monitor. Securely tighten each cable connector to the monitor.
7. Turn on and start the tracer gas monitor. Clear the monitor's memory and then set the monitor's datalogger to continuously record the conductance of all four sensors once every minute. Record the starting time when the monitor displays its first set of conductance values (record 1). Allow the monitoring system to run for several hours to establish the background levels preceding the tracer gas test.
8. At or after midnight, stop the monitor and record the stop time. Download the logged tracer gas data to a laptop computer and clear the monitor's memory. Confirm that the background levels of the tracer gas in each room are at or near zero. Restart the monitor and record the starting time.
9. Recheck that all doors, windows, ventilation equipment, and thermostat are in their properly configured, as defined in Step 2.
10. Inject tracer gas into the test suite by opening the valve on the tracer gas cylinder about one-half turn and carrying the cylinder once around the perimeter of every space within the suite. Walk slowly (about 10 feet every 5 seconds) while carrying the open cylinder around the suite. This procedure should result in the monitor displaying a conductance for each sensor that is equivalent to a concentration of several hundred parts per million of the tracer gas.

Tightly close the tracer gas cylinder valve after injection to ensure there is no subsequent leakage of the tracer gas into the suite.

11. To assist the initial mixing of the tracer gas by natural flows within the suite, remove the orifice plate from the blower and turn on the blower to about 50% full flow. Carry the blower around the test suite to mix air within the suite. At each room's doorway, place the blower at floor level so it is blowing into the room. Leave the blower in the doorway at least until flow out of the room is felt over top of the blower. Mix the air and tracer gas in the test suite for about 5 minutes. Turn off the blower.
12. Leave the tracer gas monitor running overnight (about 8 hours) in the unoccupied test suite to continuously record the tracer gas decay in each of the four rooms being sampled.
13. The following morning (between about 08:00 and 10:00), stop the tracer gas monitor and record the stop time. Download the logged tracer gas data to a laptop computer and clear the monitor's memory.
14. Restart the monitor and record the starting time. Allow the monitor to run until the remainder of testing of the suite is complete and background levels have returned to near zero.
15. Stop the tracer gas monitor and record the stop time. Download the final set of logged tracer gas data to a laptop computer and clear the monitor's memory. Turn off the monitor.
16. Dismantle and pack up the tracer gas system.

B.6 Test Set 6: Inter-Suite Transfer Air Fractions

Protocol to inject and mix CO_2 in a suite and then to measure the decay in concentration of CO_2 in that suite using a single-point continuous sampling system.

The procedure for the CO_2 decay test was similar to that for the tracer gas decay test described in Test Set 5. The only exceptions were that a different monitor was used, only a single point was monitored (the living room tracer gas location), and CO_2 was released instead of the tracer gas. The CO_2 was released immediately after the tracer gas. As such, the release of the CO_2 aided the mixing of the tracer gas within the test suite.

APPENDIX C: FLOOR PLANS OF TEST SUITES

This Appendix presents a floor plan of each test suite (Figures C.1 through C.10).

Each plan is identified by a building number and is plotted using the same scale (1:75). Nominal north is indicated by an arrow. The location of the exhaust devices within the suite are shown. The plans also show the location of each of the four tracer gas sensors (T1 through T4) within the suites. The CO_2 sensor location is not shown, but it was always located immediately adjacent to the tracer gas sensor in the living room.

Figure C.1: Floor Plan of Test Suite in Building 1

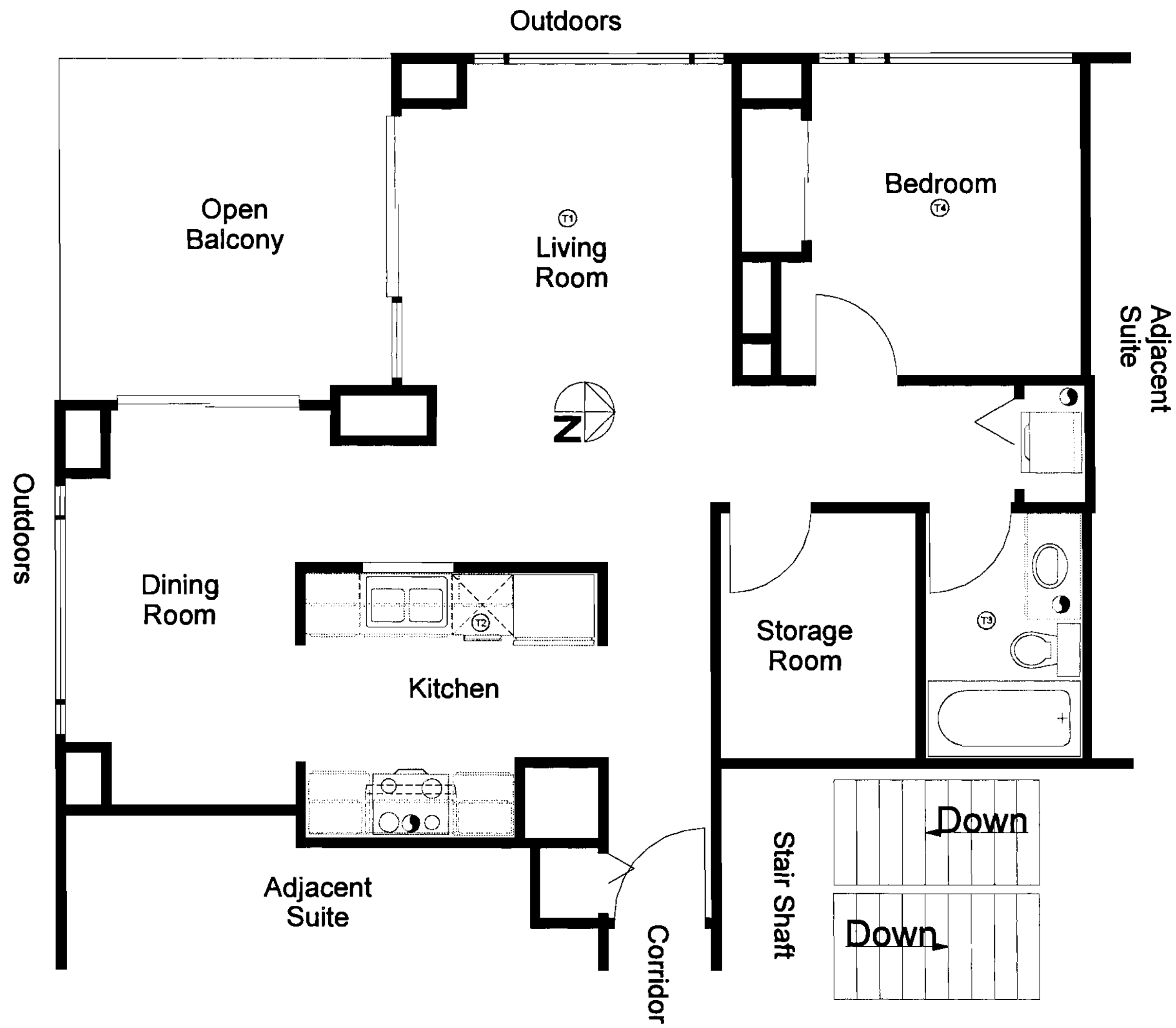

Figure C.2: Floor Plan of Test Suite in Building 2

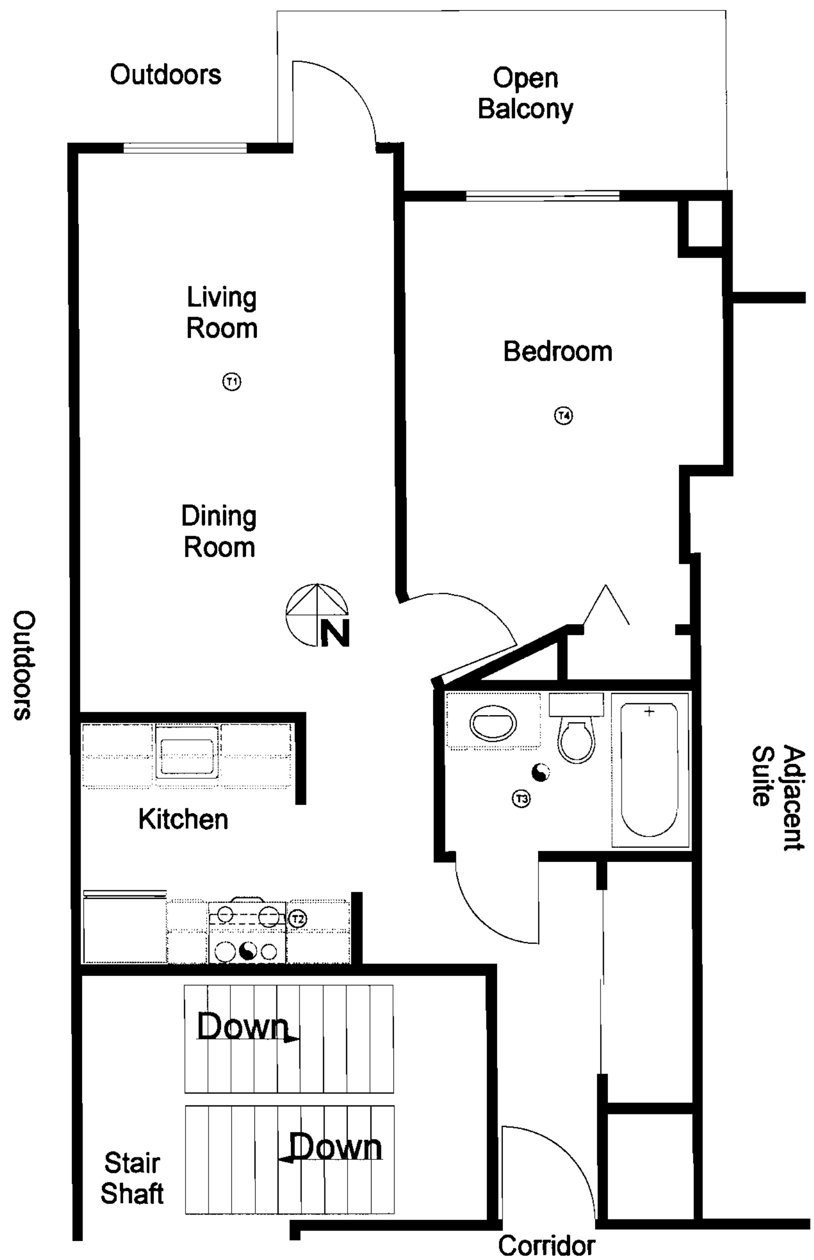

Figure C.3: Floor Plan of Test Suite in Building 3

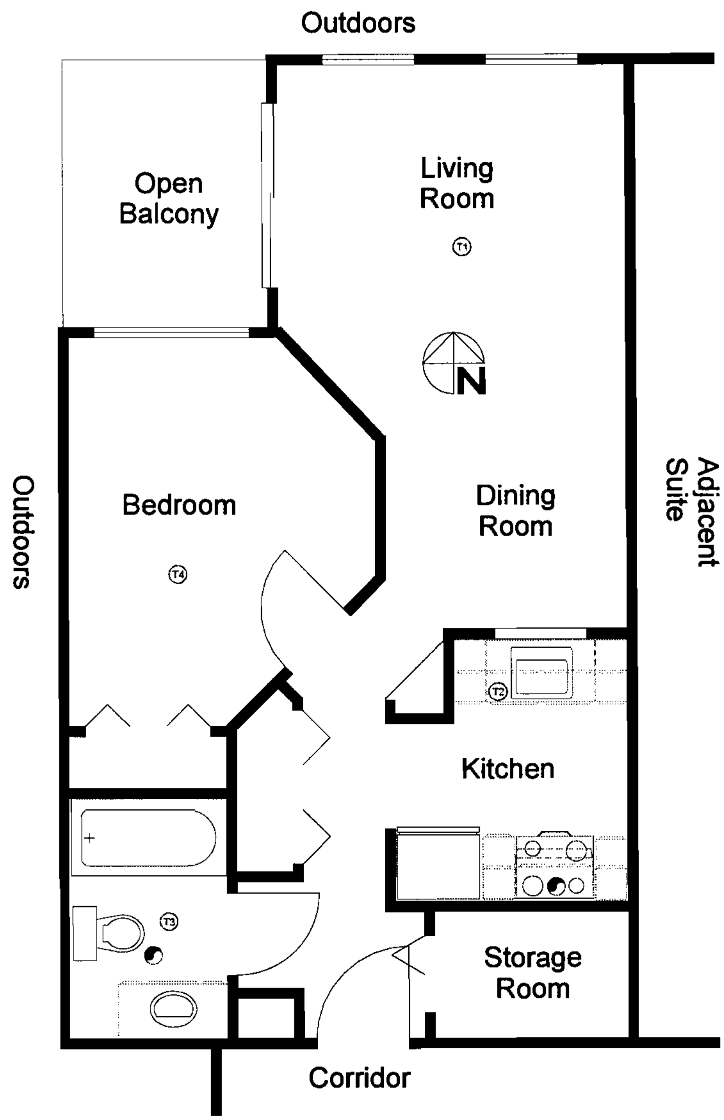

Figure C.4: Floor Plan of Test Suite in Building 4

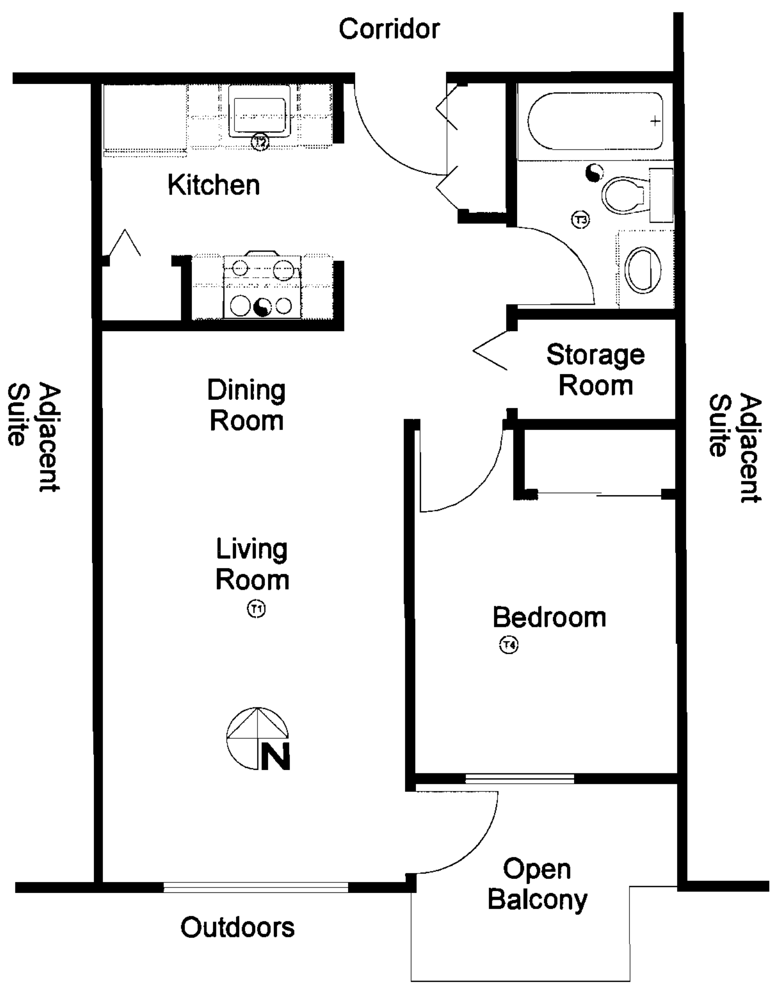

Figure C.5: Floor Plan of Test Suite in Building 5

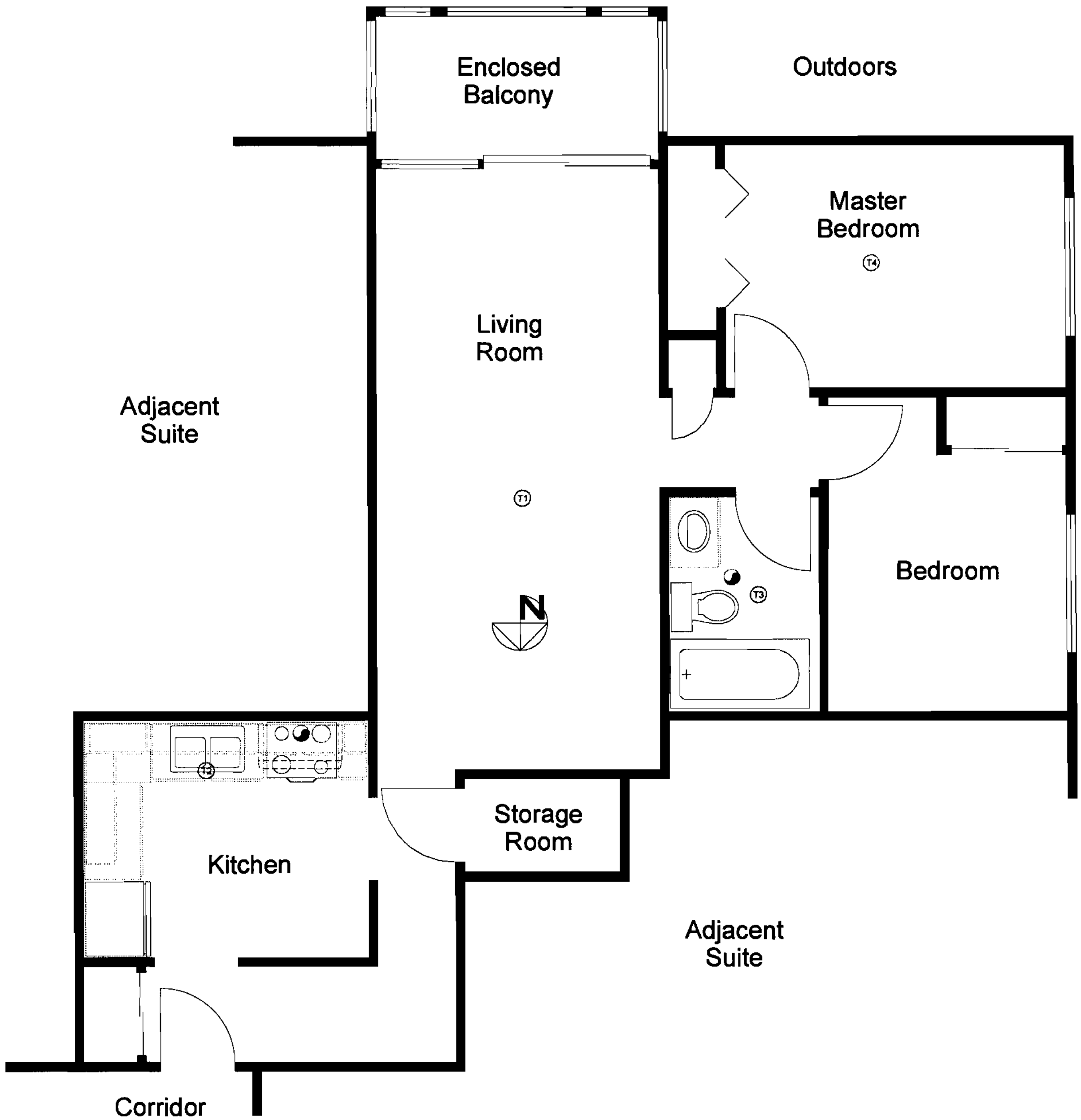

Figure C.6: Floor Plan of Test Suite in Building 6

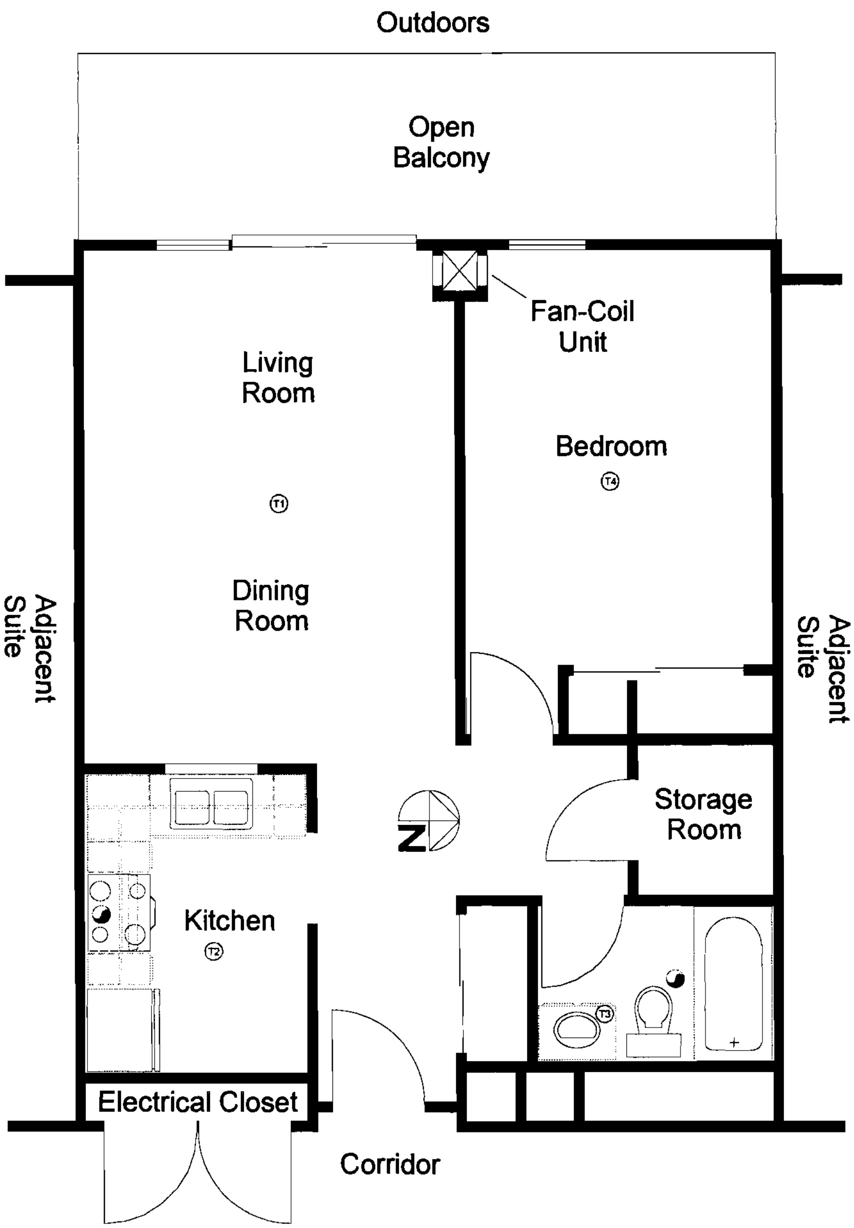

Figure C.7: Floor Plan of Test Suite in Building 7

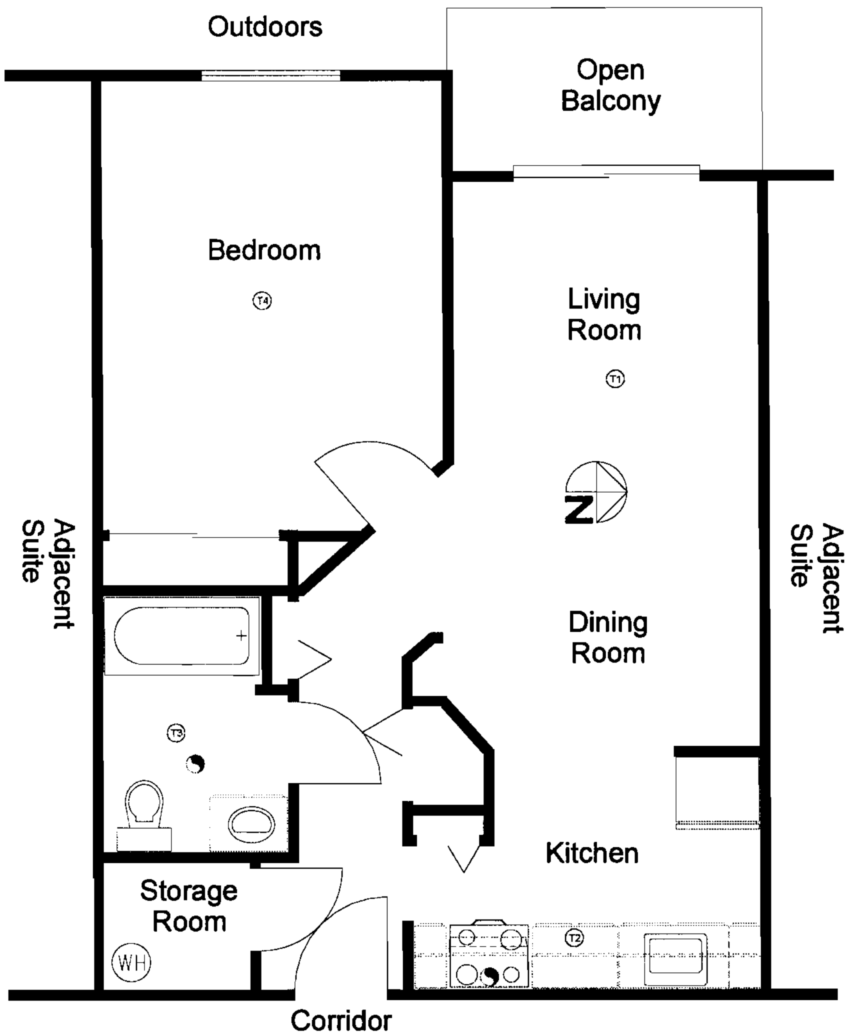

Figure C.8: Floor Plan of Test Suite in Building 8

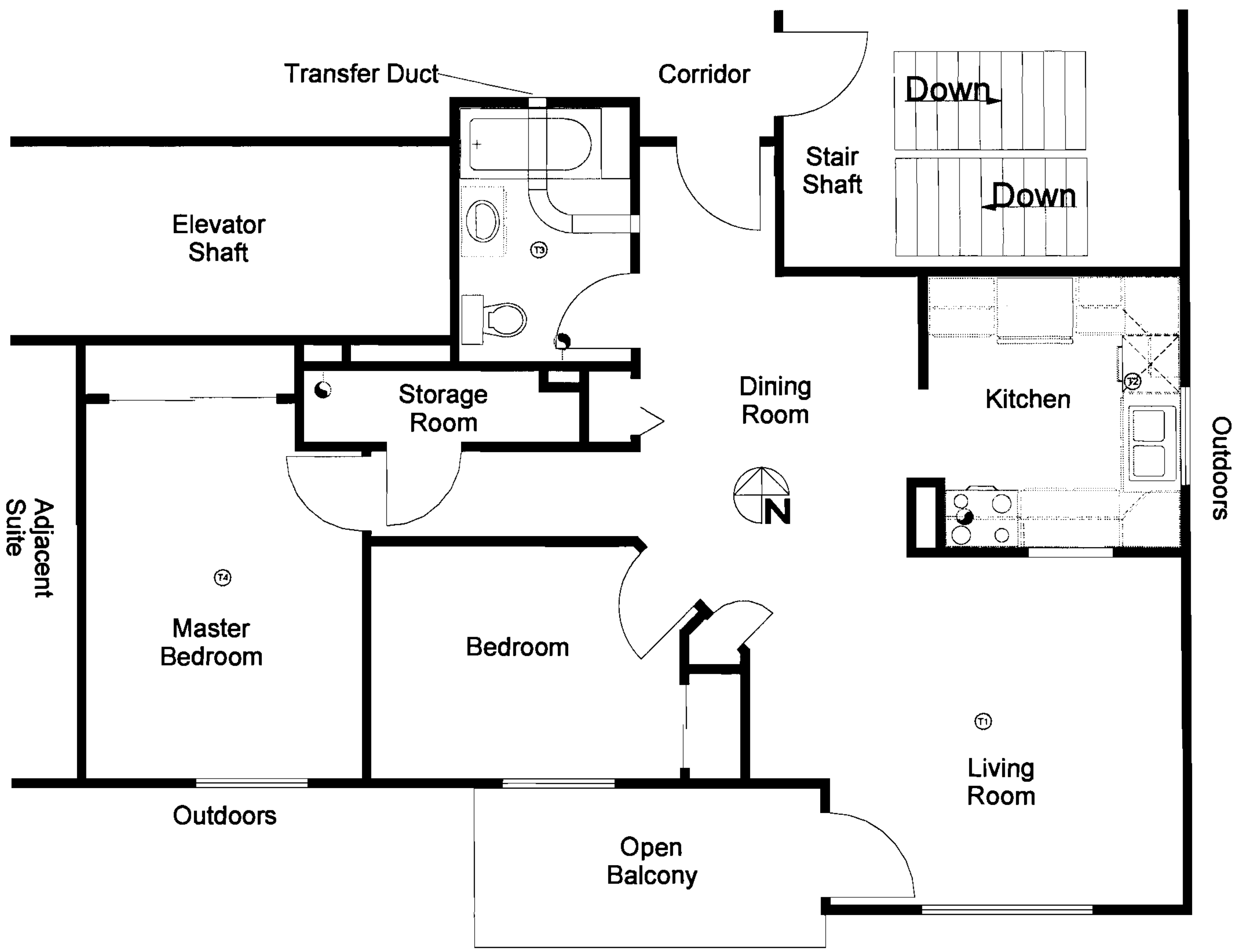

Figure C.9: Floor Plan of Test Suite in Building 9

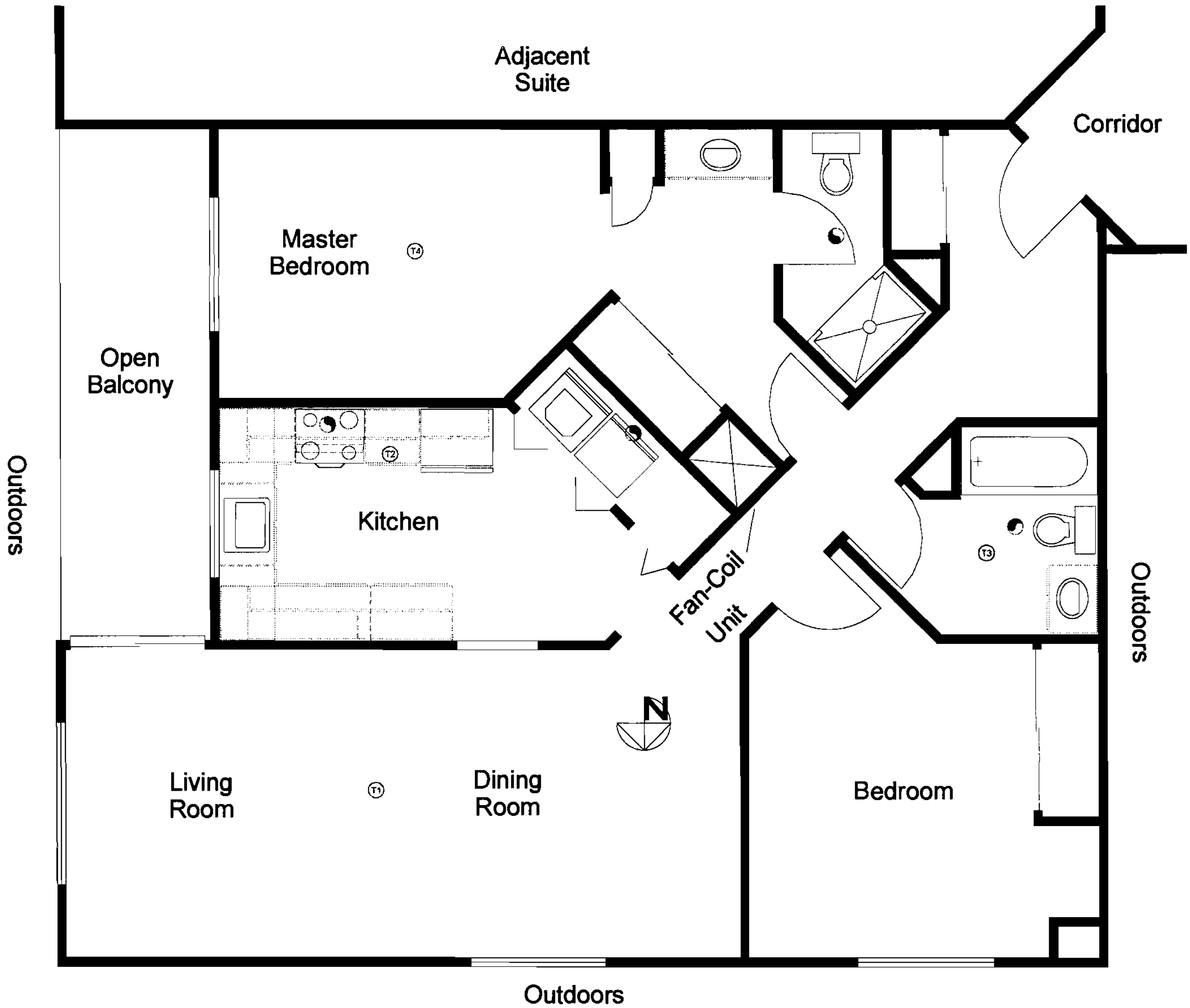

Figure C.10: Floor Plan of Test Suite in Building 10