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Controlling Stack Pressure in High-Rise Buildings by Compartmenting the Building

Presented to:

Jacques Rousseau
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High-Rise Innovation Center
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Canada Mortgage and Housing Corporation

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REPORT

Controlling Stack Pressure in High-Rise Buildings by Compartmenting the Building

Presented to:

M. Jacques Rousseau
Project Manager
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Canada Mortgage and Housing Corporation

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EXECUTIVE SUMMARY

An investigation was conducted of the effect of decreasing the air leakage area across internal partitions of a typical modern high-rise apartment. The objective of this work was to study the practicality of increased compartmentalization or separation of the living units from each other and from the corridors and vertical shafts in the building.

Typically, the main barrier to air movement through a high-rise apartment building is the exterior skin or envelope. Walls and doors between corridors, units, and elevator shafts and stairwells are much less airtight, and significant volumes of air can move between these different areas of the building interior under relatively small pressure differences.

Some disadvantages of this arrangement are that individual occupants can affect air movement through the entire building by leaving windows or balcony doors open in their units, odours and pollutants produced in one area of the building may be transferred to other areas, exterior walls and windows have large pressure differences across them which drives air and rain through any defect, and special measures to control smoke migration during fires must be provided.

The objectives of this study were to measure the actual pressure differences across various separations within a high-rise apartment building, to generate and analyze potential ways of reducing the air leakage through these separations, and to draw conclusions on their effects on air movement in the building, including changes in operation of typical current ventilation strategies and fire and smoke control measures.

A 12-storey condominium building in Nepean, Ontario was selected as the test case for the measurements. Measurements of pressure difference across 18 different partitions in the building were made under cold weather conditions, with doors across some of the separations opened and make-up air fans either operating or switched off. A total of 20 measurement sets are presented. The airflow rates through the make-up air vents on each corridor were also measured.

A computer simulation model of the airflow network within the building was developed using the CONTAM93 program. The simulation model was calibrated so that the simulated pressures and airflows matched those measured in the building.

The doors were determined to represent the element of the interior partitions which could be improved most reliably and simply. Doors are often supplied as manufactured units, prehung in frames, and much scope is possible for improving the airtightness of the manufactured product. It was felt that the best modern technology could produce interior doors providing 1/4 the leakage of the tightest doors commonly found in high-rise residential buildings.

The effect of installing such tight doors in existing buildings was simulated. Three compartmentalization strategies were simulated, as follows: separating the units from the corridors, separating the corridors from the vertical shafts, and a combination of the first two. Separating the units from the corridors was found to have greater effects than separating the corridors from the shafts, but the combination of the two measures was nearly additive and created the greatest differences from the base case in air movement and pressure differences across building elements.

Pressure differences across interior doors were increased by compartmentalization, while pressure differences across the exterior skin were reduced but not as much as expected. Exterior skin pressure differences could be reduced more by reducing the flow rate of the corridor pressurization fans. The combination strategy spread pressure differences across greater numbers of partitions, so that the peak pressure differences across interior doors were smaller with this strategy than the other two. Pressure differences across interior doors under severe conditions were less than half of the maximum level allowed for safety in fire exits, but would be noticeable to residents; door closers would mitigate this.

Unit ventilation is more uniform under compartmentalization. Units on lower floors receive more total air and more of their air from the corridor, with essentially none from infiltration. Units on upper floors receive less total ventilation, and a greater proportion of their air is from the corridor ventilation system; virtually none is from the garage via elevator shafts and stairwells. There is very little movement of air between different locations in the building; virtually all air enters the building through the corridor ventilation fans, is fed into the corridors, leaks into the units and the shafts, and exhausts to outside.

Total air leakage, and airflow through the corridor ventilation system, is reduced by up to 14 % by the combination strategy. Peak loads and required heating and cooling capacities are reduced by the same amount. The existing corridor ventilation fans were found to provide more than enough building pressurization, and corridor ventilation flow rates could be further reduced without much impact on the benefits of compartmentalization.

Further research is suggested to better quantify the benefits achievable in existing high-rise residential buildings. A program to encourage the manufacture and installation of more airtight interior doors is also put forward. For new residential buildings, revised ventilation systems are recommended, which deliver ventilation air directly to each unit, in order to allow full sealing of entrance doors between the corridors and the units.

Résumé

Une enquête a été menée sur les effets résultant de la diminution des zones de fuites d'air entre les murs de séparation d'une tour d'habitation moderne typique. Ce travail avait pour but d'étudier le bien-fondé d'une plus grande compartimentation ou de la séparation des logements entre eux et par rapport aux couloirs et aux vides techniques de l'immeuble.

De manière générale, l'enveloppe extérieure, ou revêtement, constitue la principale barrière au passage d'air dans une tour d'habitation. Les murs et les portes entre les couloirs, les logements, les puits d'ascenseur et les puits d'escalier sont beaucoup moins étanches, et des différences de pression relativement faibles peuvent provoquer d'importants déplacements d'air entre ces différents espaces à l'intérieur de l'immeuble.

Cet aménagement comporte certains désavantages : les occupants peuvent modifier la circulation d'air de tout l'immeuble en laissant les fenêtres ou les portes de balcon ouvertes dans leur logement, les odeurs et les polluants peuvent circuler d'un endroit à l'autre de l'immeuble, d'importantes différences de pression sur les murs extérieurs et les fenêtres laissent passer l'air et la pluie par la moindre défectuosité, et des mesures spéciales doivent être prises pour contrôler la propagation de la fumée en cas d'incendie.

L'étude consistait à mesurer les différences de pression entre diverses séparations dans une tour d'habitation, à concevoir et à analyser des moyens possibles de réduire les fuites d'air par ces séparations, et à tirer des conclusions concernant leurs effets sur la circulation d'air dans l'immeuble, incluant la modification du fonctionnement des types de ventilation utilisés de même que des mesures visant le contrôle du feu et de la fumée.

Un immeuble d'habitation en copropriété de 12 étages à Nepean (Ontario) a servi de cas type. On y a mesuré les différences de pression sur 18 différentes cloisons dans l'immeuble par temps froid, avec les portes ouvertes dans certaines séparations et les ventilateurs d'air d'appoint en marche ou éteints. En tout, 20 séries de mesures sont présentées. On a également mesuré les taux de circulation d'air dans les bouches d'aération d'appoint de chaque couloir.

On a établi par simulation informatique un modèle du circuit de circulation d'air dans l'immeuble à l'aide du programme CONTAM93. Le modèle de simulation a été calibré de sorte que les pressions et circulations d'air simulées correspondent à celles qui avaient été mesurées dans l'immeuble.

Il a été déterminé que les portes représentaient l'élément des murs de séparation qui pouvait être amélioré avec le plus de fiabilité et de facilité. Les portes sont souvent livrées d'une pièce, déjà fixées aux cadres, et il est possible d'améliorer considérablement l'étanchéité à l'air du produit manufacturé. Les techniques les plus modernes permettraient de fabriquer des portes intérieures laissant filtrer le quart de l'air que laissent passer les portes les plus étanches qu'on trouve actuellement dans les tours d'habitation.

On a simulé l'effet que produirait l'installation de portes aussi étanches dans les immeubles existants. Trois stratégies de compartimentation ont été simulées de la façon suivante : séparer les logements des couloirs, séparer les couloirs des vides techniques verticaux, et une combinaison des deux. On a constaté que de séparer les logements des couloirs produisait plus d'effet que de séparer les couloirs des vides techniques, mais l'effet cumulatif des deux mesures combinées créait le plus de différence dans la circulation d'air et dans les différences de pression entre les éléments de l'immeuble comparativement au cas de base.

Les différences de pression sur les portes intérieures étaient augmentées par la compartimentation, tandis que les différences de pression sur l'enveloppe extérieure étaient réduites, mais pas autant que prévu. Celles-ci pourraient être réduites davantage en réduisant le taux de débit des ventilateurs de pressurisation des couloirs. La combinaison étendait les différences de pression à un plus grand nombre de cloisons, de sorte que les différences de pression maximales sur les portes intérieures étaient plus faibles avec cette option qu'avec les deux autres. Les différences de pression sur les portes intérieures sous de rudes conditions correspondaient à moins de la moitié du maximum permis pour la sécurité des sorties de feu, mais seraient perceptibles pour les résidants; des ferme-portes atténueraient cet effet.

La ventilation des logements est plus uniforme avec la compartimentation. Les logements des étages inférieurs reçoivent plus d'air en général et une plus grande proportion d'air du couloir, et à peu près pas par infiltration. Les logements des étages supérieurs reçoivent moins d'aération dans l'ensemble, et une plus grande proportion de leur air provient du système de ventilation du couloir; il n'en arrive pratiquement pas du garage par les puits d'ascenseur et d'escalier. Il y a très peu de déplacements d'air entre les différentes parties de l'immeuble; presque tout l'air entre dans l'immeuble par le système de ventilation des couloirs, est poussé dans ces derniers, s'infiltre dans les logements et les vides techniques, et s'échappe à l'extérieur.

Grâce à la combinaison, la fuite globale d'air et la circulation d'air dans le système de ventilation des couloirs sont réduites dans une proportion allant jusqu'à 14 %. Les charges maximales, de même que les capacités nécessaires de chauffage et de refroidissement sont réduites d'autant. On a constaté que les systèmes existants de ventilation des couloirs fournissent une pressurisation de l'immeuble plus que suffisante, et les taux de débit de ventilation des couloirs pourraient être réduits encore davantage sans grand effet sur les avantages de la compartimentation.

Il est proposé de pousser davantage la recherche afin de mieux quantifier les améliorations possibles dans les tours d'habitation existantes. Un programme visant à encourager la fabrication et l'installation de portes intérieures plus étanches à l'air est aussi suggéré. Pour les nouveaux immeubles d'habitation, nous recommandons la révision des systèmes de ventilation dans l'optique d'une aération directe dans chaque logement, ce qui permettrait le scellage complet des portes entre les couloirs et les logements.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

1. INTRODUCTION

Air movement through high-rise apartment buildings is believed to have considerable impact on building performance, in the areas of occupant comfort, energy consumption, Indoor Air Quality (IAQ), and deterioration of exterior envelope components such as walls and windows. Studies of energy use in high-rise buildings have shown that they use as much energy as comparable low-rise housing, although the ratio of exterior surface area to living area is much lower in high-rise buildings; much greater uncontrolled air movement through high-rise buildings is believed to account for the difference. Cold outdoor air leaking into apartments during the winter makes them uncomfortable and can lead to safety hazards as occupants use portable heating devices to try to warm these areas. Where heating costs are billed separately, the occupant of the unit where cold air leaks in, pays to heat it; this air then moves through the building to other units, carrying with it any humidity, pollutants and odours it may have picked up. Where it leaks out through the building structure, condensation or frost buildup may occur and damage the wall and furnishings nearby.

Previous studies of high-rise residential buildings have identified that most buildings have significant air leakage areas in their envelopes, and work is continuing to better define the energy cost of this leakage. It is increasingly recognized that the major continuous driving force behind air leakage is due to buoyancy or stack effect, which causes air to enter at the bottom of the building and exit at the top during cold weather. This air must move up through vertical shafts and openings in the building, such as stairwells, elevator shafts, service shafts, and garbage chutes.

The traditional approach to reducing infiltration has been to seal the exterior skin or envelope of the building against air leakage. This works well in office buildings, where there are very few required openings in the envelope above the ground floor. In high-rise apartment buildings, maintaining the exterior skin airtight is difficult due to the large number of opening windows and doors. These are often poorly sealed when closed, and can be left open by occupants.

An alternative that has been suggested for apartment buildings is to seal the floor openings where air moves up through the interior of the building. This is a departure from normal practise, and has not been investigated in the field in a controlled way. It is not clear how the sealing of the shafts and holes in a typical high-rise building could be done, both during the design phase, and as a retrofit of an existing building. Some potentially unacceptable side effects of this approach are that doors, including elevator and fire exit doors, might become very difficult to operate, and the design of the typical corridor make-up air supply system may be unsuitable.

In response to a suggestion from the NHRC Working Group on High-Rise Buildings, CMHC requested proposals to carry out a preliminary study of the feasibility and side effects of compartmenting high-rise residential buildings to a much greater extent than is current practise. The objectives of this study were to:

- *Measure the actual pressure differences across various separations within high-rise apartment buildings, during various operating conditions and weather.*

- *Generate and analyze potential methodologies for air sealing the various separations, making use of knowledge gained during the course of research on fire and smoke control, carried out by Dr. Shaw of the National Research Council.*

- *Draw conclusions on the changes that would be required to building systems to ensure appropriate ventilation, fire and smoke control, and operation of other building systems in a compartmentalized building under all operating and weather conditions.*

Morrison Hershfield Ltd. was selected to carry out this work. The proposed approach was to concentrate on matching measurements of pressure differences in high-rise apartment buildings with computer simulations of air flow and pressure difference; the computer models can then be used to greatly enhance the understanding of the effects of compartmentalization on stairwells, elevator shafts, and ventilation systems. This will allow restricting costly field testing to only the most promising situations.

2. APPROACH AND METHODOLOGY

2.1 Compartmentalization Strategies

While the Request for Proposal specifically mentioned "compartmenting the floors" of high-rise apartment buildings, there are in fact three sets of interior compartments within the typical high-rise apartment building, comprising:

- Perimeter walls, floor, and ceiling of each apartment form the boundaries of one set of compartments, the living units. They have windows that can be opened to the outside, and doors which connect to the corridors and are opened occasionally to allow access. Depending on the specific building, they may have washroom exhaust via a central system or via individual exhaust ducts to the outside. Dryer exhaust ducts and kitchen fan exhaust ducts may also be found in units so equipped.

- The corridors form another set of compartments, having many interconnections between the other sets of compartments, but typically little or no boundary exposed to outdoors. Air moving through the building under wind pressure typically must pass through a corridor at some point. Most of the interconnections of the corridors to other compartments are in the form of doors, of which at least one is open a significant proportion of the time. Typically, a ventilation system supplies air to the corridors, which is intended to pressurize them above the level of other compartments. This has the benefits of preventing smoke and odours from moving out of the units, and of providing ventilation air to the units via leakage under the doors.

- The vertical shafts form a third set of compartments. Some such as the elevator and stair shafts may be interconnected only to the corridors; others such as the pipe and electrical chases may be interconnected to both the units and the corridors. Some of these shafts may have significant openings to outside at top and/or bottom. Most of the air leakage moving through the building under stack effect will travel through one of these shafts at some point.

The typically large number and total area of interconnections between the three sets of compartments means that there is significant flow from one set to another under small pressure differences. In improving the compartmentalization, we wish to increase the pressure difference taken over the boundaries between compartments, as a proportion of the total pressure difference imposed by stack effect, wind pressure, and the building ventilation system. Of these forces, it is believed stack effect produces the largest continuous force moving air through the building, at least during cold weather.

The compartmentalization sealing strategy seeks to isolate the living units from other compartments so that they equalize pressure with the exterior; there is then no driving force to cause air leakage to or from outside. This can be done in the following ways:

- Isolate the units from each other and from the corridors and shafts they are connected to, but do not isolate the corridors from the shafts. This is called "unit compartmentalization" in this report.

- Isolate the units from each other and from the shafts, and isolate the corridors from the shafts, but do not isolate the units from the corridors. This is called "floor-by-floor compartmentalization" in this report.

- Isolate the units from each other and from the corridors and shafts, and isolate the corridors from the shafts also. This is called "double compartmentalization" in this report.

Each of these options brings potential benefits and potential problems. In the first option, a large proportion of the pressure difference will be taken over the doors connecting the units to the corridors; this will make them more difficult to open or close, and may produce annoying whistling at any defects. The second option transfers this problem to the elevator and stairwell doors at each floor. The third option splits the pressure difference across both sets of doors, but increases the amount and cost of airsealing required. In the first and last options, with the typical apartment ventilation system, the make-up air delivered to the corridor cannot be assumed to replace air vented through individual exhausts in the units, and make-up air would have to be delivered directly to each unit either by a dedicated supply or by leakage through the envelope. In the second option, the lack of a seal between units and corridor will allow air movement between units on the windward side and units on the leeward side under high wind pressure.

It is likely that the best choice of strategy will vary with the characteristics of the building, its site, and its mechanical system. Our approach allows investigating each of these strategies and developing some recommendations for selecting a strategy given the characteristics of the building and the budget.

2.2 Building Selection and Set-Up for Measurements

High-rise residential buildings, with residents constantly coming and going, can be difficult to set-up and carry out field testing in. The following describes some of the requirements with respect to building selection and set-up for the field measurement portion of this project.

The work plan was based on taking all measurements when the condition of all doors and windows (open or closed) was known, the elevators were not moving in their shafts, and the weather was appropriate. In terms of weather, our approach included measurement sets taken in cold weather in both windy and calm conditions, with the corridor make-up air system operating and shut off, so that there are measurements on the same building under four combinations of operating conditions and weather. Our methodology called for doing the measurements between the hours of 1 A.M. and 5 A.M., and allowed quick measurement of a large number of pressure differences using pressure tap tubing led from each location of interest to a central measurement site and using two micromanometers at one time to make the measurements; thus minimizing the possibility that doors are opened or elevators operated by occupants during the measurement. This methodology also made it relatively easy to find a suitable building in the Ottawa area, as a minimum of occupant disruption was required.

A key characteristic of any internal compartmentalization strategy must be that it will not cause undue problems in operation of any other building systems under any normal building condition. In high-rise apartment buildings, one or more doors connecting various compartments will be open a significant proportion of the time as people enter and exit the building and their floors and units. It makes sense to make measurements of pressure drop across partitions under a number of different possible scenarios of door openings, as well as the most typical situation of all doors being closed. Our approach was to select and set-up the building such that we were able to make pressure difference measurements under the following building conditions:

- All doors closed
- Garage door open. In this building, the garage exhaust fans are controlled by a Carbon Monoxide (CO) monitor, and are off most of the time. We felt that the garage door did not need to be open completely, as the garage pressure would equalize with outside under only a partial opening; for security reasons this measurement was made with the service garage door open 300 mm. at the bottom.
- Lobby door to outside open, all others closed
- Elevator at lobby level, elevator doors open, all other doors closed
- Doors connecting lobby to 1st floor corridors open, all other doors closed.

This has provided useful data not just on the typical condition, but on a large number of the variations in pressure difference that occur across internal partitions during the normal use of the building.

2.3 Determining Effects of Strategies on the Functionality of Building Systems

It is evident that compartmentalizing the building will have a significant effect on some of the building functions. In most high-rise apartment buildings a portion of suite ventilation is provided by pressurizing the corridors using a central corridor make-up air system; this air leaks into the individual units often under the doors, and replaces stale air exiting the unit through bathroom and kitchen exhausts and through leaks in the windows and walls. Sealing the units from the corridor in order to better compartmentalize them may reduce the functionality of this system, and suites would depend more on the in-suite systems.

Better compartmentalization would limit the spread of smoke between the compartments of a building, but might inhibit the operation of some typical systems for smoke control. The effects of compartmentalization on the building during a fire emergency would need to be carefully evaluated to ensure that conditions are not degraded.

The easy operation of doors is an important facet of building functionality. Doors that are used frequently, such as lobby doors, elevator doors, and unit doors, are very annoying when a lot of effort is required to open them, or in elevators when they stick and will not close completely. Doors that are difficult to open or difficult to close are even more of a liability during an emergency situation. Some idea of the effects of each compartmentalization strategy on door operation is required in order to ensure that these effects are managed to minimize problems.

Our approach to analyzing these effects was to develop a computer simulation of the target building using the CONTAM93 program, with which we can make changes to the leakage area between each compartment of the building and determine the changes in pressure difference across all partitions. CONTAM93 is a development of the AIRNET program, written by George Walton of the National Institute of Standards and Technology (NIST) of the United States. It is a multiple-zone, multiple floor airflow network analyzer which is able to model stack effect, wind effect, and mechanical pressurization due to ventilation systems. Morrison Hershfield made extensive use of AIRNET to model airflows and pressure differences within a high-rise office building, as part of ASHRAE Research Project 661 on Stack Effect in Tall Buildings.

In order to develop the input files for the CONTAM93 program, the various zones and the air leakage areas between them were defined using the building plans and data from walk-through inspections of the building. This data can be further calibrated using the measured pressure differences. Once a reasonable representation of the building as measured had been produced, the effects of compartmentalization were simulated by reducing or eliminating the leakage areas between some of the building elements. The CONTAM93 program output shows not only the pressure differences but the airflows between each zone, which is useful in determining the effect on ventilation, humidity, and indoor air quality of the compartmentalization strategies. The CONTAM93 program contains a capability to trace the movement of pollutants through the various zones of the building; although that has not been used in this project, such studies can easily be carried out using the simulation file.

CONTAM93 provides a graphic user interface which much improves the process of making changes to the simulation, both in terms of time and of error-checking.

2.4 Effectiveness of Sealing Measures

As a good number of the connections between compartments are intended to be opened and closed on a regular basis, it is unlikely that perfect seals will be obtained through any measure, short of complete replacement of every door with an airtight design. The choice of measures for sealing opening doors will have to balance the quality of the seal when closed, to the ease of using the door and the cost of sealing; some leakage area will remain.

Those leakage areas that are hidden in pipe and wiring chases may be more difficult to access in order to seal them, but are easier to seal permanently airtight as there is little or no movement of the seal required. However, the common use of concrete block partition walls is a difficult sealing problem to address in existing units, as the block itself is relatively porous and there are often large gaps between the top of the wall and the floor slab above. Thus the drywall finish of a unit may be required as the compartment air barrier, and will require careful sealing at all floor-wall joints and electrical/pipe penetrations. The degree of airtightness achieved and the cost of doing so are likely to vary significantly among buildings due to differences in construction quality, materials, systems, and techniques. These characteristics make this element difficult to simulate.

It is very difficult to improve the sealing of elevator doors once installed, because of their sliding action and requirements of the Elevator Safety Code on maximum power of door closers. However, this is an area that should be investigated in further detail by the elevator manufacturers, each of whom has a proprietary door design. Changes in door design which provide better sealing of the doors when closed is an approach to improving floor compartmentalization which avoids the extra cost and inconvenience of providing vestibules around elevator lobbies on each floor.

Based on the airflow results from the calibrated simulation, we concluded that leakage through doors, both standard doors and elevator doors, represented the majority of leakage area between shafts and corridors, and between corridors and units. By reducing the leakage area of the doors alone, the units and floors could be compartmentalized such that the unit leakage area to outside was significantly greater than that to the corridor, and that leakage area between the shafts and the corridors was roughly equal to leakage area between the corridors and the units. Our investigation of compartmentalization was therefore based on the degree of airtightness achieved by replacing the appropriate doors with what we consider to be “Best Currently Feasible” doors with respect to air leakage when closed. This involves reducing the leakage rate of doors and elevator doors to one quarter of the rate for a good quality door currently used for interior applications.

3.0 FIELD MEASUREMENTS

3.1 Test Building Description

The following selection criteria were developed for the test building:

- The building should be 10 to 20 storeys in height. This allows enough height to generate measurable pressure differences between top and bottom on cold days, but is not so high that co-ordination between measurements at the top and at the bottom of the building is too difficult. It also represents the majority of high-rise residential buildings which might benefit from compartmentalization.

- The building should contain an enclosed underground garage. This allows field measurement of both types of buildings; those with underground enclosed garages, and those without, because by opening the garage doors, the garage pressure is equalized with outdoors as it would be with no enclosed parking garage. This also allows simulation and measurement of airflow from the garage area into the building, for the purpose of analysing movement of contaminants into the building from the soil and from the garage.

- The building should be relatively new. The measurements are more likely to reflect current practise, building materials and systems; they will thus be more relevant for application to designs of new buildings. In particular, the greater emphasis placed on minimizing smoke movement in newer buildings means that compartmentalization should be easier to achieve, because the doors will be a greater proportion of the total leakage area between zones. Also, the windows in newer units are better performance and are generally in much better condition than those in older buildings; this results in a tighter envelope, making it more difficult to achieve the objective of pressure-equalization of the units with the outside air. We also wanted to avoid buildings having central washroom and kitchen exhaust systems, as they are less common in new buildings and they act against the concept of compartmentalization by connecting the units to each other and the outside via a vertical shaft.

- As the simulation requires area takeoffs of every zone within the building, data on the construction types of zone separations (concrete block, drywall on steel stud, cast concrete, etc.) and on the mechanical systems such as fans and ducts, a complete set of architectural and mechanical plans was a requirement.

In the process of selecting a test building, we contacted four property management organizations and inspected three buildings offered by them as subjects for the study. The building selected met all the above criteria, and its management and owners were happy to participate and cooperate in the study. It is located in Nepean, Ontario in a mixed residential - retail neighbourhood. The building was completed in 1990, and is owned by a condominium corporation, and most units are owner-occupied. It contains nearly 200 condominium units on 12 floors, with two levels of underground enclosed parking below. It is a fully-electric building, with central air conditioning provided through the corridor ventilation systems. Its exterior envelope area is approximately 9,200 m^2, and approximately 25 % of the wall area is glazed.

Figure 3.1 shows the floorplan for Parking Level 1 at the building. The elevator shaft contains three passenger elevators, one of which can also be used as a freight elevator. The elevator doors and the stairwell doors are surrounded by vestibules, which are connected to a vestibule pressurization fan system. This fan is controlled by the parking garage Carbon Monoxide monitor, and is normally off. We have assumed that when the fan is off, the outside air dampers for this system seal perfectly and no air enters from outside. It thus acts to equalize pressure among all the vestibules.

The steel-frame doors from the vestibules to the parking garage are weatherstripped; the doors to the storage lockers and to the stairwell are not weatherstripped and have significant leakage area. Parking garage air is able to reach the vestibules easily through the storage lockers.

The garbage room is connected to the elevator vestibule by a well-fitted door, and to the parking garage by a pair of doors which allow access for the container to be rolled out to the service garage door. The garbage exhaust fan runs continuously and draws from the garbage room, into which the garbage chute empties.

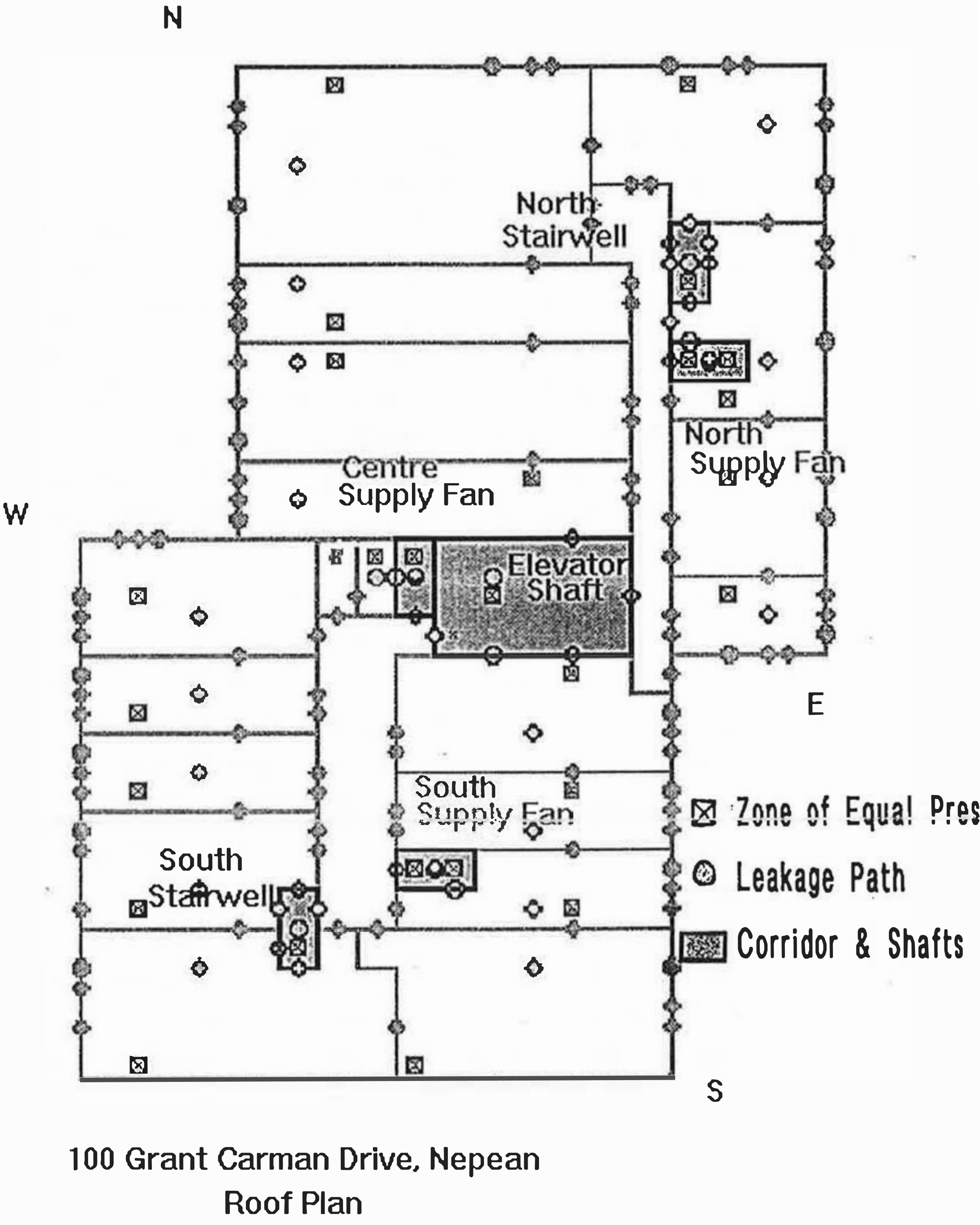

Figure 3.4

Roof Plan - Test Building

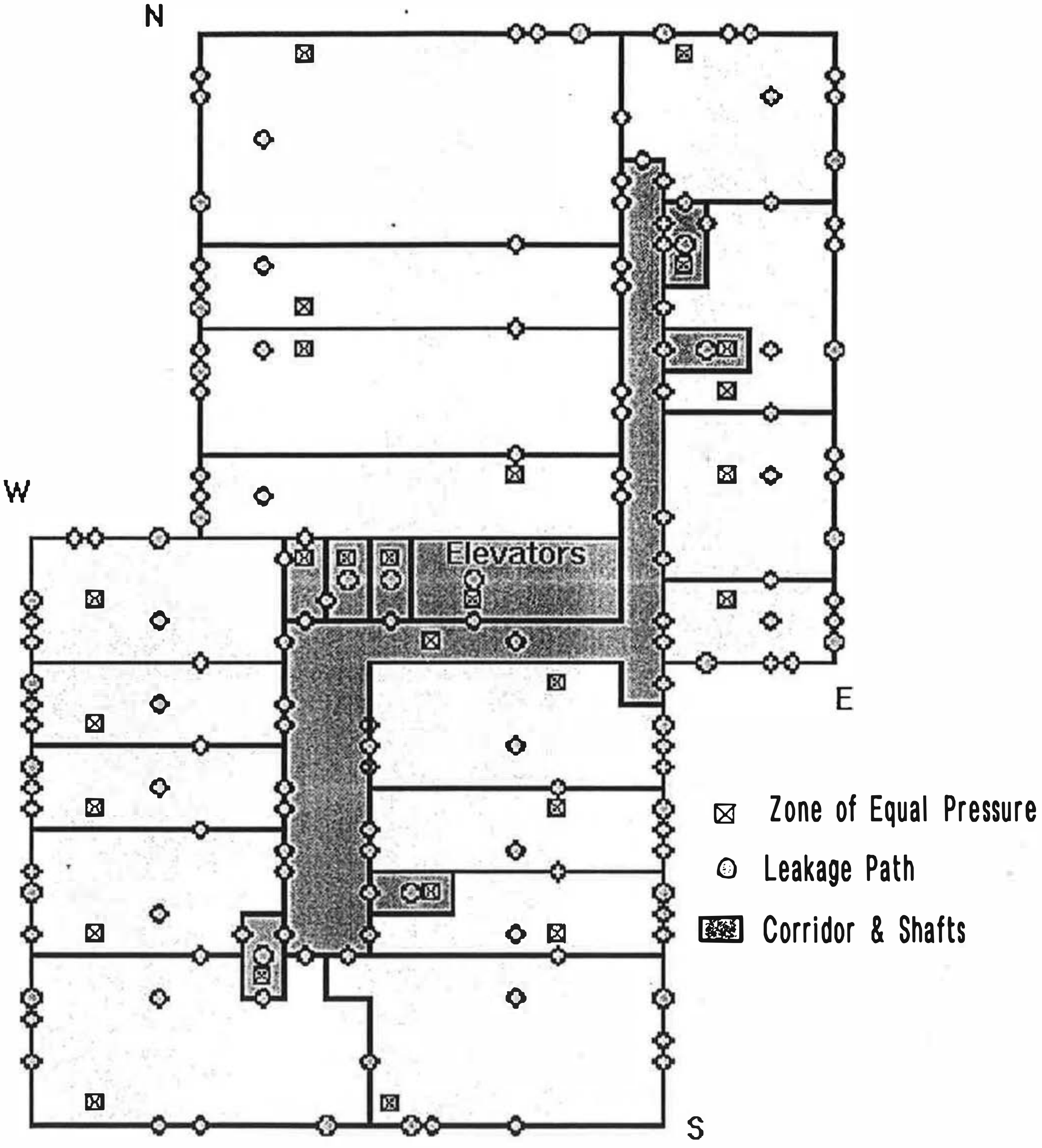

Figure 3.3

Typical Floor Plan - Test Building

Figure 3.3 shows the floor plan for a typical floor containing 17 units. The majority of these are two bedroom units but along the South wing there are 4 one bedroom units. These have smaller numbers of windows and fewer exhaust fans than the two-bedroom units, especially the corner units. They have the same unit door and approximately the same corridor wall length as the two bedroom units, so we can expect these units to show smaller pressure drops across their entrance doors and larger drops across their exterior walls, as their corridor leakage area will be a larger percentage of the total than in other units.

The corridor ventilation system airshafts and the grilles connecting them to the typical corridor are shown as shaded areas, along with the garbage room and chute, the elevator shaft and the stairwells. All are connected to the corridor; the stairwell shafts and garbage room are connected to the adjacent units via leakage area through their concrete block walls. The elevator and ventilation shafts are assumed to have negligible leakage area into adjacent units, as they are precast concrete or metal-lined shafts.

Figure 3.4 shows the roof plan. The stairwell tops are precast concrete, with access to the open flat roof through a weatherstripped steel door. Each supply fan has an intake grille and filtration which uses a significant portion of the fan's available static pressure. The elevator shaft is precast concrete but is penetrated by an emergency pressurization fan system, which operates only when a fire is detected. Above the elevator shaft is the elevator machinery room, accessed via a weatherstripped steel door from outside. Six tension cable holes of about 100 cm^2 each, and six guide cable holes of about 50 cm^2 each, connect this room to the elevator shaft below.

3.2 Measurement Methodology

In order to be able to make measurements of pressure differences across building partitions when conditions were appropriate, we installed pressure taps and tubing to allow all measurements to be made in the North stairwell; with one micromanometer located at ground level and a second micromanometer at the 12th floor level. The building was outfitted with 18 separate pressure taps, as follows:

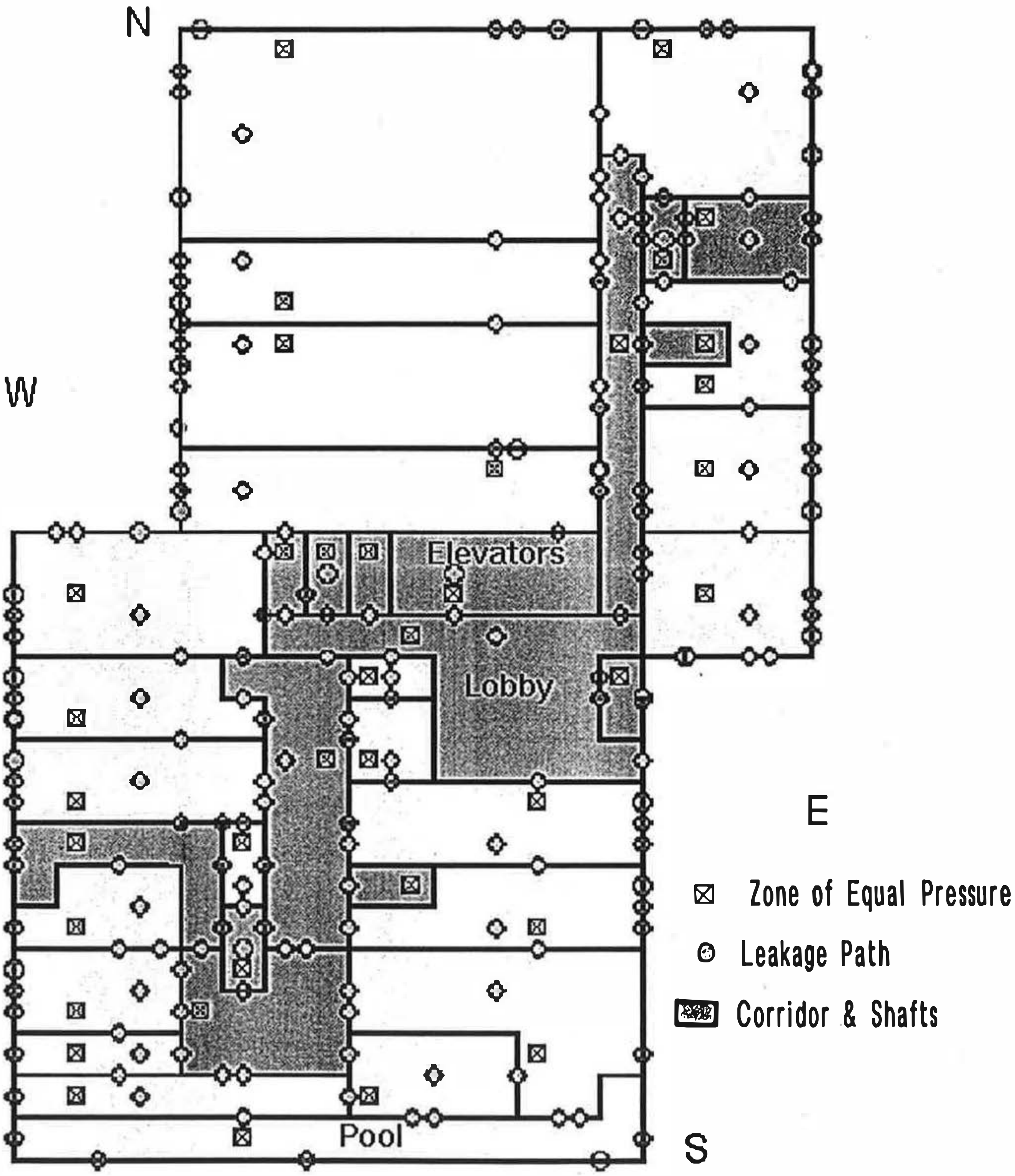

Figure 3.2

Ground Floor Plan - Test Building

On Parking Level 1, there is a room behind the elevator shaft which is used to store furniture and goods during moving. This room has its own elevator door, allowing use of the freight elevator; it is also connected to the parking garage through an exhaust fan which is manually-controlled, normally off and does not have a shut-off damper. Air from the parking garage can move through this fan and room to the elevator shaft, bypassing the vestibules.

The parking garage has two large vehicle doors and four man-doors opening to outside. The main vehicle access door is located on the East side at the North end of the parking garage. The service vehicle access door is used primarily for garbage pickup and is located in the centre of the West side of the garage.

There are a number of other connections between the parking garage and outside which provide air leakage paths. The garage is fitted with a ventilation system which is Carbon-Monoxide controlled; four large exhaust fans draw air from the garage while the vestibule supply fan pressurizes the vestibules when the alarm level of Carbon Monoxide is exceeded. This system operates very infrequently; the exhaust fans are fitted with automatic dampers, but these do not provide a perfect seal when closed. There is also an emergency generator, which draws its cooling air from the garage and exhausts to outside, and the main electrical transformer which is cooled from outside. All of these require openings to outside through the walls and roof of the parking garage, resulting in a significant air leakage area between outside and the garage.

Figure 3.2 shows the floorplan for the ground floor of the test building. The main entrance door leads into a vestibule which is poorly sealed from the lobby. The ground floor corridors are also separated from the lobby by doors and partitions which have significant leakage area at the bottom. At the South end of the ground floor is the indoor pool and party area. Separate fire exits are provided from each stairwell. The stairwell doors are standard steel leaf and frame without seals or weatherstripping. The unit doors are wood leaf in frame and are much tighter fitting, especially at the sill, although there is no weatherstripping. The garbage chute is accessed via a small room off the lobby; the chute door is steel and quite tightly fitted

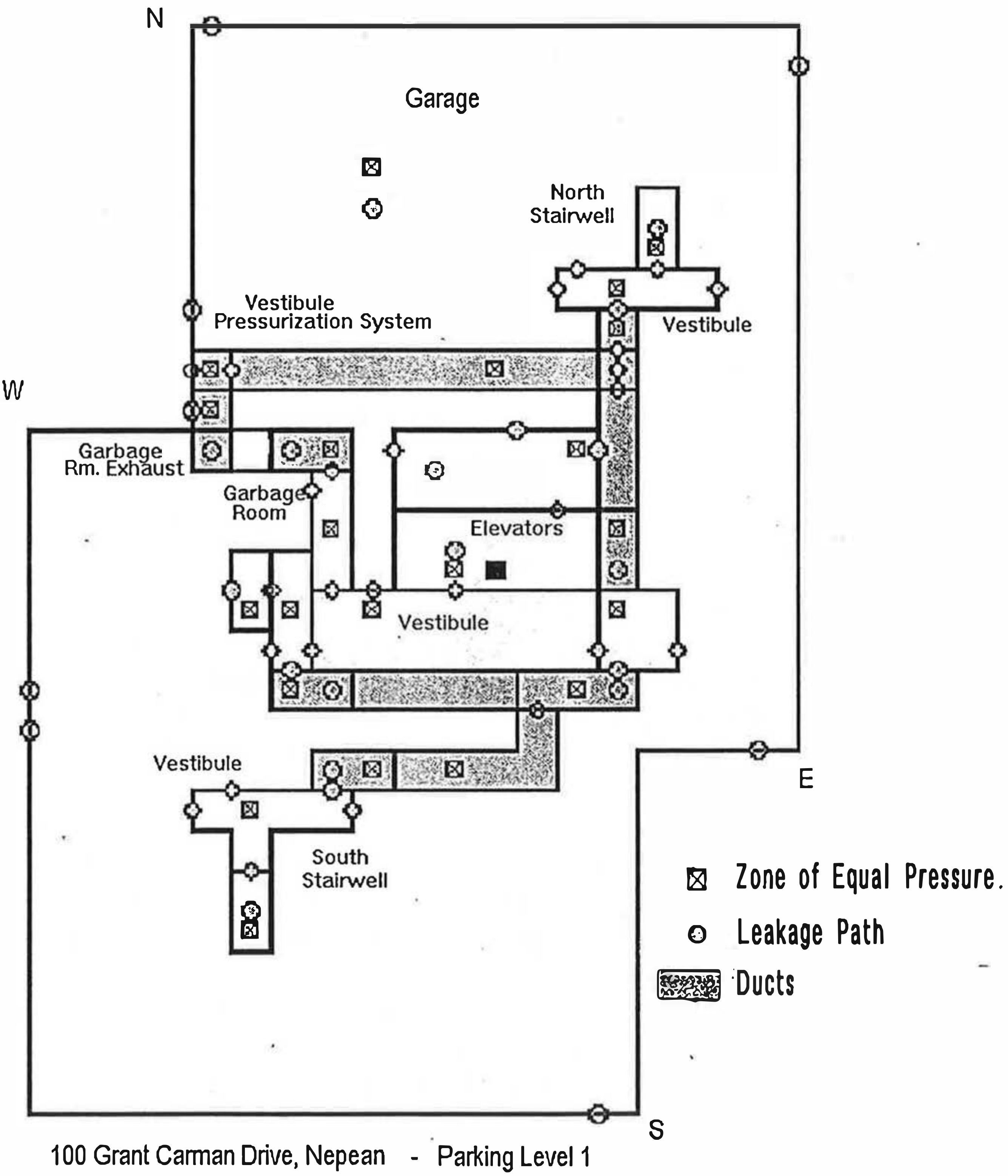

Figure 3.1

Parking Level 1 Floorplan - Test Building

12th Floor	Ground Floor
Roof	Ground Floor, North Corridor
Elevator Machine Room	Lobby Vestibule
Elevator Shaft	Lobby by elevators
12th Floor Corridor	North Corridor Ventilation Grille
12th Floor Garbage Room	Unit 103
Unit 1212	Unit 111
Unit 1202	Garage
12th Floor North Ventilation Grille	Garbage Room and Shaft
	Outside - East Side
	Outside - West Side

We used 1/8" dia. HDPE tubing, which had to be treated with care in order to avoid kinks. The pressure taps consisted of plastic tee fittings with barb ends; the tube was fitted on the base of the tee; this arrangement minimizes dynamic pressure effects on the measurement due to wind or air movement near leakage areas. Pressure lines were led under doorways and other obstructions using 1/16" dia. copper tubing.

Measurement sets were made on two different days having differing weather conditions. The first set was taken on Feb. 15, 1995, between the hours of 1:30 A.M. and 5. 00 A.M. At 12 A.M. the Airport weather office reported -10 °C and winds from the South at 11 km/h. The measured conditions at the test building were -9.6 °C and winds at 6.5 km/h at ground level. The second set was taken on March 3, 1995, between 2:00 A.M. and 4:30 A.M. The Weather Office reported -13 °C and winds from the South at 9 km/h at midnight; conditions measured at the building were -12.5 °C and 4.6 km/h at ground level at 1 A.M.

Measurements of the pressure differences at each of the 18 taps were taken under each of the following conditions:

Measurement Set	Building Condition
1	Vent. Fans On, All Doors Closed
2	Vent. Fans On, Lobby Entrance Door Open
3	Vent. Fans On, Lobby/Corridor Door Open
4	Vent. Fans On, Elevator Door Open at Lobby
5	Vent. Fans On, Parking Garage Door Open 300 mm.
6	Vent Fans Off, All Doors Closed
7	Vent Fans Off, Lobby Entrance Door Open
8	Vent Fans Off, Lobby/Corridor Door Open
9	Vent Fans Off, Elevator Door Open at Lobby
10	Vent Fans Off, Parking Garage Door Open 300 mm.

Electronic micromanometers were used to take the pressure difference readings. Once the building had been set up in terms of doors and fans, each of the taps was connected in turn to the signal port of the micromanometer; the reference port was left free, so that a reading of pressure difference between the tap location and the stairwell was measured and displayed. These were recorded along with the time the measurement was taken. These measurements are presented in Appendix A for the Feb. 15 measurements and Appendix B for the March 3 measurements.

Airflow measurements were taken using a Shortridge electronic flowhood placed over the discharge grilles. The readings are automatically compensated for backpressure of the device; however on the grilles of the centre corridor ventilation system, trim projection around the discharge grille prevented obtaining a perfect seal of the hood to the grille. The leakage area due to the projection was small compared to the throat area of the instrument, but this probably resulted in indicated measurements higher than actual flow, due to the backpressure compensation of the instrument being affected by the leakage.

3.3 Pressure Difference Measurements

The absolute pressure of the stairwell will change with each set of measurements depending on their effect on the flowpaths which include the stairwell; therefore, in order to interpret the measurements properly, they need to be referenced to a relatively stable pressure which is not changed by the changes made to the building. We have used the outside pressure at ground level as this reference. The pressure in the stairwell is essentially the same from top to bottom unless a large volume of air is flowing in it; according to the CONTAM93 program, the pressure at the top of the stairwell is about 0.1 Pa. less than the pressure at the bottom due to flow losses up the stairwell. By adding the pressure difference between the stairwell and the East outside pressure tap to all measurements, we can convert all measurements to reference pressures in each zone, which can then be compared across sets of measurements where the outdoor pressure has not changed. Appendices A and B report the measured pressure differences between each zone and the stairwell, and the reference pressure of the zone to outside at ground level, for each measurement set.

The pressure difference measurements divide naturally into two distinct sets: those with the ventilation fans on, and those with the fans off. The effect of fan operation is to pressurize the building significantly (by about 15 Pascals on average), so that the ground floor is under only minor negative pressure with respect to outside, and leakage of cold air into ground floor areas is minimal. Without the fans operating, the ground floor areas are subjected to negative pressures from 10 to 20 Pa., enough to drive significant cold air in through any leakage area.

The effects of opening doors in the building are largest for the garage door opening, but are much less significant than the changes due to the fan operation. The other door openings cause minor changes in pressure in zones in the immediate vicinity of the door.

3.4 Fan Airflow Measurements

Table 3.1 presents the measured data for airflow from the corridor ventilation grilles, with the corridor ventilation fans operating, measured on April 30, 1995.

Table 3.1
Measured Airflow Through Corridor Supply Grilles

	South Corridor		Centre Corridor		North Corridor		Total	
Floor	**Design**	**Msd.**	**Design**	**Msd.**	**Design**	**Msd.**	**Design**	**Msd.**
	litres/ sec.	litres/ sec.	litres/ sec.	litres/ sec.	litres/ sec.	litres/ sec.	litres/ sec.	litres/ sec.
1	137	117	375	301	215	269	727	687
2	137	125	375	327	215	271	727	723
3	137	169	375	334	215	251	727	754
4	137	177	375	292	215	256	727	725
5	137	177	375	304	215	240	727	721
6	137	153	375	327	215	241	727	721
7	137	184	375	297	215	210	727	691
8	137	319	375	225	215	208	727	752
9	137	160	375	276	215	212	727	648
10	137	161	375	261	215	180	727	602
11	137	123	375	216	215	156	727	495
12	137	103	375	191	215	134	727	428
Total	1644	1968	4500	3351	2580	2628	8724	7947

It is important to note that the measurements taken for the centre fan were obstructed by a piece of trim which prevented a good seal of the flowhood over the grilles. The measurements reported above for the centre fan are not compensated for backpressure and are likely about 10% to 20% low.

Overall, the fan flows are approximately equal to the design flows, which provide a make-up air flow into the corridor of about 43 litres/second per unit. It is notable that the vertical distribution of measured flow is not even; there is more flow at the lower floors and less at the upper floors; this would appear to be a balance setting chosen to increase pressure at the lower floors and decrease pressure at the upper floors. During cold weather, this would minimize cold drafts at the ground and lower floors. The fresh make-up air provided at the 12th floor drops to 25 litres/second per unit, which approximates the minimum recommended for a 100 m^2 suite according to ASHRAE Standard 62-1989, which calls for 0.35 air changes per hour in living areas.

The garbage exhaust fan flow was measured at 294 litres/second.

4.0 CONTAM93 SIMULATION

4.1 CONTAM93 Program

CONTAM93 is a multi-zone, multi-floor building airflow and contaminant analysis program package. It is the result of several years development of building airflow network simulation programs and contaminant analysis carried out at the National Institute for Science and Technology (NIST) of the United States.

CONTAM93 contains two programs. One is a graphic data input and processing program, the other is the network simulator which computes the airflows, pressure differences, and contaminant concentrations in each zone of the building. The user must develop a detailed description of all of the zones in the building and the connections between them, whether ducts and fans, doorways, or leakage areas.

The description of the building is created and edited using the SketchPad. This is a graphic array of cells which the user defines as the various elements of each floor level, whether walls, doors, zones, fans, or other connections. A simple graphic floorplan is displayed on the screen to establish the geometric and naming relationships of the relevant building features. Attached to the skatchpad are various data entry screens which allow quick definition of the flow-pressure-leakage area characteristics of the airflow connections between various zones of the building.

Some of the features of CONTAM93 are:

- A wide variety of different models for the airflow/pressure difference relationship are available, including leakage area, single-point and multiple-point measurements, two-way flow openings, and fans. Similar features such as doorways which appear in many locations in the building are defined once under a unique name, and referenced by name wherever they appear.

- Data is error-checked during input; this catches most input errors before carrying out any simulations.

- The graphical interface makes the simulation results much easier to display and understand.

- The simulation program is capable of solving very large networks of zones and connections in a minimal number of iterations, making use of a well-developed and tested algorithm. Both instantaneous and time-based simulations over 24 hours can be done, with steady or changing weather conditions and contaminant sources.

Some aspects of CONTAM93 which created difficulties in this work were:

- There is no model available to simulate devices containing backdraft dampers. The unit exhaust ducts in this building all contain backdraft dampers which close when outside pressure is higher than inside. This greatly reduces the leakage into the units on lower floors.

- There are no models for ducts, only for complete air handling systems, and definition of simple exhaust ducts or supply ducts is made difficult by the floor-by-floor layout of the graphical model. For areas having a lot of ductwork, a new level needs to be defined to avoid conflict with the floor areas of that level.

4.2 Input Data Development

The simulation model for the building was developed using the architectural and mechanical plans for the building, field measurements of some of the leakage areas between zones of the building, and published data on air leakage measurements of some typical building features. Relevant points are:

- The interior wall, exterior wall, window area, and zone volumes for each unit were taken from the architectural plans. The floor area for each unit was asssumed to be 100 m^2.

- Doors were classified into one of four categories as shown below:

Category	Crack Size	Leakage Rate
Weatherstripped	2 mm	100 l/s at 75 Pa.
Tight	3 mm	130 l/s at 75 Pa.
Standard	4 mm	180 l/s at 75 Pa.
Leaky	5 mm	240 l/s at 75 Pa.

- The following initial leakage values were used for typical construction:
  1.1 cm^2/m^2 for interior walls constructed of low-density concrete block,
  0.68 cm^2/m^2 for exterior walls (clay brick masonry) (Both from ASHRAE 1993 Fundamentals, Table 3, pg. 23.15)
  3.5 L/s per 100 m^2 at 6.8 Pa. for floor leakage (from Shaw's work at IRC)
  Door leakage numbers from ASHRAE 1993 Fundamentals, Fig. 11, pg. 23.16 (which are originally from Shaw's work)
  Window leakage area 0.8 cm^2/m crack length, from ASHRAE 1993 Fundamentals, Table 3, pg. 23.15

- The corridor ventilation fan models were developed from the rated flow and pressure increase of the specific rooftop HVAC units installed. The garbage exhaust fan and control room exhaust fan models were also developed from the rated flow and pressure rise of the fan units. Each of these fans includes a filter which results in significant pressure drop, so that only a portion of the rated pressure rise is available from the fan. Coils, dampers, and heating elements in the fan duct, which contribute further flow resistance and pressure drop, have been neglected.

4.3 Calibration of Simulation to Measured Data

The first set of simulation runs were intended to match the simulation results to the measured values of pressure difference. To simplify the calibration, only the measurements taken under "no wind" conditions on March 3, 1995 were used, and no wind was assumed in the simulation. The simulated outdoor temperature was -10 C, and simulated indoor temperature was 20 C; this matches the temperatures measured at the start of the measurements, but the outdoor temperature fell about 5 C during the night, so that the last measurements made with the fans off have a greater temperature difference than used in the simulation.

Results from the initial runs of the simulation did not match the measurements well; with fans on, the simulation showed high building pressurization, and the distribution of simulated pressure with fans off indicated that the simulation was missing significant leakage area at the top and the bottom of the building, but not in the elevator shafts or stairwell.

Review of the defined leakage areas in the garage indicated that leakage area through connections such as transformer ventilation grilles, emergency generator intakes and exhausts, and the closed garage exhaust dampers was significantly larger than first defined. The measured pressure differences between the ventilation shaft and the corridors also indicated significant leakage area through the HVAC units when switched off. Once these two leakage areas were redefined, the simulation with fans off matched the measured results quite well, except for ground floor units and corridors. Here, the lack of a good model for backdraft dampers on exhaust grilles results in inaccurate pressures in the simulation.

The simulation with fans on still indicated that simulated pressures were higher than measured in the building, although the simulated fan flows into the corridors were well-matched to the measurements. The simulated ratio of pressure drop between corridors and units to that between units and outside was a good match to the measurements. This indicated that both the leakage area between the corridors and the units, and the leakage area between the units and outside, was too small. We therefore increased the leakage areas through the floors, walls, and windows of the building; in order to reach good agreement with the measured values, these leakage areas were increased from three to four times the ASHRAE-recommended values. As the door leakages were based on tested values, they were not adjusted.

Appendix B presents, in table form, the comparison between measured and simulated values for each of the ten building conditions measured in the "No Wind" set of measurements of March 3. In general, the simulated pressure differences are within 2 Pa. of the measured differences, except for the ground floor with the fans switched off. In that case, the ground floor corridors were measured as much more depressurized than the simulation shows; this is a result of the backdraft dampers on the unit exhaust grilles preventing much cold air entering the units at ground level; the simulation is unable to model this.

Table 4.2 shows some results of the simulation runs which model the existing building with the corridor make-up air fans running. The fans are able to pressurize the corridors and units of the building such that the pressure difference between inside and outside at the ground floor is small; this avoids cold drafts at the lobby when the main entrance door is open. The total airflow entering the building consists of about 8,300 l/sec. through the make-up fans and about 800 l/sec through the garage. Of the 800 l/sec entering through the garage, about 400 l/sec enters the elevator and stairwell shafts, less than 100 l/sec passes through the ground floor slab in various discontinuities, and the remainder is drawn into the garbage room and exhausted. The air entering the elevator and stairwell shafts from the basement mixes with air drawn in from the first six or seven floors' corridors, and spills out into the upper floor corridors.

The flow through each unit, with no in-suite exhaust units operating, varies from 21 l/sec through ground floor units to 71 l/sec at top floor units, where the standard delivery of about 45 l/sec from the make-up air system is supplemented by air drawn from the garage and from lower-floor units. For comparison purposes, ASHRAE Standard 62-1989 requires 0.35 air changes/hour, which for a unit of 100 m^2 floor area works out to 24 l/sec.

The pressure differences across interior doors are generally small, less than 10 Pa. This would require a force of less than 20 N. to crack the door open, hardly noticeable beyond the normal effort required to open doors. The largest pressure drop is across the exterior skin of the building at the 12th floor.

Less than 10 % of the ventilation air escapes through the shafts at the top of the building. There is still a significant opportunity to reduce heating load, energy consumption, and peak electricity demand by sealing the elevator machinery room, using a split-system air conditioner to cool the machinery, and reducing the ventilation fan flow . The leakage through the elevator machinery room alone contributes a load of nearly 14 kW at -10°C.

Table 4.3 shows the same results for the runs with the make-up air fans shut off. The ground floor is now significantly lower pressure than the outside, and air is drawn in through the ground floor units, the lobby and the fire doors. The flow into the garage is about double that when the fans are operating, and over one third of the total of

Table 4.2

Simulation Statistics - Existing Building - Ventilation Fans On

Airflow/Pressure Difference Statistic	Simulation Fans On, All doors closed	Simulation Fans On, Garage Dr. open 300 mm	Simulation Fans On, Entrance Door open	Simulation Fans On, Elevator Door Open at 1st Fl	Simulation Fans On, Corridor Door Open at 1st Fl.
Flow through top of elevator shaft at roof sla	338	341	339	341	339
Flow through corridor ventilation fan - North	2742	2737	2742	2742	2742
Flow through corridor ventilation fan - Centr	3589	3581	3588	3590	3586
Flow through corridor ventilation fan - South	1991	1985	1991	1989	1990
Flow through stairwell at roof slab - North	95	96	95	95	95
Flow through stairwell at roof slab - South	95	96	95	95	95
Peak flow in elevator shaft	1377 (F8)	1405 (F8)	1379 (F8)	1430 (F7)	1385 (F8)
Peak flow in stairwell - North	384 (F7)	399 (F7)	384 (F7)	378 (F8)	381 (F7)
Peak flow in ventilation shaft - North	2741 (Fan)	2737 (Fan)	2742 (Fan)	2742 (Fan)	2742 (Fan)
Peak flow in garbage chute	71 (F1)	69 (F1)	71 (F1)	71 (F1)	71 (F1)
Flow - elevator shaft at 1st floor slab	299	371	299	263	294
Flow - stairwell at 1st floor slab - North	115	133	115	113	113
Flow - stairwell at 1st floor slab - South	114	132	114	112	112
delP across 12th floor unit windows	19.2	19.5	19.3	19.4	19.3
delP across 12th floor unit doors	8.8	8.9	8.8	8.9	8.8
delP across 12th floor elevator doors	8.5	8.7	8.5	8.7	8.5
delP across 12th floor stairwell doors - South	7.9	8.2	8	7.9	7.9
delP across 1st floor unit windows	0.7	2.1	0.8	0.7	0.4
delP across 1st floor unit doors	0.9	1.6	0.9	0.9	0.5
delP across 1st floor elevator doors	5.1	5.1	5.1	3.1	5.8
delP across 1st floor stairwell doors - South	6.3	7.4	6.3	6	6.2
Flow in through main entrance door	9	8	19	25	11
Flow through N. and S. fire exit doors	34	30	35	35	35
Flow through elevator doors at lobby	236	237	238	423	254
Flow through 12th floor elevator doors	314	318	314	319	315
Garbage exhaust flow	280	283	280	281	280
Flow in through small garage door	108	882	108	108	111
Flow through all other garage leakage area	678	234	678	681	704
Flow through unit - 12th floor (1211)	71	71	71	71	71
Flow through unit - 6th floor (611)	53	54	53	53	53
Flow through unit - 1st floor (111)	21	31	21	21	17

Table 4.3

Simulation Statistics - Existing Building - Ventilation Fans Off

Airflow/Pressure Difference Statistic	Simulation Fans Off, All doors closed	Simulation Fans Off, Garage Dr. open 300 mm	Simulation Fans Off, Entrance Door open	Simulation Fans Off, Elevator Door Open at 1st Fl	Simulation Fans Off, Corridor Door Open at 1st Fl.
Flow through top of elevator shaft at roof sla	258	263	260	259	262
Flow through corridor ventilation fan - North	321	326	323	322	323
Flow through corridor ventilation fan - Centr	324	329	326	324	330
Flow through corridor ventilation fan - South	309	313	310	309	310
Flow through stairwell at roof slab - North	74	75	74	74	74
Flow through stairwell at roof slab - South	74	76	74	74	74
Peak flow in elevator shaft	1514 (F7)	1588 (F7)	1539 (F7)	1549 (F7)	1584 (F7)
Peak flow in stairwell - North	469 (F6)	497 (F8)	471 (F6)	466 (F6)	460 (F6)
Peak flow in ventilation shaft - North	467 (F8)	480 (F8)	470 (F8)	465 (F8)	463 (F8)
Peak flow in garbage chute	54 (F1)	48 (F1)	54 (F1)	54 (F1)	56 (F1)
Flow - elevator shaft at 1st floor slab	566	693	571	541	551
Flow - stairwell at 1st floor slab - North	178	215	178	178	168
Flow - stairwell at 1st floor slab - South	176	212	175	175	165
delP across 12th floor unit windows	9.7	10	9.8	9.7	9.9
delP across 12th floor unit doors	3.6	3.8	3.7	3.6	3.7
delP across 12th floor elevator doors	7.3	7.6	7.4	7.4	7.6
delP across 12th floor stairwell doors - South	8.6	9.2	8.6	8.5	8.4
delP across 1st floor unit windows	16.3	10.6	6	6.2	8.3
delP across 1st floor unit doors	1.3	0.7	1.3	1.3	3.6
delP across 1st floor elevator doors	3.6	3.9	4.6	1.8	8.3
delP across 1st floor stairwell doors - South	12	15.4	12.2	12	7.4
Flow in through main entrance door	85	82	207	89	70
Flow through N. and S. fire exit doors	76	69	76	76	78
Flow through elevator doors at lobby	195	204	224	314	310
Flow through 12th floor elevator doors	288	296	291	292	296
Garbage exhaust flow	262	268	263	262	262
Flow in through small garage door	186	1543	185	186	199
Flow through all other garage leakage area	1283	530	1273	1287	1392
Flow through unit - 12th floor (1211)	45	46	46	45	46
Flow through unit - 6th floor (611)	19	17	18	19	17
Flow through unit - 1st floor (111)	40	37	39	40	50

about 3700 l/sec. of air entering the building does so through the basement. Opening the garage door increases the total ventilation rate by about 10 % to 4000 l/sec., about half of which travels through the garage before reaching the upper floor units.

The air flow rate through the upper and lower floor units is now adequate, but is low in the middle floor units. Units on the middle floors have not only low air flow rates, but much of the air that goes through them has passed through the garage before reaching them.

Pressure across the closed entrance doors at the lobby is increased to about 16 Pa., which would impose a force of 32 N. required to crack the door open. This is still barely one-third of the maximum allowable for fire doors of 90 N. force, but is noticeable when attempting to open the door.

5.0 COMPARTMENTALIZATION STRATEGIES

5.1 Strategies Simulated

Analysis of the leakage into the units and leakage from shafts into corridors shows that leakage through doors represents the majority of the total leakage between these zones. Doors also represent a relatively simple item to upgrade, as they are easily accessible and typically quite standardized within a building; there are generally only two or three types of door used. Sealing performance is generally not a design or purchasing criterion for interior doors; thus there is significant scope for improvement, whether in retrofit or in replacement.

Two strategies can be considered for upgrading the leakage performance of doors. The first is to increase the number of doors connecting one compartment to another in series, by creating vestibules. The second is to upgrade the existing door sealing performance.

The first strategy has the advantage that there will still be significant flow resistance between the separate compartments when one door is open. However the separation of the compartments is not greatly increased when a second standard interior door is added to form a vestibule between two compartments; a tightly-sealing door is required. Thus, this option would be best used in situations where connecting the two compartments by opening the door between them would make a significant change in the operation of the building. Our measurements and the simulation results indicate that in the typical high-rise, opening one door between zones in the building causes minimal change due to the large number of interconnections between zones. Thus the expense and inconvenience of adding vestibules to doors which connect different compartments is generally not justified.

The second strategy aims simply to upgrade or replace the existing door with one which has much-improved sealing performance when closed. We have assumed that with relatively minimal design and construction effort and cost, an interior door having a leakage rate of 25 l/sec at 75 Pa. (one-fourth of the "weatherstripped door" used in the simulation model) represents the best current technology which provides acceptable durability of performance and ease of operation. Such a door system might contain moveable seals at the sill, operated by the latching mechanism, or might contain a fixed sill with compression seals such as are found on car doors. Special care would be taken to prevent air leakage through the latching mechanism, which on current doors commonly penetrates the door and provides a leakage path.

Similarily, the typical elevator door is not designed to provide an airtight seal when closed, but this would not be a difficult or expensive task. It might be easier to implement on elevator doors, in fact, which already have a power operator and a regular maintenance schedule, and are provided by a limited number of manufacturers. We have assumed that elevator doors having a leakage rate of 75 L/sec at 75 Pa. represent an achievable target for manufacturers to reach; this is less than one quarter of the leakage rate of the typical elevator door.

Our compartmentalization strategy simulations are based on reducing leakage area between compartments solely via the replacement of all door connections between zones forming part of each compartment with "Best-Technology" doors as described above.

5.2 Unit by Unit Compartmentalization

In the "Unit-by-Unit" compartmentalization strategy, the doors between the units and the corridors are replaced by "Best Technology" doors as described above. The simulation was rerun with the fans operating, under two building conditions: first with all doors closed, and second with a unit door open at the 12th floor level.

Table 5.1 shows the results of the two simulation runs. The make-up air fans are now able to pressurize the building down to the basement level, and air now exits the building at the basement level as well as all other levels. Total airflow entering the building has dropped from 9,100 l/sec to 7,900 l/sec, all through the corridor make-up air fans. This measure has eliminated the problem of air from the garage moving into the building.

Surprisingly, the flow through the units has become more uniform. Air flows through the first floor units at an average rate of 28 l/sec, acceptable under ASHRAE

Table 5.1

Simulation Statistics - Unit-by-Unit Strategy

Airflow/Pressure Difference Statistic	Existing Bldg. Fans On, All doors closed	Unit-by-Unit Fans On, All doors closed	Unit-by-Unit Fans On, 12th floor unit door open
Flow through top of elevator shaft at roof slab	338	382	381
Flow through corridor ventilation fan - North	2742	2641	2644
Flow through corridor ventilation fan - Centre	3589	3386	3392
Flow through corridor ventilation fan - South	1991	1867	1871
Flow through stairwell at roof slab - North	95	105	105
Flow through stairwell at roof slab - South	95	105	104
Peak flow in elevator shaft	1377 (F8)	969 (F9)	1011 (F9)
Peak flow in stairwell - North	384 (F7)	242 (F9)	250 (F9)
Peak flow in ventilation shaft - North	2741 (Fan)	2641 (Fan)	2644 (Fan)
Peak flow in garbage chute	71 (F1)	81 (F1)	81 (F1)
Flow - elevator shaft at 1st floor slab	299	168	146
Flow - stairwell at 1st floor slab - North	115	57	60
Flow - stairwell at 1st floor slab - South	114	63	66
delP across 12th floor unit windows	19.2	16.8	40.5 *
delP across 12th floor unit doors	8.8	25.4	0.03 *
delP across 12th floor elevator doors	8.5	4.3	5.6
delP across 12th floor stairwell doors - South	7.9	1.4	2.8
delP across 1st floor unit windows	0.7	2.1	2.1
delP across 1st floor unit doors	0.9	4.4	4.3
delP across 1st floor elevator doors	5.1	2.6	2.7
delP across 1st floor stairwell doors - South	6.3	2.8	3
Flow in through main entrance door	9	49	48
Flow through N. and S. fire exit doors	34	25	23
Flow through elevator doors at lobby	236	163	166
Flow through 12th floor elevator doors	314	215	250
Garbage exhaust flow	280	290	290
Flow in through small garage door	108	36	39
Flow through all other garage leakage area	678	185	198
Flow through unit - 12th floor (1211)	71	65	198 *
Flow through unit - 6th floor (611)	53	53	53
Flow through unit - 1st floor (111)	21	28	28

* - At unit with open door

62-1989, whereas flow in the 12th floor units has dropped from 71 l/sec. to 65 l/sec., but all is fresh air.

The pressure drops across the unit doors have increased significantly, especially at the 12th floor where a force of 50 N. acts to prevent the door from latching shut. A strong door closer device would be required to counteract this pressure; otherwise the door will be difficult to close, and will tend to blow open when the knob is turned on cold days. The pressure drop ratio between corridor wall and exterior wall has changed from 30%/70% to 60%/40% at the 12th floor, thus there is still a significant component of pressure drop across the exterior wall. We must call this result "semi-compartmentalization" since the benefits of compartmentalization are only half-realized; with the existing make-up air system, more even air flow is evident, but the overpressurization of the building by the fans results in a fairly small drop in pressure difference across the exterior walls at the 12th floor from 19 Pa. to 17 Pa. There is still potential to drive humid air into the exterior wall and cause problems.

When the unit door of unit 1212 was opened, as in the second run, the pressure across the exterior walls of the unit suddenly more than doubled to 40 Pa., and the airflow through that suite also tripled to 200 l/sec. However, the net effect on pressures and flows elsewhere in the building is quite minor.

It is likely that the corridor make-up fan output can be reduced while maintaining the advantages of this strategy. The absolute pressures at the 12th floor corridor are still close to those at ground level, so that very little pressure drop occurs over the separations between shafts and corridors within the building. A reduction of the fan output and rebalancing of the system to provide a small, steady pressure drop moving up the shafts would reduce the total pressure taken over the corridor and exterior walls at the 12th floor to somewhat less than the available buoyancy-induced pressure difference of 50 Pa.

The unit-by-unit compartmentalization has some significant benefits. The drop in peak heating load due to the reduced fan output is about 50 kW at -10°C. The overall annual heating energy savings in Ottawa would be in the tens of thousands of kWh. The overall indoor air quality would likely be improved, as well as the ventilation of the lower-floor units. Without changing the ventilation system, there is minimal change in the pressures across the upper floor envelope, and pressures across the unit doors, at the 12th floor at least, are high enough to be objectionable.

5.3 Floor by Floor Compartmentalization

In the "Floor-by-Floor" compartmentalization strategy, the doors between the corridors and the stairwells and elevator shafts are replaced by "Best Technology" doors as described above. The simulation was rerun with the fans operating, under two building conditions: first with all doors closed, and second with an elevator door open at the 12th floor level.

Table 5.2 shows the results of the two simulation runs. The effect of floor-by-floor compartmentalization is less pronounced than that of unit-by-unit, but has generally the same characteristics. Infiltration into the basement is much reduced but not eliminated; flow through ground floor units is increased but not as much as in the unit-by-unit strategy. Pressures across the exterior wall and across the corridor walls of units were reduced, but overall the changes were rather minor, and again do not add up to "compartmentalization". Pressures across elevator and stairwell doors are increased, but to about half of the difference over the unit doors in the "unit-by-unit" strategy. Total airflow through the building is reduced from 9,100 l/sec. to 8,600 l/sec., but flow through the fans is actually increased by a marginal amount; the reduced airflow is solely due to reduced infiltration into the garage.

The most important finding is that in this strategy, the opening of an elevator door at the 12th floor has a noticeable effect on all the 12th floor units. Pressure across the unit door and exterior wall increases, and total ventilation flow into each unit increases by about 10 %. Pressures and flows in other zones are also changed more than with other strategies where doors are opened.

5.4 Double Compartmentalization

In the "Double" compartmentalization strategy, the doors between the corridors and the units, and the stairwells and elevator shafts are replaced by "Best Technology" doors as described above. The corridors thus become separate compartments from both the units and the shafts. The simulation was rerun with the fans operating, under

Table 5.2

Simulation Statistics - Floor-by-Floor Strategy

Airflow/Pressure Difference Statistic	Existing Bldg. Fans On, All doors closed	Floor-by-Floor Fans On, All doors closed	Floor-by-Floor Fans On, 12th floor elevator door open
Flow through top of elevator shaft at roof slab	338	329	312
Flow through corridor ventilation fan - North	2742	2748	2748
Flow through corridor ventilation fan - Centre	3589	3594	3596
Flow through corridor ventilation fan - South	1991	2000	2000
Flow through stairwell at roof slab - North	95	91	91
Flow through stairwell at roof slab - South	95	91	91
Peak flow in elevator shaft	1377 (F8)	666 (F8)	886 (F9)
Peak flow in stairwell - North	384 (F7)	308 (F8)	298 (F8)
Peak flow in ventilation shaft - North	2741 (Fan)	2748 (Fan)	2748 (Fan)
Peak flow in garbage chute	71 (F1)	66 (F1)	68 (F1)
Flow - elevator shaft at 1st floor slab	299	209	256
Flow - stairwell at 1st floor slab - North	115	55	56
Flow - stairwell at 1st floor slab - South	114	56	55
delP across 12th floor unit windows	19.2	15.1	17.4
delP across 12th floor unit doors	8.8	6	8.1
delP across 12th floor elevator doors	8.5	13.4	5.4
delP across 12th floor stairwell doors - South	7.9	12	7.6
delP across 1st floor unit windows	0.7	1.8	1.6
delP across 1st floor unit doors	0.9	1.3	1.3
delP across 1st floor elevator doors	5.1	10.1	13.2
delP across 1st floor stairwell doors - South	6.3	10.8	10.6
Flow in through main entrance door	9	29	26
Flow through N. and S. fire exit doors	34	16	17
Flow through elevator doors at lobby	236	89	105
Flow through 12th floor elevator doors	314	106	454
Garbage exhaust flow	280	281	281
Flow in through small garage door	108	83	87
Flow through all other garage leakage area	678	409	528
Flow through unit - 12th floor (1211)	71	62	67
Flow through unit - 6th floor (611)	53	56	55
Flow through unit - 1st floor (111)	21	26	25

three building conditions: with a unit door open at the 12th floor, with all doors closed, and with an elevator door open at the 12th floor level.

Table 5.3 shows the results of the three simulation runs. Double compartmentalization gives generally the same characteristics as the other two strategies, in greater magnitude. The make-up air fans pressurize the building down to the basement, but enough infiltration occurs to feed the garbage exhaust fan. Total airflow entering the building has dropped to 7,800 l/sec. through the corridor ventilation fans, and air moves down into the garage from the rest of the building. The flow through the units is now reduced on the 12th floor to 59 l/sec., but the flow in the middle and lower floors is increased, and the ground floor unit airflow now meets ASHRAE Standard 62-1989 for ventilation.

Pressure across the exterior walls at the 12th floor is reduced, but is still substantial at almost 15 Pa. Pressure across the unit door at the 12th floor is less than in the "Unit-by-Unit" strategy, but is still high enough to be noticeable. Opening the unit door results in a significant increase in envelope pressure and unit ventilation rate, somewhat less than under the "unit-by-unit" strategy. Similarily, the effect of opening an elevator door is smaller in this strategy than in the "floor-by-floor" strategy. The best points of both the "unit-by-unit" and "floor-by-floor" strategies are combined in the "double" strategy, while the negative points of each are mitigated. However, the "double" strategy is not significantly better than the "unit-by-unit" strategy.

Table 5.3

Simulation Statistics - Double Compartmentalization Strategy

Airflow/Pressure Difference Statistic	Existing Bldg. Fans On, All doors closed	Double Fans On, All doors closed	Double Fans On, 12th floor Unit door open	Simulation Fans On, 12th floor elevator door open
Flow through top of elevator shaft at roof slab	338	378	377	369
Flow through corridor ventilation fan - North	2742	2622	2625	2620
Flow through corridor ventilation fan - Centre	3589	3335	3341	3334
Flow through corridor ventilation fan - South	1991	1846	1849	1844
Flow through stairwell at roof slab - North	95	94	93	94
Flow through stairwell at roof slab - South	95	86	86	87
Peak flow in elevator shaft	1377 (F8)	590 (F10)	605 (F10)	770 (F10)
Peak flow in stairwell - North	384 (F7)	169 (F8)	172 (F8)	160 (F8)
Peak flow in ventilation shaft - North	2741 (Fan)	2622 (Fan)_	2625 (Fan)	2620 (Fan)
Peak flow in garbage chute	71 (F1)	83 (F1)	82 (F1)	84 (F1)
Flow - elevator shaft at 1st floor slab	299	8	18	79
Flow - stairwell at 1st floor slab - North	115	15	15	15
Flow - stairwell at 1st floor slab - South	114	19	19	19
delP across 12th floor unit windows	19.2	14.6	33.1 *	15.8
delP across 12th floor unit doors	8.8	21	0 *	24.5
delP across 12th floor elevator doors	8.5	9.9	12	3.1
delP across 12th floor stairwell doors - South	7.9	5.4	3.2	10
delP across 1st floor unit windows	0.7	2.2	2.2	2.2
delP across 1st floor unit doors	0.9	4.7	4.6	4.6
delP across 1st floor elevator doors	5.1	8.8	8.9	10.3
delP across 1st floor stairwell doors - South	6.3	16.2	16.4	15.9
Flow in through main entrance door	9	66	66	65
Flow through N. and S. fire exit doors	34	10	9	9
Flow through elevator doors at lobby	236	82	83	90
Flow through 12th floor elevator doors	314	88	99	334
Garbage exhaust flow	280	291	290	290
Flow in through small garage door	108	38	40	44
Flow through all other garage leakage area	678	195	200	132
Flow through unit - 12th floor (1211)	71	59	170 *	63
Flow through unit - 6th floor (611)	53	58	58	58
Flow through unit - 1st floor (111)	21	28	28	28

6.0 CONCLUSIONS

6.1 Airflow and Pressure Differences in Measured Building

- The corridor make-up air fans provide approximately 8000 L/s to the building when operating, which should provide about 40 L/s to each of the approximately 200 units in the building. The total design flow through the corridor grills of the make-up air system, as shown on the design drawings, is over 8700 L/s, about 10% greater than actually measured.

- When the corridor make-up air fans are operating, the garage pressure remains higher than that of the vertical shafts during cold weather, and a significant amount of air enters the building through the garage, travels into the building through the elevator and stairwell shafts while mixing with air from lower floors, and travels into the upper floor corridors and units.

- There is significant airflow through the ventilation fan shafts and out through fans when the fans are shut off - the shut-off dampers are not very effective, if there. This was found by noting pressure drops between corridors and ventilation shaft at top and bottom with fans off, and via simulation showing higher pressures on upper floor corridors than should have been found when the fans were switched off and dampers closed.

- The top of the elevator shaft contains significant leakage area, which contributes the equivalent of five extra apartment units in leakage. However, this leakage area also keeps the elevator shaft pressure down and minimizes the pressure difference across the elevator doors.

6.2 Validity of Simulation

- The simulation originally used leakage areas as recommended in literature for specific types of construction:

1.1 cm^2/m^2 for interior walls constructed of low-density concrete block,
0.68 cm^2/m^2 for exterior walls (clay brick masonry) (Both from ASHRAE 1993 Fundamentals, Table 3, pg. 23.15)
3.5 L/s per 100 m^2 at 6.8 Pa. for floor leakage (from Shaw's work at IRC)
Door leakage numbers from ASHRAE 1993 Fundamentals, Fig. 11, pg. 23.16 (which are originally from Shaw's work)
Window leakage area 0.8 cm^2/m crack length, from ASHRAE 1993 Fundamentals, Table 3, pg. 23.15

- Although the door leakage performance numbers provided appropriate pressure drops when plugged into the simulation, all the rest were found to be low, in that the measured flow rates through the corridor make-up air fans caused excessive pressurization in the simulated building. In the process of calibrating the simulation to the measured values, these leakage areas were increased; the final calibrated version of the simulation uses:

  3.0 cm^2/m^2 for interior walls
  2.0 cm^2/m^2 for exterior walls
  3.2 cm^2/m crack length for the slider windows
  12 cm^2/m^2 for the corridor floor leakage areas
  20 litres/second leakage at 6.7 Pa through unit floors.

  All of the above leakage areas are significantly greater than those presented in the literature. This is for a recently completed, quality building, in which complaints concerning cold drafts and excess heating bills are minimal. This indicates that currently-published figures for leakage of construction types and elements are much lower than the mainstream of current construction, and must be used with extreme caution to avoid underestimating the ventilation rates and heating loads in high-rise residential buildings.

- The resulting match between measurements of airflow and pressure difference and simulated results is very good. Simulated pressure differences in the key zones of the garage, the lobby, the corridors, and the elevator shaft are within 2 Pa. of the corresponding measured values, for the "fans on" case. For the "fans off" case, agreement at the 12th floor level is good; the situation at the ground floor and parking garage is not as good. The primary reason for this is believed to be the inability of the simulation program to model the action of the backdraft dampers on the unit exhaust ducts. These close when the unit is negatively pressurized with respect to outdoors, as the 1st floor units are when the corridor make-up air fans are not running. The program's author, George Walton of NIST, has been alerted to this weakness in the CONTAM93 package, and the next version of the program may correct this problem.

- The technique for measurement of pressure difference between the corridor and the ventilation shaft was evidently in error in that the ventilation shaft measurement point was not inserted far enough through the grill to clear the throat of the opening, so that much of the available static pressure had been converted to dynamic pressure at the measurement point.

6.3 Compartmentalization

6.3.1 Effect on Pressure Differences in Building

In general, compartmentalization increases the pressure difference across interior doors. The "Unit-byUnit" strategy resulted in significant pressure differences across unit doors at the 12th floor, which would likely be found unacceptable by a significant proportion of occupants unless compensated for by door closers. There would also be a risk of these doors whistling, although this does not usually become a problem until pressure differences of 50 Pa. or more are reached.

The door pressure differences created by the "Floor-by-Floor" strategy are less than half those of the "Unit-by-Unit", and are created on elevator doors (which have their own power closers) and on stairwell doors (which are much less frequently used). The "Double" strategy spreads the door pressure increases more evenly over the two sets of doors.

6.3.2 Effect on Unit Air Flow and Indoor Air Quality

Compartmentalization as investigated in this study may provide improvements in air flow and indoor air quality in the building. The main benefit is that the garage area is neutralized as a source of infiltration, so that virtually all air supplied to the corridors and the units travels through the corridor make-up air system. Pollutants which may be produced in the garage are forced to exit to the exterior of the building, and pollutants from below-grade sources cannot enter the garage due to the higher pressure in it.

The higher pressures provided in lower floor corridors due to compartmentalization means that air flow through lower floor units remains adequate to much colder temperatures than without compartmentalization.

6.3.3 Effect on Air Leakage and Energy Use

Compartmentalization leads to smaller variation in unit ventilation rates over the height of the building; this allows the overall rate of ventilation to be reduced closer to the ASHRAE Standard of 0.35 air changes per hour applied over the entire building. The annual savings on heating (and where central air-conditioning is provided, cooling) can be substantial; in the order of thousands of dollars for the specific building measured in this study. Where heating is by staged electric resistance coils or central air-conditioning is provided, there are significant peak demand savings to be gained as well. The approximate drop in overall ventilation rate, without adjusting the make-up air fan speeds, from the compartmentalization strategies were as follows:

Base Case	Total Flow:	9,208 l/sec.	
Unit-by-Unit	Total Flow:	8,115 l/sec	-12%
Floor-by-Floor	Total Flow:	8,824 l/sec	-4 %
Double	Total Flow	7,928 l/sec	-14%

The following calculation provides some idea of the size of energy cost savings if compartmentalization was implemented in the measured building in Nepean, Ontario. The reduction in total flow would likely average about 50% of the difference between the Base Case and the Double Compartmentalization case listed above. If we assume that:

- the heating season is 120 days
- the average temperature rise is from 0 °C to 21 °C
- the cost of electricity for heating is $0.08/kWh

the annual savings in energy cost for heating is nearly $3,700. The peak demand reduction is in the range of 35 kW for the coldest month of the year. The total savings would be in the order of $5,000 per year.

There is also some opportunity to reduce the fan speeds to further reduce ventilation rate. The simulations of the “Double” and “Unit-by-Unit” strategies indicate that the garage is significantly pressurized with respect to outdoors under these strategies, and the exterior walls of all units are also pressurized beyond what is necessary to prevent infiltration.

6.3.4 Effect on Building Operation and Durability

While pressures across the exterior envelope are reduced by the compartmentalization strategies, this effect is much smaller than expected, partially due to the excess pressurization created by the make-up air fans. The split of pressure drop between unit/corridor partition, exterior wall, and corridor/shaft partition was changed significantly by the compartmentalization strategies, so that much less of the total pressure drop was carried by the exterior envelope; however a larger peak total pressure drop occurred at the top of the building, so that the exterior envelope was still carrying a significant pressure drop. Thus one of the main benefits of compartmentalization, that of equalizing unit pressures with outdoors, was not realized in the strategies simulated.

However, with compartmentalization, a greater proportion of the air travelling through a unit has not travelled through any other unit prior to this one; that is, it has travelled directly from the corridor make-up air supply grille to the unit. The overall humidity of the air exiting the 12th floor unit will be reduced, as well as the driving pressure difference being reduced.

Reducing the make-up air fan flow would result in lower pressure drops at the 12th floor exterior skin, without eliminating the other benefits of compartmentalization. This potential should be further investigated to determine the full scope of pressure reduction across the exterior envelope at the top of the building, and reduced make-up air flow and associated energy savings.

6.4 Summary

The research described in this study indicates that compartmentalization has significant potential benefits in high-rise residential buildings exposed to cold weather. These include:

- Better indoor air quality and ventilation. Upper floor units receive less air exiting from the garage and lower floor units, while lower floor units achieve higher overall ventilation rates due to the increased ability of the make-up air fans to pressurize the building.

- Reduced overall ventilation rates and energy use. The variability in unit ventilation rates is reduced, so that the worst units are better ventilated and those units that were receiving a large volume of air leaking from the garage no longer receive it. Overall ventilation can be reduced by up to 14 % by implementing the simple strategies investigated, and greater savings are possible by reducing make-up air fan speeds, while continuing to supply enough air to maintain adequate ventilation in all units.

- One major note is that the corridor make-up air system requires no modification in order to work in a compartmentalized building; it simply pressurizes the corridors to a higher level to force nearly the same amount of air into each unit through the reduced door opening. As the variation in buoyancy-induced pressure plays a smaller part in the unit airflow rate, the flow rate becomes more even top to bottom. This approach may be less successful in buildings where the make-up air fans have limited pressure rise capability.

- Reduced peak pressure across exterior envelope during normal operation. The amount of this reduction is small under the strategies simulated, but greater reductions are possible by reducing make-up air fan speeds. On the other hand, greater peak pressures across the exterior envelope are seen when doors forming part of the compartment strategy are opened.

- Overall pressures across interior doors are increased by the compartmenting strategies. Pressures across elevator doors do not go higher than 15 Pa. for this building; such pressures should not cause problems for most automatic elevator door openers. Pressures across stairwell doors also are not more than 15 Pa. and these doors are much less frequently used, so that the increase in force required to open them would not be judged objectionable. Pressures across unit doors go as high as 25 Pa. at the 12th floor, a level that would require significant effort to close the door against, and would be objectionable due to its frequent use. Automatic door closers might be required on these doors to mitigate that problem.

Of the three strategies for compartmentalization analyzed, the best performance was obtained from the "Double Compartmentalization" strategy, which isolates the vertical shafts, the corridors, and the units from each other. The technological difficulty in this strategy is in refitting the elevator doors to provide a good seal when closed. These currently do not exist, and need to be developed. Exterior doors which provide an exceptional seal when closed are already available, but the interior doors required for compartmentalization do not require the same thermal performance of exterior doors and should thus be cheaper. The cost increment for a interior sealing door should be in the range of $100 in quantity, $200 to $250 if a self-closing device is also required. In the test building, approximately 200 unit doors would be upgraded to implement the "Unit-by-Unit" strategy, at an approximate cost of $40,000 to $50,000. The "Floor-by-Floor" strategy requires upgrade of 30 stairwell doors which do not require self closers, and would cost about $3,000 for this portion of the strategy. It would also require the upgrade of 43 elevator door sets; the cost of this requires further investigation.

6.5 Recommendations

The research described in this study indicates that compartmentalization has significant potential benefits in high-rise residential buildings exposed to cold weather. A number of questions remain concerning the extent to which this study, which applies to a specific high-rise building, is applicable to typical high-rise residential buildings in Canada, as follows:

- What is the effect of increasing height on the compartmentalization results ?

- What is the effect of central exhaust systems on compartmentalization ?

- What is the effect of sealing the elevator mechanical room on compartmentalization ?

- Should elevator shafts and stairwells be pressurized by a make-up air system to prevent large pressure drops across the doors to them, and to prevent garage air from entering them ?

- Does extra effort put into identifying and sealing leakage areas other than doors in apartment buildings result in large benefits in terms of compartmentalization ?

- By how much can the existing fan flowrates be reduced to maintain the benefits of full building pressurization while reducing overall ventilation rates and total energy consumption ?

- This building is relatively new and built for a luxury market in a cold climate, yet its generalized leakage rates through opaque walls and windows appear to be three to four times the amounts reported as typical in the literature. Is the study building atypical, are the simulations and measurements made in this study flawed, or does the literature report laboratory measurements of leakage through building elements which are overly optimistic ?

- How do pollutants and odours move from their sources within a compartmentalized building ? Is indoor air quality within the suites of a building improved by compartmentalization ?

These questions can be answered relatively easily using the CONTAM93 simulation program, and we recommend that further work be undertaken to expand the range of situations and high-rise buildings in which compartmentalization is analyzed, and to further refine the specific strategies for compartmentalization.

The compartmentalization of high-rise buildings will require that interior doors be designed and installed to achieve a much higher level of airtightness than the current standard. We recommend that a development and testing program be implemented on both standard entry doors and on elevator doors to enhance the ability of manufacturers to supply new doors and to enhance the ability of the construction and renovation industry to install them. This program would start by testing a variety of current doors and elevator doors to determine their air leakage characteristics. Elevator manufacturers currently have testing facilities which could be used for this program, and should be approached to participate.

The results of this study indicate that the greater the levels of airtightness between all partitions within a building, the better it will perform in controlling buoyancy force or stack effect in the building. However, there must be a point, dependant upon the fan installed, beyond which the existing ventilation system will no longer be able to force air into the units at an adequate rate. This level of air leakage appears to be significantly lower than the levels simulated in this study. We recommend that studies similar to this one be undertaken prior to implementing compartmentalization in any existing building, to ensure that the existing ventilation system will continue to perform adequately. In order to avoid this problem in new buildings, we recommend that ventilation systems be designed to provide ventilation directly to each individual unit.

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APPENDIX A

Pressure Difference Measurements - Wind

Field Measurements of Pressure Differences in High-Rise Building

Definition of Terms in Tables

Condition of Building:	The five rows under this heading at the top of the page indicate how the doors and ventilation fans were set during the measurements taken. The shaded box describes the condition of that element.
Weather Condition:	Sets of measurements were taken when the windspeed was above 10 km/hr (Wind) and when the windspeed was below 10 km/hr (No Wind).
Point Measured:	The pressure difference between the reference point and the point described under this heading was measured and recorded as the Pressure Difference, in Pascals (Pa.) The reference point for the first eight measurements was the North stairwell at the 12th floor; the reference point for the last ten measurements was the North stairwell at the ground floor.
Pressure Difference:	The measured pressure difference between the reference point and the point measured, in Pascals (Pa). A positive reading means that the point measured was higher pressure than the reference; a negative means that the point measured was lower pressure than the reference.
Reference Pressure:	The absolute pressure of the air in the stairwell changes depending on the set-up of the building. In order to compare pressure differences between different sets of measurements, they must be referenced to a point whose absolute pressure does not change with the building set-up. The point used for this is the Outside East Side, Ground Floor measurement. All the pressure differences in this column are between the "Point Measured" and Outside East Side.

Simulated Reference Pressure: The numbers in this column (which is only on the Tables in Appendix B - No Wind Measurements) are the calculated pressure differences between the Point Measured and the absolute reference, taken to be Outside East Side, Ground Floor. The numbers are calculated by the CONTAM93 simulation program under the same building set-up and weather conditions that the measurements were made. These numbers can therefore be compared with the measurements to calibrate the CONTAM93 simulation to the measurements.

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-60	1:38	-64.9
Elevator Machine Room	-28	1:48	-32.9
Elevator Shaft	3	1:36	-1.9
12th Fl. corridor	-7	1:41	-11.9
12th Fl. garbage room	-7	1:39	-11.9
Unit 1212	-17	1:40	-21.9
Unit 1202	-11	1:41	-15.9
12th Fl. Supply Vent	-4	1:40	-8.9
Ground Fl. corridor	5.5	1:40	0.7
Ground Fl. lobby vest.	4.8	1:37	0
Ground Fl. by elevators	5.1	1:37	0.3
Ground Fl. Supply vent	7.8	1:47	3
Unit 103	5.2	1:48	0.4
Unit 111	4.2	1:49	-0.4
Garage	6.2	1:50	1.4
Garbage Chute Shaft	-17	1:51	-21.8
Outside W. Side	10.8	1:52	6
Outside E. Side	4.8	1:53	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building

Corridor Fan	[✓ On]	Off
Lobby Entrance Door	[✓ Open]	Shut
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-55	2:08	-60.3
Elevator Machine Room	-29	2:11	-34.3
Elevator Shaft	3	2:11	-2.3
12th Fl. corridor	-7	2:10	-12.3
12th Fl. garbage room	-7	2:13	-12.3
Unit 1212	-18	2:13	-23.3
Unit 1202	-11	2:12	-16.3
12th Fl. Supply Vent	-5	2:09	-10.3
Ground Fl. corridor	5.8	2:17	0.6
Ground Fl. lobby vest.	5.1	2:17	-0.1
Ground Fl. by elevators	4.6	2:17	-0.6
Ground Fl. Supply vent	8.8	2:17	3.6
Unit 103	4.1	2:17	-1.1
Unit 111	4.6	2:17	-0.6
Garage	6.1	2:17	0.9
Garbage Chute Shaft	-16.5	2:17	-21.7
Outside W. Side	8.8	2:17	3.6
Outside E. Side	5.2	2:17	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	[✓ Open]	Shut
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-48	2:27	-53.1
Elevator Machine Room	-30	2:28	-35.1
Elevator Shaft	3	2:29	-2.1
12th Fl. corridor	-7	2:31	-12.1
12th Fl. garbage room	-7	2:31	-12.1
Unit 1212	-18	2:32	-23.1
Unit 1202	-11	2:31	-16.1
12th Fl. Supply Vent	-5	2:30	-10.1
Ground Fl. corridor	5.3	2:29	0.3
Ground Fl. lobby vest.	5.3	2:29	0.3
Ground Fl. by elevators	5.3	2:29	0.3
Ground Fl. Supply vent	8	2:29	3
Unit 103	4.5	2:29	-0.5
Unit 111	3.9	2:29	-1.1
Garage	6	2:29	1
Garbage Chute Shaft	-16.5	2:29	-21.5
Outside W. Side	9.3	2:29	4.3
Outside E. Side	5	2:29	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	[✓ Open]	Shut
Parking Garage Door	Open	[✓ Shut]

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-58	2:50	-62.7
Elevator Machine Room	-31	2:51	-35.7
Elevator Shaft	3	2:52	-1.7
12th Fl. corridor	-8	2:50	-12.7
12th Fl. garbage room	-8	2:50	-12.7
Unit 1212	-19	2:53	-23.7
Unit 1202	-11	2:54	-15.7
12th Fl. Supply Vent	-5	2:53	-9.7
Ground Fl. corridor	5.2	2:50	0.6
Ground Fl. lobby vest.	-0.2	2:50	-4.8
Ground Fl. by elevators	-1.1	2:50	-5.7
Ground Fl. Supply vent	7.9	2:50	3.3
Unit 103	4	2:50	-0.6
Unit 111	3.7	2:50	-0.9
Garage	6	2:50	1.4
Garbage Chute Shaft	-17	2:50	-21.6
Outside W. Side	11.5	2:50	6.9
Outside E. Side	4.6	2:50	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	[✓ Open]	Shut

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-56	3:08	-61.7
Elevator Machine Room	-31	3:08	-35.7
Elevator Shaft	3	3:09	-1.7
12th Fl. corridor	-8	3:10	-12.7
12th Fl. garbage room	-8	3:11	-12.7
Unit 1212	-19	3:10	-23.7
Unit 1202	-11	3:12	-15.7
12th Fl. Supply Vent	-5	3:11	-9.7
Ground Fl. corridor	6.3	3:10	1.7
Ground Fl. lobby vest.	4.4	3:10	-0.2
Ground Fl. by elevators	4.6	3:10	0
Ground Fl. Supply vent	8.7	3:10	4.1
Unit 103	5.4	3:10	0.8
Unit 111	4.6	3:10	0
Garage	8.8	3:10	4.2
Garbage Chute Shaft	-16.2	3:10	-20.8
Outside W. Side	11.5	2:50	6.9
Outside E. Side	4.6	2:50	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	On	Off
Lobby Entrance Door	Open	Shut
Lobby/Corridor Door	Open	Shut
Lobby Elevator Door	Open	Shut
Parking Garage Door	Open	Shut

Weather Condition Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-35	3:41	-56.7
Elevator Machine Room	-18	3:42	-37.7
Elevator Shaft	1	3:42	-20.7
12th Fl. corridor	-7	3:44	-28.7
12th Fl. garbage room	-7	3:43	-28.7
Unit 1212	-12	3:44	-33.7
Unit 1202	-8	3:43	-29.7
12th Fl. Supply Vent	-7	3:44	-28.7
Ground Fl. corridor	4.9	3:41	-16.7
Ground Fl. lobby vest.	2	3:41	-19.6
Ground Fl. by elevators	-0.7	3:41	-22.3
Ground Fl. Supply vent	-3.1	3:41	-24.7
Unit 103	7.6	3:41	-14
Unit 111	11.3	3:41	-10.3
Garage	17.6	3:41	-4
Garbage Chute Shaft	-10.9	3:41	-32.5
Outside W. Side	25.2	3:41	3.6
Outside E. Side	21.6	3:41	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	On	[✓ Off]
Lobby Entrance Door	[✓ Open]	Shut
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-34	3:54	-54.8
Elevator Machine Room	-18	3:55	-38.8
Elevator Shaft	1	3:54	-19.8
12th Fl. corridor	-7	3:55	-27.8
12th Fl. garbage room	-7	3:55	-27.8
Unit 1212	-12	3:55	-32.8
Unit 1202	-9	3:56	-29.8
12th Fl. Supply Vent	-7	3:55	-27.8
Ground Fl. corridor	5.2	3:55	-15.5
Ground Fl. lobby vest.	19.6	3:55	-1.1
Ground Fl. by elevators	0.5	3:55	-20.2
Ground Fl. Supply vent	-3	3:55	-23.7
Unit 103	8.5	3:55	-12.2
Unit 111	11.1	3:55	-9.6
Garage	17.7	3:55	-3
Garbage Chute Shaft	-11	3:55	-31.7
Outside W. Side	25.4	3:55	4.7
Outside E. Side	20.7	3:55	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	On	[✓ Off]
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	[✓ Open]	Shut
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-33	4:07	-53.9
Elevator Machine Room	-18	4:08	-38.9
Elevator Shaft	1	4:07	-19.9
12th Fl. corridor	-7	4:10	-27.9
12th Fl. garbage room	-7	4:09	-27.9
Unit 1212	-12	4:09	-32.9
Unit 1202	-8	4:08	-28.9
12th Fl. Supply Vent	-7	4:08	-27.9
Ground Fl. corridor	1.9	4:07	-18.9
Ground Fl. lobby vest.	4.4	4:07	-16.4
Ground Fl. by elevators	1.9	4:07	-18.9
Ground Fl. Supply vent	-3.2	4:07	-24
Unit 103	7.4	4:07	-13.4
Unit 111	9.8	4:07	-11
Garage	17.7	4:07	-3.1
Garbage Chute Shaft	-10.8	4:07	-31.6
Outside W. Side	25.4	4:07	4.6
Outside E. Side	20.8	4:07	0

C.M.H.C. Compartmentalization In High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	On	[✓ Off]
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	[✓ Open]	Shut
Parking Garage Door	Open	[✓ Shut]

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-33	4:20	-54.2
Elevator Machine Room	-18	4:21	-39.2
Elevator Shaft	1	4:20	-20.2
12th Fl. corridor	-7	4:22	-28.2
12th Fl. garbage room	-7	4:22	-28.2
Unit 1212	-12	4:23	-33.2
Unit 1202	-8	4:22	-29.2
12th Fl. Supply Vent	-7	4:23	-28.2
Ground Fl. corridor	4.6	4:35	-16.5
Ground Fl. lobby vest.	1	4:35	-20.1
Ground Fl. by elevators	-2	4:35	-23.1
Ground Fl. Supply vent	-2.7	4:35	-23.8
Unit 103	5	4:35	-16.1
Unit 111	11	4:35	-10.1
Garage	17.4	4:35	-3.7
Garbage Chute Shaft	-10.9	4:35	-32
Outside W. Side	24.4	4:35	3.3
Outside E. Side	21.1	4:35	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fans	On	[✓ Off]
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	[✓ Open]	Shut

Weather Condition: Wind

Date: Feb. 15, 1995

Point Measured	Pressure Difference	Time	Reference Pressure
Roof	-36	3:26	-56.2
Elevator Machine Room	-19	3:28	-39.2
Elevator Shaft	1	3:27	-19.2
12th Fl. corridor	-7	3:28	-27.2
12th Fl. garbage room	-7	3:29	-27.2
Unit 1212	-13	3:30	-33.2
Unit 1202	-9	3:29	-29.2
12th Fl. Supply Vent	-7	3:30	-27.2
Ground Fl. corridor	4.8	3:27	-15.3
Ground Fl. lobby vest.	1.6	3:27	-18.5
Ground Fl. by elevators	-1.4	3:27	-21.5
Ground Fl. Supply vent	-4	3:27	-24.1
Unit 103	7.2	3:27	-12.9
Unit 111	11.1	3:27	-9
Garage	22.1	3:27	2
Garbage Chute Shaft	-10.5	3:27	-30.6
Outside W. Side	23.8	3:27	3.7
Outside E. Side	20.1	3:27	0

APPENDIX B

Comparison of Measured and Simulated Pressure Differences for Test Building - No Wind

Field Measurements of Pressure Differences in High-Rise Building

Definition of Terms in Tables

Condition of Building:	The five rows under this heading at the top of the page indicate how the doors and ventilation fans were set during the measurements taken. The shaded box describes the condition of that element.
Weather Condition:	Sets of measurements were taken when the windspeed was above 10 km/hr (Wind) and when the windspeed was below 10 km/hr (No Wind).
Point Measured:	The pressure difference between the reference point and the point described under this heading was measured and recorded as the Pressure Difference, in Pascals (Pa.) The reference point for the first eight measurements was the North stairwell at the 12th floor; the reference point for the last ten measurements was the North stairwell at the ground floor.
Pressure Difference:	The measured pressure difference between the reference point and the point measured, in Pascals (Pa). A positive reading means that the point measured was higher pressure than the reference; a negative means that the point measured was lower pressure than the reference.
Reference Pressure:	The absolute pressure of the air in the stairwell changes depending on the set-up of the building. In order to compare pressure differences between different sets of measurements, they must be referenced to a point whose absolute pressure does not change with the building set-up. The point used for this is the Outside East Side, Ground Floor measurement. All the pressure differences in this column are between the "Point Measured" and Outside East Side.

Simulated Reference Pressure: The numbers in this column (which is only on the Tables in Appendix B - No Wind Measurements) are the calculated pressure differences between the Point Measured and the absolute reference, taken to be Outside East Side, Ground Floor. The numbers are calculated by the CONTAM93 simulation program under the same building set-up and weather conditions that the measurements were made. These numbers can therefore be compared with the measurements to calibrate the CONTAM93 simulation to the measurements.

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	On	Off
Lobby Entrance Door	Open	Shut
Lobby/Corridor Door	Open	Shut
Lobby Elevator Door	Open	Shut
Parking Garage Door	Open	Shut

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-49	2:18	-55.2	N/A
Elevator Machine Room	-30	2:18	-36.2	-37.6
Elevator Shaft	3	2:18	-3.2	-5.3
12th Fl. corridor	-7	2:18	-13.2	-13.8
12th Fl. garbage room	-8	2:18	-14.2	-14.2
Unit 1212	-17	2:18	-23.2	-22.6
Unit 1202	-11	2:18	-17.2	-20.9
12th Fl. Supply Vent	-11	2:18	-17.2	41.4
Ground Fl. corridor	6	2:21	-0.1	1.2
Ground Fl. lobby vest.	4.9	2:21	-1.2	-0.3
Ground Fl. by elevators	4.6	2:21	-1.5	-0.3
Ground Fl. Supply vent	8.4	2:21	2.3	31.8
Unit 103	4.4	2:21	-1.7	-0.1
Unit 111	4.9	2:21	-1.2	0.3
Garage	6.9	2:21	0.8	1
Garbage Chute Shaft	-19.7	2:21	-25.8	-25.8
Outside W. Side	10.8	2:21	4.7	N/A
Outside E. Side	6.1	2:21	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	[✓ On]	Off
Lobby Entrance Door	[✓ Open]	Shut
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-49	2:31	-55.5	N/A
Elevator Machine Room	-29	2:31	-35.6	-37.6
Elevator Shaft	3	2:31	-3.6	-5.3
12th Fl. corridor	-7	2:31	-13.6	-13.8
12th Fl. garbage room	-8	2:31	-14.6	-14.2
Unit 1212	-17	2:31	-23.6	-22.6
Unit 1202	-10	2:31	-16.6	-20.9
12th Fl. Supply Vent	-10	2:31	-16.6	41.4
Ground Fl. corridor	6.1	2:34	-0.4	1.2
Ground Fl. lobby vest.	5.9	2:34	-0.6	0
Ground Fl. by elevators	5	2:34	-1.5	-0.2
Ground Fl. Supply vent	8.5	2:34	2	31.8
Unit 103	4.5	2:34	-2	0
Unit 111	5	2:34	-1.5	0.3
Garage	7.1	2:34	0.6	1
Garbage Chute Shaft	-19.7	2:34	-26.2	-25.8
Outside W. Side	9.6	2:34	3.1	N/A
Outside E. Side	6.5	2:34	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	[✓ Open]	Shut
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-50	2:43	-56.9	N/A
Elevator Machine Room	-30	2:43	-36.9	-37.6
Elevator Shaft	3	2:43	-3.9	-5.2
12th Fl. corridor	-8	2:43	-14.9	-13.8
12th Fl. garbage room	-8	2:43	-14.9	-14.1
Unit 1212	-18	2:43	-24.9	-22.6
Unit 1202	-11	2:43	-17.9	-20.9
12th Fl. Supply Vent	-10	2:43	-16.9	41.4
Ground Fl. corridor	5.4	2:47	-1.4	0.5
Ground Fl. lobby vest.	5.5	2:47	-1.3	0.4
Ground Fl. by elevators	5.4	2:47	-1.4	0.5
Ground Fl. Supply vent	8.1	2:47	1.3	31.8
Unit 103	5.1	2:47	-1.7	-0.1
Unit 111	4.9	2:47	-1.9	-0.1
Garage	7.2	2:47	0.4	0.8
Garbage Chute Shaft	-19.6	2:47	-26.4	-25.8
Outside W. Side	9.6	2:47	2.8	N/A
Outside E. Side	6.8	2:47	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	[✓ Open]	Shut
Parking Garage Door	Open	[✓ Shut]

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-50	2:59	-56.6	N/A
Elevator Machine Room	-29	2:59	-35.6	-37.5
Elevator Shaft	3	2:59	-3.6	-4.9
12th Fl. corridor	-8	2:59	-14.6	-13.6
12th Fl. garbage room	-8	2:59	-14.6	-14
Unit 1212	-18	2:59	-24.6	-22.5
Unit 1202	-11	2:59	-17.6	-20.8
12th Fl. Supply Vent	-11	2:59	-17.6	41.4
Ground Fl. corridor	5.2	3:02	-1.3	1.1
Ground Fl. lobby vest.	-0.7	3:02	-7.2	-1.5
Ground Fl. by elevators	-1.3	3:02	-7.8	-1.9
Ground Fl. Supply vent	8.3	3:02	1.8	31.9
Unit 103	4	3:02	-2.5	-0.2
Unit 111	4.9	3:02	-1.6	0.2
Garage	6.8	3:02	0.3	1
Garbage Chute Shaft	-19.8	3:02	-26.3	-25.7
Outside W. Side	7.2	3:02	0.7	N/A
Outside E. Side	6.5	3:02	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	[✓ On]	Off
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	[✓ Open]	Shut

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-50	3:21	-55.5	N/A
Elevator Machine Room	-30	3:21	-35.5	-37.5
Elevator Shaft	3	3:21	-2.5	-4.8
12th Fl. corridor	-8	3:21	-13.5	-13.5
12th Fl. garbage room	-8	3:21	-13.5	-13.8
Unit 1212	-18	3:21	-23.5	-22.4
Unit 1202	-11	3:21	-16.5	-20.7
12th Fl. Supply Vent	-11	3:21	-16.5	41.8
Ground Fl. corridor	6.3	3:24	0.9	3.2
Ground Fl. lobby vest.	4.7	3:24	-0.7	0.2
Ground Fl. by elevators	4.7	3:24	-0.7	0.2
Ground Fl. Supply vent	8.5	3:24	3.1	32.3
Unit 103	4.7	3:24	-0.7	1.2
Unit 111	5	3:24	-0.4	1.6
Garage	9	3:25	3.6	3.7
Garbage Chute Shaft	-19.7	3:25	-25.1	-24.6
Outside W. Side	9.5	3:27	4.1	N/A
Outside E. Side	5.4	3:27	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	On	Off
Lobby Entrance Door	Open	Shut
Lobby/Corridor Door	Open	Shut
Lobby Elevator Door	Open	Shut
Parking Garage Door	Open	Shut

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-33	3:43	-54.1	N/A
Elevator Machine Room	-19	3:43	-40.1	-41.8
Elevator Shaft	2	3:43	-19.1	-21.3
12th Fl. corridor	-7	3:43	-28.1	-28.6
12th Fl. garbage room	-7	3:43	-28.1	-28.7
Unit 1212	-12	3:43	-33.1	-32.2
Unit 1202	-8	3:43	-29.1	-31.4
12th Fl. Supply Vent	-7	3:43	-28.1	-23.4
Ground Fl. corridor	5.3	3:45	-15.7	-7.9
Ground Fl. lobby vest.	2	3:45	-19	-14.5
Ground Fl. by elevators	-1.3	3:45	-22.3	-17.8
Ground Fl. Supply vent	-3.5	3:45	-24.5	-23
Unit 103	8.5	3:47	-12.5	-7.2
Unit 111	11.6	3:47	-9.4	-6.6
Garage	19.3	3:47	-1.7	-5
Garbage Chute Shaft	-14.4	3:47	-35.4	-34.7
Outside W. Side	19.6	3:48	-1.4	N/A
Outside E. Side	21	3:48	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	On	[✓ Off]
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	[✓ Open]	Shut
Parking Garage Door	Open	[✓ Shut]

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-35	4:33	-60.4	N/A
Elevator Machine Room	-20	4:33	-45.4	-41.7
Elevator Shaft	2	4:33	-23.4	-21.1
12th Fl. corridor	-7	4:33	-32.4	-28.5
12th Fl. garbage room	-7	4:33	-32.4	-28.6
Unit 1212	-12	4:33	-37.4	-32.1
Unit 1202	-9	4:33	-34.4	-31.3
12th Fl. Supply Vent	-7	4:33	-32.4	-33.6
Ground Fl. corridor	5.3	4:37	-20	-8
Ground Fl. lobby vest.	0.5	4:37	-24.8	-15.8
Ground Fl. by elevators	-2.1	4:37	-27.4	-19.4
Ground Fl. Supply vent	-3.2	4:37	-28.5	-23
Unit 103	8.3	4:38	-17	-7.3
Unit 111	12.6	4:38	-12.7	-6.7
Garage	19.3	4:39	-6	-5.1
Garbage Chute Shaft	-15.2	4:39	-40.5	-34.8
Outside W. Side	26.3	4:39	1	N/A
Outside E. Side	25.3	4:39	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	On	[✓ Off]
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	[✓ Open]	Shut

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-34	3:31	-54.7	N/A
Elevator Machine Room	-20	3:31	-40.7	-41.5
Elevator Shaft	0	3:31	-20.7	-20.3
12th Fl. corridor	-8	3:31	-28.7	-28
12th Fl. garbage room	-9	3:31	-29.7	-29.1
Unit 1212	-14	3:31	-34.7	-31.8
Unit 1202	-10	3:31	-30.7	-30.9
12th Fl. Supply Vent	-8	3:31	-28.7	-23
Ground Fl. corridor	4.5	3:34	-16.1	-4.3
Ground Fl. lobby vest.	0.7	3:34	-19.9	-13.6
Ground Fl. by elevators	-2.5	3:34	-23.1	-16.6
Ground Fl. Supply vent	-4.8	3:35	-25.4	-22.3
Unit 103	7.2	3:35	-13.4	-3.4
Unit 111	11.2	3:36	-9.4	-4.9
Garage	23.3	3:36	2.7	2.1
Garbage Chute Shaft	-14.9	3:36	-35.5	-32
Outside W. Side	24.6	3:36	4	N/A
Outside E. Side	20.6	3:36	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	On	[✓ Off]
Lobby Entrance Door	[✓ Open]	Shut
Lobby/Corridor Door	Open	[✓ Shut]
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-33	3:53	-56.6	N/A
Elevator Machine Room	-19	3:53	-42.6	-41.7
Elevator Shaft	2	3:53	-21.6	-21
12th Fl. corridor	-7	3:53	-30.6	-28.4
12th Fl. garbage room	-7	3:53	-30.6	-28.5
Unit 1212	-12	3:53	-35.6	-32.1
Unit 1202	-8	3:53	-31.6	-31.2
12th Fl. Supply Vent	-7	3:53	-30.6	-23.2
Ground Fl. corridor	5.7	3:56	-17.8	-7.7
Ground Fl. lobby vest.	22.8	3:56	-0.7	0
Ground Fl. by elevators	0.2	3:56	-23.3	-16.5
Ground Fl. Supply vent	-3.3	3:57	-26.8	-22.8
Unit 103	8.7	3:57	-14.8	-7.1
Unit 111	12.5	3:58	-11	-6.5
Garage	19.7	3:58	-3.8	-4.9
Garbage Chute Shaft	-14.7	3:58	-38.2	-34.5
Outside W. Side	23.6	4:00	0.1	N/A
Outside E. Side	23.5	4:02	0	0

C.M.H.C. Compartmentalization in High-Rise Residential Buildings
Field Measurements

Condition of Building		
Corridor Fan	On	[✓ Off]
Lobby Entrance Door	Open	[✓ Shut]
Lobby/Corridor Door	[✓ Open]	Shut
Lobby Elevator Door	Open	[✓ Shut]
Parking Garage Door	Open	[✓ Shut]

Weather Condition: No Wind

Date: 3-Mar-95

Point Measured	Pressure Difference	Time	Reference Pressure	Simulated Reference Pressure
Roof	-34	4:24	-58.5	N/A
Elevator Machine Room	-20	4:24	-44.4	-41.6
Elevator Shaft	2	4:24	-22.5	-20.7
12th Fl. corridor	-7	4:24	-31.5	-28.3
12th Fl. garbage room	-7	4:24	-31.5	-28.5
Unit 1212	-12	4:24	-36.5	-32
Unit 1202	-9	4:24	-33.5	-31.2
12th Fl. Supply Vent	-7	4:24	-31.5	-23.2
Ground Fl. corridor	1.8	4:27	-22.6	-12.4
Ground Fl. lobby vest.	4.9	4:27	-19.5	-10.2
Ground Fl. by elevators	1.8	4:27	-22.6	-12.4
Ground Fl. Supply vent	-3.6	4:27	-28	-22.8
Unit 103	7.4	4:28	-17	-9.7
Unit 111	10.9	4:28	-13.5	-8.7
Garage	19.3	4:28	-5.1	-6.3
Garbage Chute Shaft	-14.7	4:29	-39.1	-34.7
Outside W. Side	26.9	4:30	2.5	N/A
Outside E. Side	24.4	4:30	0	0