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# Suite Ventilation Characteristics of Current Canadian Mid- and High-Rise Residential Buildings

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## ABSTRACT

This paper characterizes ventilation in residential suites located in ten buildings in major metropolitan areas of Canada. All buildings were between six and thirty-two stories tall and were built between 1990 and 1995.

The key findings from field performance tests of these buildings were:

1. Corridor supply airflows usually did not meet design flows.
2. Makeup air paths for suite exhaust were not properly designed.
3. Suite access door leakage was highly variable and usually did not meet smoke control requirements.
4. Airflow from the corridor through the suite access door leakage appeared to be the primary ventilation air supply for suites.
5. Suites were usually well-ventilated, but some were marginally- or under-ventilated.
6. Poor pressure control often allowed transfer air from one suite to another. Inter-suite transfer air fractions ranged from 0 to 45%, with an average of 19%.

In summary, this work showed suite ventilation can be highly influenced by corridor supply flows, by the treatment of corridor access doors, and by transfer airflows. As a result, suite ventilation at any given time in current mid- and high-rise residential buildings is very difficult to predict.

To ensure suite ventilation performs as intended under all operating conditions, the building industry needs to address the identified problems through improved ventilation design, operation, and maintenance practices.

## INTRODUCTION

Providing reliable, controlled ventilation for every suite in a mid- and high-rise residential building is essential to maintaining the health, safety, and comfort of

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occupants. In addition, controlled ventilation is important for maintaining building envelope durability and can also reduce the total energy consumption of the building.

The National Building Code of Canada (NBCC 1990) was the code applicable to the buildings tested in the reported work. It has few specific ventilation requirements and is notable in that it does not require mechanical ventilation systems. However, in spite of this, typical mid- and high-rise residential buildings have at least two separate types of mechanical ventilation systems. One type supplies conditioned 100% outdoor air through ducts to the common corridors on each floor, with no return. The other type exhausts contaminated air from suites through ducts. One or more exhaust ducts may lead from fans within each suite directly to outdoors. Alternatively, one exhaust duct may connect several suites together before exhausting to outdoors through a common fan.

One design intent for these supply and exhaust systems is effectively to pressurize common corridors (Theaker and Wray 2000). Pressurization is seen as a means to satisfy building code requirements, such as preventing contaminated air from moving between suites through the corridors and providing makeup air for suite exhaust systems.

Suite ventilation itself is often at best only a secondary intent of these mechanical systems. As a result, designers seldom specify mechanical systems to provide *controlled* airflows at all times to or from the suites or to distribute air within each suite. Instead, to ventilate each suite, they often rely upon uncontrolled transfer airflows from the common corridor around suite access doors or through transfer grilles, intermittent or continuous use of exhaust fans, uncontrolled outdoor air infiltration and natural ventilation across the building envelope, and haphazard mixing patterns within the suites.

Due to revisions incorporated into the 1995 National Building Code of Canada (NBCC 1995), the “design” strategy described above became insufficient. Now, residential buildings must at least provide a capability to supply mechanical ventilation to every suite at rates defined by ASHRAE Standard 62 (1990a). This revision is a first attempt at recognizing the need for *controlled* ventilation that delivers conditioned and uncontaminated air to occupied regions of suites.

Performance-based building codes are now being developed in Canada. To be able to use such codes, there is a need to understand the complex synergistic effects of building configuration, weather, and mechanical system operation on suite ventilation. Unfortunately, designers have little or no data to assess the performance implications of the many parameters that affect suite ventilation. As a step toward addressing this issue, this paper provides “snapshots” of suite ventilation characteristics in ten Canadian mid- and high-rise residential buildings.

## BUILDING LOCATIONS AND TEST WEATHER CONDITIONS

Four of the ten test buildings were located in a maritime climate (Vancouver, British Columbia); three in a western climate (Winnipeg, Manitoba); and three in a central climate (two in Toronto, Ontario and one in Montreal, Quebec). The tests were carried out over a one-day period in each building during late February and early March 1996. Table 1 describes the range of weather conditions during the tests.

**TABLE 1. Test Period Weather Conditions**

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

## BUILDING AND SUITE CHARACTERISTICS

All the test buildings were built between 1990 and 1995. Occupancy in all but one of these buildings was near 100%. In Building 1, which was new, the occupancy was only about 30% of its maximum. One suite in each building was tested. All the test suites were corner suites with two exterior walls, except in Buildings 4, 6, and 7. Each of these three other test suites had only one exterior wall. Table 2 lists several general configuration characteristics of the test buildings and suites.

**TABLE 2. General Characteristics of Test Buildings and Suites**

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

## Mechanical Supply and Exhaust Systems

Every test building had a rooftop corridor supply air system equipped with a heating section. These systems operated continuously during the tests, except in Building 7. In this building, the corridor supply air system was out of service.

The exhaust systems are described in more detail here, because of the diversity of approaches. Seven of the ten test buildings had separate intermittent exhaust systems for the kitchen and bathroom(s) in each suite. Each of these systems was ducted laterally to outdoors. All of these systems were off during the overnight tracer gas tests.

Building 7 had 15 intermittent central exhaust systems that served either the bathrooms or kitchens of several stacked suites. Each of these systems had a rooftop exhaust fan controlled by a time clock, which switched the fans on at 07:00 and off at 23:00. The kitchen exhaust system in each suite also had an intermittent inline fan that could be operated from within the suite. At the time of testing, some of the rooftop central exhaust fans were out of service, including the one serving the bathroom of the test suite (and of all suites above and below). However, the rooftop fan for the kitchen exhaust of the test suite was operative. During the overnight tracer gas tests, the bathroom and kitchen exhaust fans for the test suite were off.

The remaining two test buildings (8 and 10) each had one continuous central exhaust system that served the kitchens and bathrooms of several suites at a time. In Building 8, the exhaust system also served ensuite storage rooms. In both buildings, the exhaust system had several vertical shafts that connected together to a single central rooftop exhaust fan. The fan operated continuously during all tests.

## Suite Access Doors

Typically, primary access to suites in these buildings is through a single door between the suite and the adjacent common corridor. Leaks around these doors are often the largest leakage area between the corridor and suite. Geometric characteristics of the door for each test suite are listed in Table 3. Door-frame gap data were not collected for Buildings 1 and 2, because the use of these data in theoretical calculations of leakage area was not recognized until the tests in Building 3.

**TABLE 3. Geometric Characteristics of Suite Access Doors**

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

The suite access door in Building 9 fit poorly in its frame. This door could swing in and out at the latch side about 6 mm (0.25 in), even when the door was latched. This range of motion was due to a significantly oversized latch hole in the door frame. The access doors for the other test suites did not move significantly when latched.

Weather-stripping is an important characteristic of these doors, because it affects the door leakage area and is subject to change throughout the life-cycle of the building. Three of the ten test suites had fully weather-stripped access doors (Buildings 1, 3, and 8). However, the weather-stripping on the access doors for these three suites was often not completely in contact with some part of the door, threshold, or floor. Two other test suites had partially weather-stripped doors (Buildings 4 and 7). There was a spring-loaded sweep on the bottom of the access door in Building 4, but this sweep did not contact the floor. In Building 7, only about 67% of the latch side of the door was weather-stripped. There was no weather-stripping on the access doors of the other five test suites (Buildings 2, 5, 6, 9, and 10).

## TEST RESULTS

The test results are presented as seven groups of comparisons. These results are based on analyses of field data that were collected in the ten test buildings. Brief descriptions of the relevant test methods that were used are presented with each comparison. Details are available in a report by Sheltair Scientific (1998).

### 1. Corridor Supply Airflows

Figure 1 shows a comparison of the design and measured corridor supply airflows for the ten test buildings. These airflows are at standard conditions on a per suite basis. There are no measured data for Building 7, because its corridor supply system was inoperable.

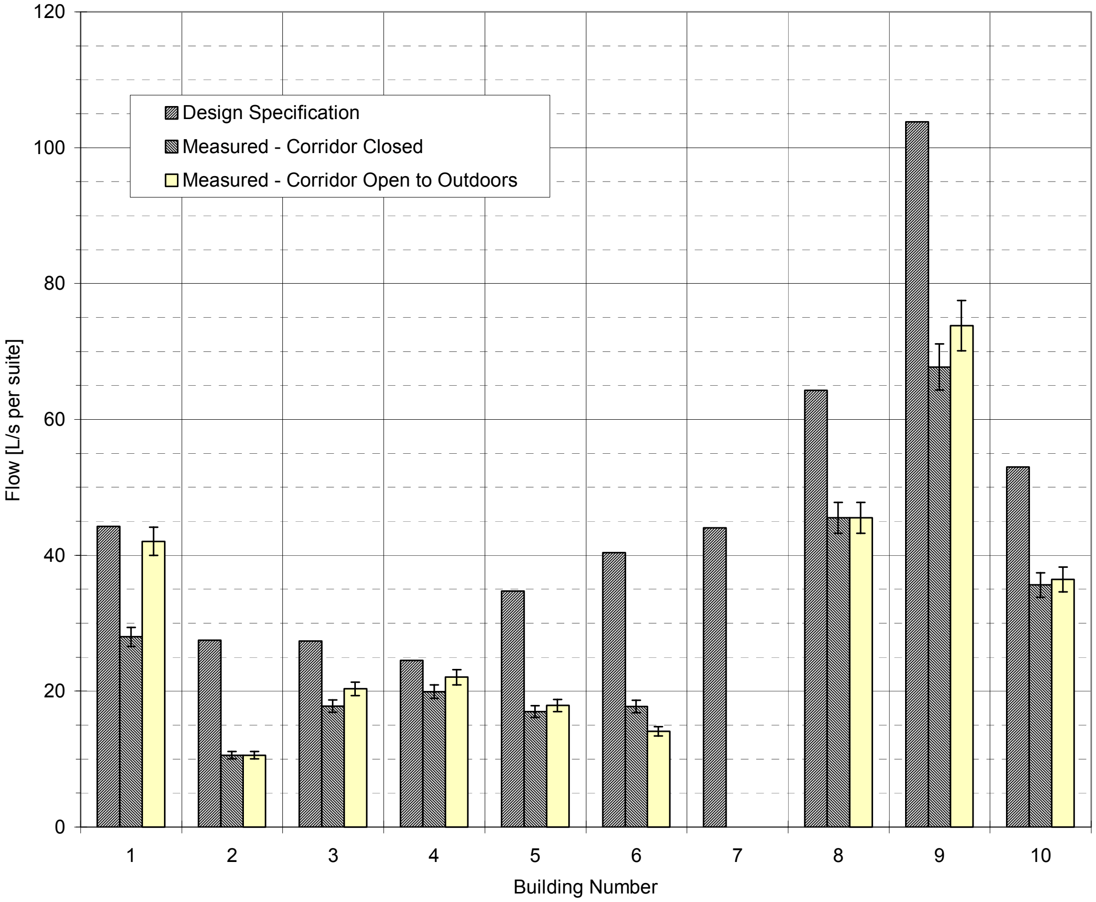
The corridor supply airflow per suite was calculated by dividing the total measured corridor supply airflow equally among all suites adjoining the corridor. This analysis used the common design assumption that leakage areas of the suite access doors are similar and that design airflow rates are based only on the number of suites or on the capacity of installed exhaust devices in these suites. The design airflows in Figure 1 were derived from a review of available drawings and specification documents for the test buildings.

Corridor supply airflows were measured using a fan-compensated flow hood with a rated accuracy of about 5%. The measurement procedure was based on the procedure described in Appendix A4 of ASHRAE Standard 136 (1993a). Two separate tests were carried out in the corridor adjoining the test suite.

The first test occurred under normal operating conditions during the day following the overnight tracer gas tests. Normal conditions were defined as the suite's exterior doors and windows closed, its interior doors open, the corridor supply air and central exhaust air systems operating (unless these systems could not be operated), and the intermittent ventilation equipment in the test suite not operating.

A second corridor supply airflow test was carried out immediately after the first test, but with significantly increased leakage between the corridor and outdoors. The purpose of this test was to examine the impact on supply airflows of changing the corridor leakage area. Such a change can occur when occupants or building owners open corridor windows.

**FIGURE 1. Comparison of Corridor Supply Airflows (Design vs. Measured)**



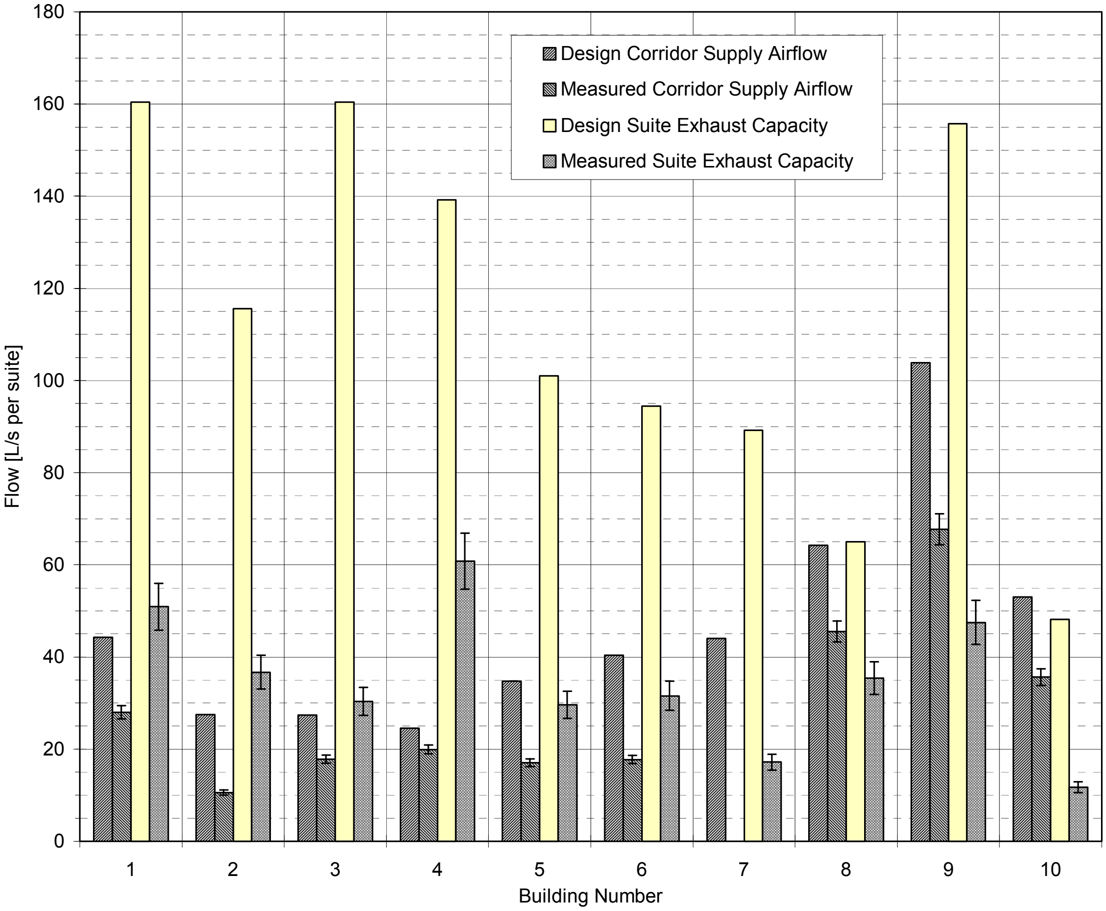
## 2. Corridor Supply Airflows vs. Suite Exhaust Capacities

Figure 2 shows a comparison of the design specifications for the corridor supply airflows and suite exhaust airflows for the ten test buildings. It also shows the measured airflows for these buildings. These airflows are at standard conditions and are presented on a per suite basis.

The design and measured corridor supply airflows in Figure 2 are the same as in Figure 1. Measured supply airflows for each building are from the closed corridor test described earlier. Exhaust capacities in Figure 2 are based on information that was derived from a review of available building drawings and specification documents.

The measured exhaust capacity per suite for each building was determined with all exhaust devices in the test suite operating and using a single-point test based on the measurement procedure described in Appendix A1 of ASHRAE Standard 136 (1993a). The rated accuracy of the flow measurement was about 5%. These capacities represent the exhaust system performance while the test suite was depressurized using the exhaust fans and a blower door to 20 Pa (0.08 in w.c.) with respect to outdoors. That depressurization was selected to reduce the likelihood of wind-induced pressure interference in the measurement and to standardize the results.

**FIGURE 2. Comparison of Corridor Supply Airflows and Suite Exhaust Capacities (Design vs. Measured)**



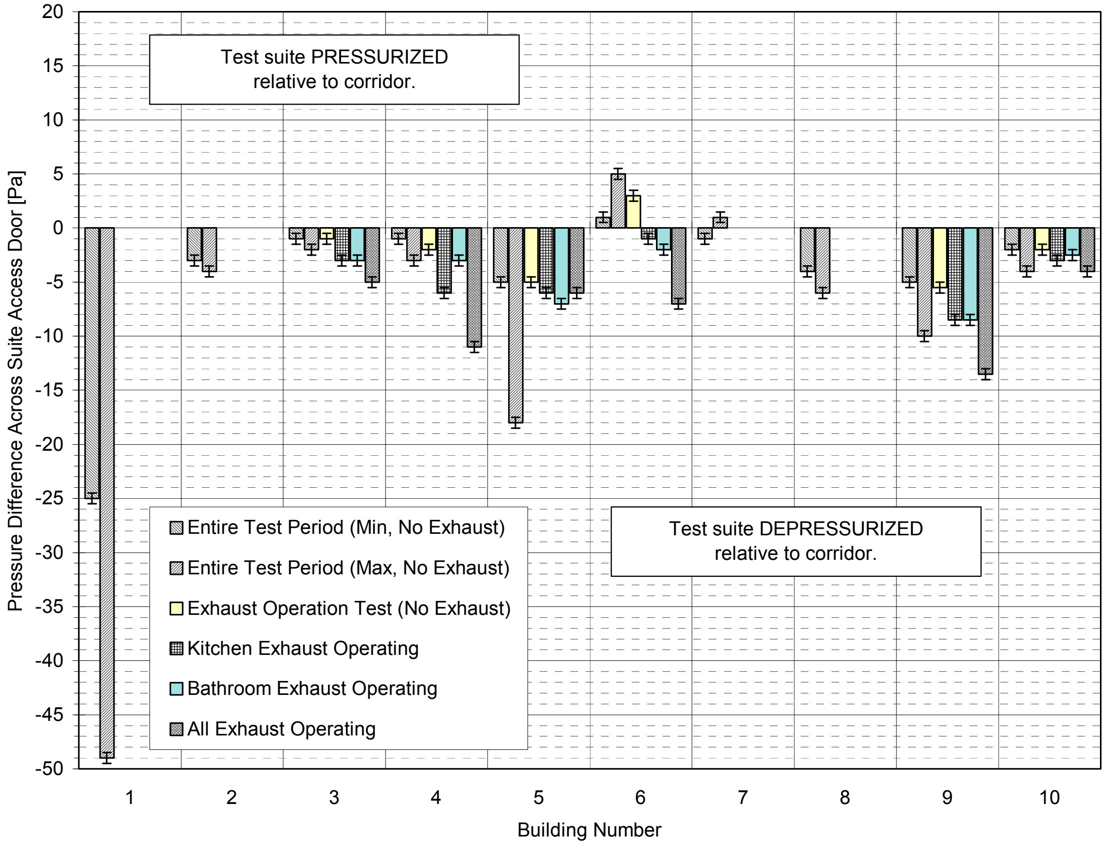
Actual flows through the suite exhaust devices under normal operating conditions are probably near the measured capacities. During prototype trials of a fan test rig (Sikorski and Moffatt 1996), performance tests were carried out on residential exhaust fans similar to those found in the test suites. Relationships between flow and back pressure were developed. Based on those relationships, it is expected that a 20 Pa suite depressurization relative to outdoors will reduce exhaust flows by less than 10% compared to the flow that would occur under normal suite depressurization when the fan is operating.

## 3. Pressure Differences Between the Test Suite, Corridor, and Outdoors

Figures 3 and 4 show the range of measured pressure differences between the suite and corridor or outdoors in the ten test buildings during each of the one-day test periods. The measurement accuracy was about ±0.5 Pa (0.002 in w.c.).

Figures 3 and 4 also show the measured pressure differences between the suite and corridor or outdoors when exhaust equipment was operated in the test suite and when the exhaust equipment was turned off and the ensuite grilles were blocked. The pressure differences due to exhaust operation were collected in six of the ten buildings (3 through 6, 9, and 10). Only one pressure difference is shown for the case when one of the two bathroom fans in the test suite of Building 9 was operating. Identical results were obtained when either bathroom fan was operated in this suite.

**FIGURE 3. Measured Pressure Differences between Suite and Corridor (With and Without Suite Exhaust)**



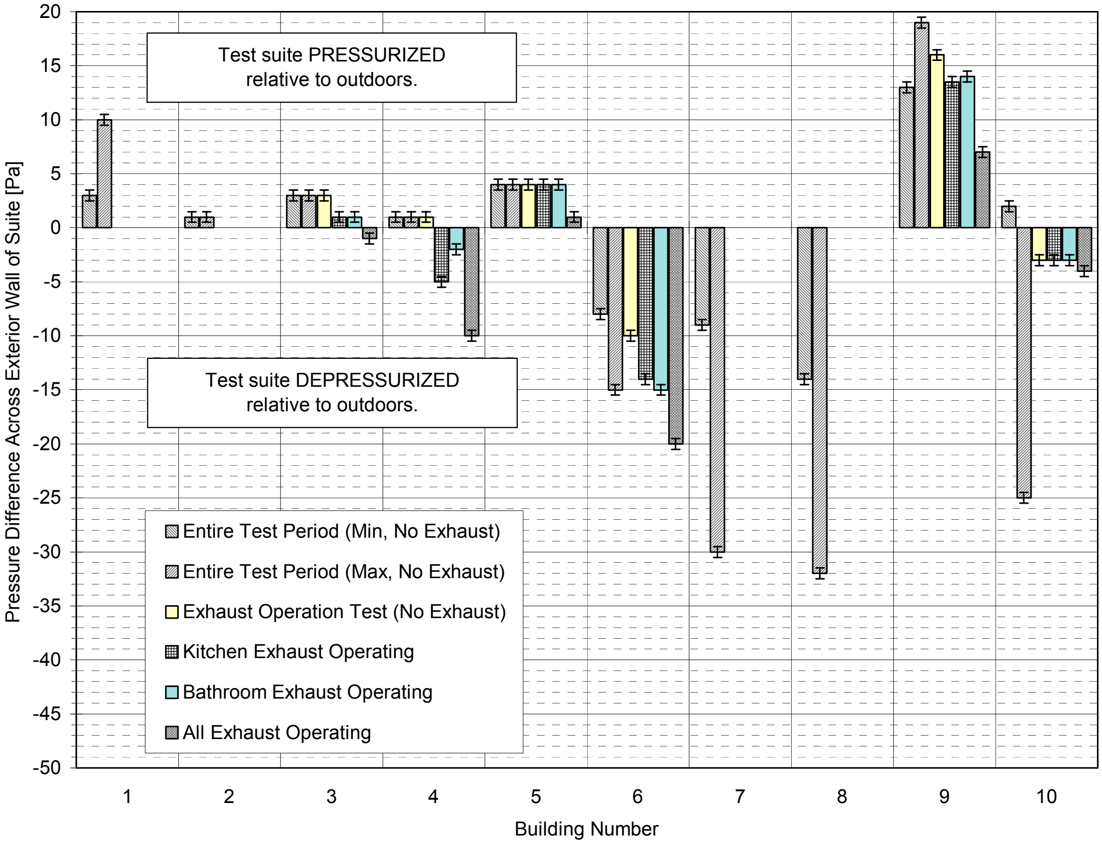
In all cases, positive pressure differences represent suite pressurization relative to the corridor or outdoors; negative pressure differences represent suite depressurization.

## 4. Leakage Areas of Suite Access Doors

Figure 5 shows the measured and theoretical equivalent leakage areas (ELA) of the access door from each test suite to the adjacent corridor. These leakage areas are referenced to a pressure difference of 10 Pa (0.04 in w.c.) and a discharge coefficient of 0.611.

The measured ELAs include the leakage between the door and its frame, the leakage of the door itself, and the effects of weather-stripping. ELA was determined using a multi-point test that incorporated the requirements of CGSB Standard 149.10 (1986) and ASTM Standard E783 (1984). The uncertainty in the calculated ELAs was calculated in accordance with ASHRAE Guideline 2 (1990b) and is about 5 to 7%.

**FIGURE 4. Measured Pressure Differences between Suite and Outdoors (With and Without Suite Exhaust)**



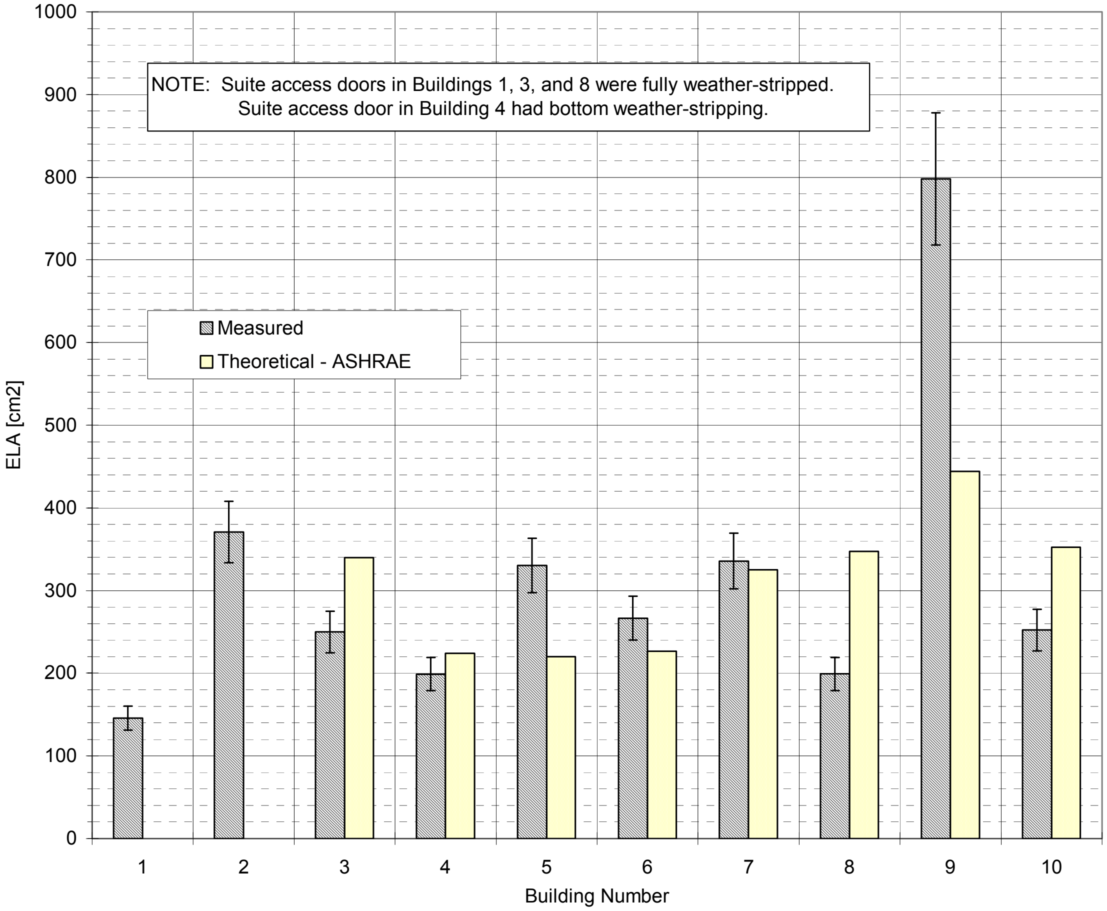
Theoretical ELAs for the suite access doors were determined using the method of Gross and Haberman, as described by ASHRAE (1992). Unlike the measured ELAs, the theoretical ELAs only include door-frame gap leakage and exclude the effects of weather-stripping. The ELA of the door itself is not expected to be significant in comparison to the gap leakage. Theoretical ELAs were not calculated for the suite access doors of Buildings 1 and 2, because their door-frame gaps were not measured.

## 5. Range of Airflows through Suite Access Doors During Tests vs. Measured Corridor Supply Airflows

Figure 6 shows the range of “measured” airflows through the suite access doors in the ten test buildings during the tests. A comparison of these airflows with the measured corridor supply airflows is also included. The airflows are presented on a per suite basis. Positive airflows represent flows from the corridor to the test suite. Negative airflows represent the reverse of these flows. The measured corridor supply airflow for each building in Figure 6 is from the closed corridor test described earlier.

The “measured” airflows through the suite access doors were not directly measured during the tests. Instead, these “measured” flows were calculated using Sherman’s (1980) relation $Q = C (\Delta P)^n$. For each test suite, the flow coefficient and pressure exponent of the test suite’s access door that had been calculated using door leakage test data were combined with minimum and maximum pressure differences that had been measured between the test suite and adjoining corridor at the time of the tests while the suite was operating normally. It is estimated that the uncertainty in the "measured" flows is in the order of about 5 to 10%.

**FIGURE 5. Comparison of Leakage Areas of Suite Access Doors (Measured vs. Theoretical)**

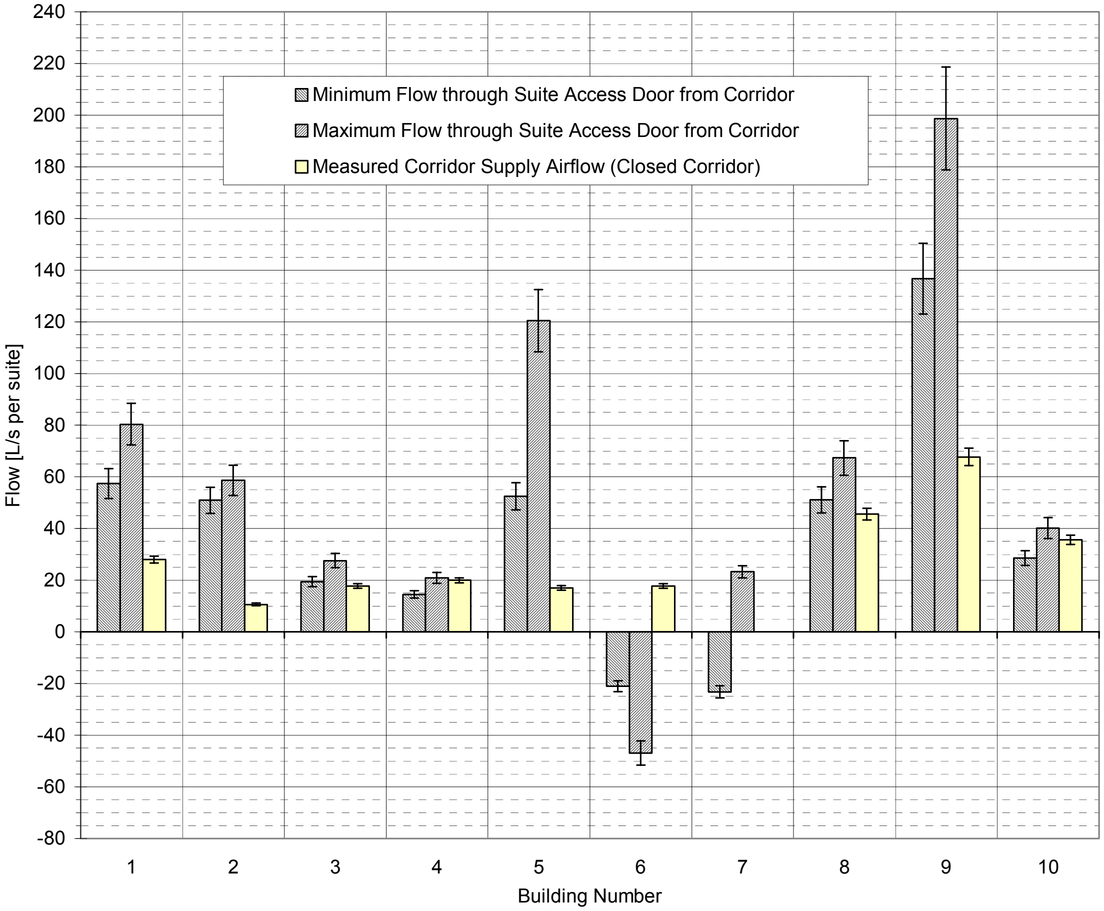


The "measured" airflow through the suite access door for Building 8 includes estimates of the flows through the transfer duct adjacent to the door. This duct connects the test suite and adjoining corridor in parallel with the door. The leakage area of the transfer duct was not measured. Instead, it was estimated using manufacturer's flow versus pressure drop data for the grilles and standard duct design procedures (ASHRAE 1993b). Measured pressure differences between the test suite and corridor were then used to estimate the airflows through this transfer duct. The duct airflows were estimated to be in the range of 19 to 25 L/s (40 to 53 cfm), based on the measured corridor pressurization of 4 to 7 Pa (0.02 to 0.03 in w.c.) relative to the test suite.

## 6. Air Exchange Rates for Suites and Their Rooms

Figure 7 shows the range of measured air exchange rates for various rooms in each test suite. These rates were determined using an R134a tracer gas decay test based on ASTM Standard E741 (1983). The measurements in each test suite were made during an eight-to ten-hour overnight period while the unoccupied suite was operating normally. The uncertainty in the measured air exchange rates is estimated to be about 10%.

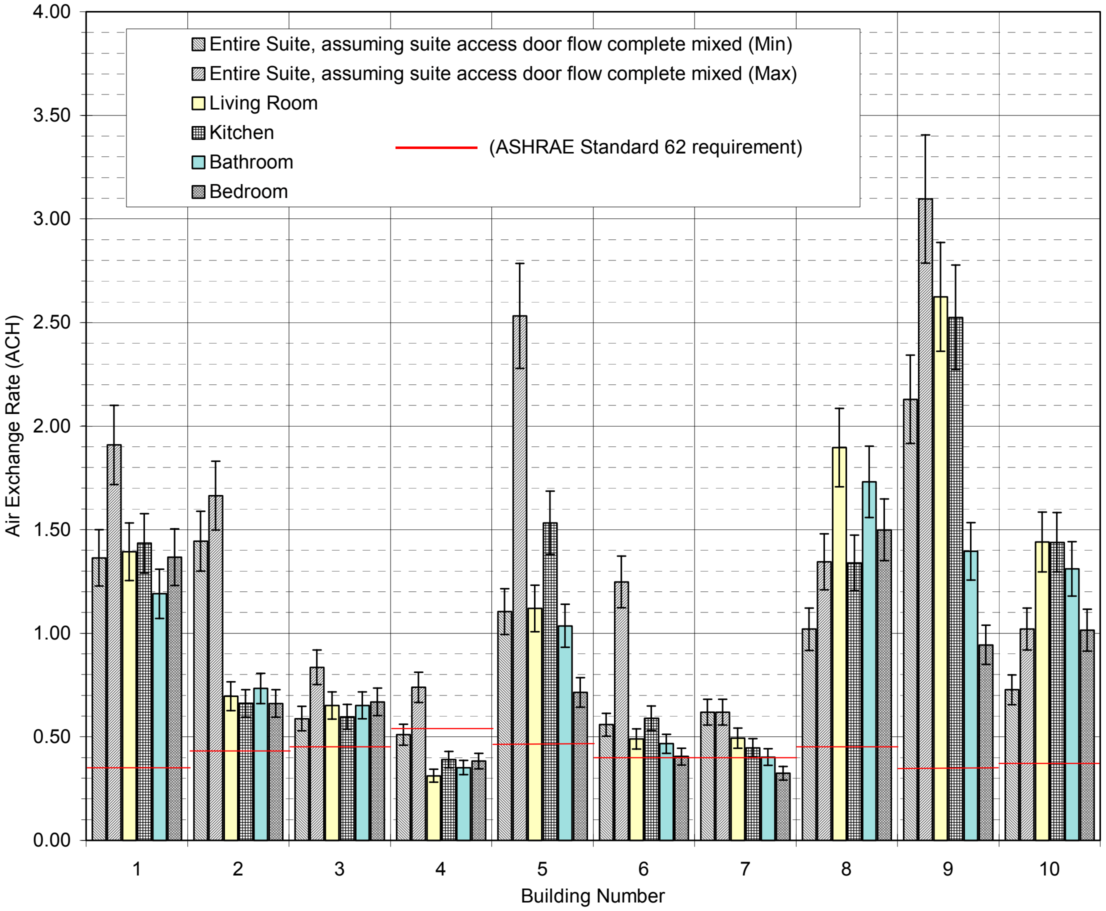
**FIGURE 6. Range of Airflows through Suite Access Doors During Tests vs. Measured Corridor Supply Airflows**



It is important to recognize that the measured air exchange rates represent minimum effective air change rates, because of the potential interference from interzonal transfers of tracer gas between rooms within the test suite. Actual effective air exchange rates at the time of the test could be greater. It should also be kept in mind that the measured air exchange rates do not necessarily represent outdoor air exchange. Instead, they represent the total amount of air entering or leaving a room. Therefore, some or all of this air may be transfer air from other spaces in the building.

Figure 7 also includes a comparison of the measured air exchange rates with the rates calculated using the range of "measured" airflows through the suite access doors (including the transfer duct for Building 8). For simplicity, only the magnitudes of the door flows were used in determining these rates. Each pair of door-flow-based air exchange rates was determined by dividing the minimum and maximum "measured" door flows by the total volume of the test suite. An implicit assumption of this method is that the door flows are completely mixed with all the air in the suite. Although this is not necessarily true, it serves as a first approximation for comparison purposes.

**FIGURE 7. Comparison of Air Exchange Rates for Suites and Their Rooms (Interior Doors Open)**



## 7. Inter-Suite Transfer Air Fractions

The inter-suite transfer air fraction represents the amount of indirect and direct transfer of air from occupied suites within the test building compared to the total amount of air entering the test suite when the building is at near steady-state conditions. It is important to recognize that this fraction is based on $CO_2$ transfer by direct flows from occupied suites outside the test suite and by indirect flows from these suites through shafts and corridors into the test suite. It does not account for transfer air that bypassed occupied suites. Pollutants other than $CO_2$ could contaminate some of this transfer air.

The inter-suite transfer air fraction for each test suite was calculated using the following relation (Sheltair Scientific 1998):

$$F_t = \frac{C_{eq} - C_o}{C_t - C_o} \qquad \textbf{(1)}$$

where

$C_{eq}$ = equilibrium $CO_2$ concentration in test suite , ppm by volume,

$C_t$ = average $CO_2$ concentration in other suites that have transfer airflows into the test suite, ppm by volume, and

$C_o$ = $CO_2$ concentration in outdoor air, ppm by volume.

For each test suite, the equilibrium $CO_2$ concentration was calculated using data from a $CO_2$ decay test that was carried out in the test suite at the same time as the R134a decay test described earlier. The $CO_2$ concentrations during the decay test were measured using a portable non-dispersive infra-red datalogging monitor that has been used to measure $CO_2$ exchange for a single leaf during plant respiration experiments. The monitor automatically zeros itself once per minute through a soda lime scrubber and was calibrated with certified reference gas daily. Its calibrated accuracy was approximately ±10 ppm.

The average $CO_2$ concentration in the other suites communicating with the test suite was calculated using pollutant and airflow mass balances; measured outdoor, test suite, and corridor $CO_2$ concentrations; the calculated suite access door airflows; the measured suite air exchange rates; and assuming $CO_2$ was generated by an average of two sleeping occupants in the other suites (Sheltair Scientific 1998). The latter assumption included an error estimate of plus or minus one occupant on average. Even with this seemingly large error range, our uncertainty analyses indicated it is still likely the average $CO_2$ concentration in these other suites can be estimated within ±100 ppm.

Table 4 shows the $CO_2$ concentrations that were measured or determined for use in Equation 1. Table 4 also presents the mean values calculated for the inter-suite transfer air fractions. The calculated uncertainties associated with these measured fractions are listed as well. They were calculated in accordance with ASHRAE Guideline 2 (1990b).

**TABLE 4. Comparison of Inter-Suite Transfer Air Fractions**

| | **CO2 Concentrations** | | | | **Inter-Suite Transfer Air Fraction** | |
|---|---|---|---|---|---|---|
| **Building Number** | **Average Outdoors [±10 ppm]** | **Test Suite Equilibrium [±10 ppm]** | **Adjoining Corridor [±10 ppm]** | **Average for Other Suites [±100 ppm]** | **Mean** | **Uncertainty** |
| 1 | 375 | 375 | 375 | 475 | 0% | 14% |
| 2 | 398 | 415 | 419 | 657 | 6% | 6% |
| 3 | 400 | 446 | 409 | 710 | 15% | 6% |
| 4 | 374 | 374 | 379 | 1038 | 0% | 2% |
| 5 | 370 | 405 | 498 | 609 | 14% | 8% |
| 6 | 373 | 450 | 373 | 767 | 20% | 6% |
| 7 | 392 | 649 | 649 | 963 | 45% | 8% |
| 8 | 374 | 382 | 381 | 444 | 12% | 27% |
| 9 | 380 | 402 | 393 | 436 | 40% | 75% |
| 10 | 394 | 446 | 395 | 549 | 33% | 23% |

# DISCUSSION

## Corridor Supply Airflows

Based on the closed corridor supply airflow test, Figure 1 shows the measured corridor supply airflows on the test floors ranged from 38 to 81% of the design flows, with an average of 60%. Figure 1 also shows that there can be substantial variations in actual corridor supply airflows when corridor leakage area changes in tall buildings with tight corridors like Building 1. The possibility of confounding factors during the corridor supply airflow tests could not be eliminated. These factors include changes in building envelope leakage due to occupants opening windows in their suites. Further tests at different times of the year or multi-compartment computer simulations are needed to study the impact of leakage changes, as well as temperature and wind variations, on airflows.

## Makeup Air for Ensuite Exhaust Systems.

As Figure 3 shows, all the test suites were depressurized 1 to 5 Pa (0.004 to 0.02 in w.c.) relative to the corridor and no exhaust condition when operating only one exhaust device within the suite. With all the exhaust devices operating within a suite, the depressurization relative to the corridor and no exhaust condition remained about the same in some cases while doubling in other cases. A similar trend across the exterior wall can be observed in Figure 4. The larger depressurizations tended to occur in the suites with relatively high capacity exhaust devices and tight suite access doors.

It is clear from the discussion above that the suite exhaust systems were not “balanced”. Furthermore, the pressure differences that occurred when suite exhaust systems operated were largely a result of designers not ensuring there is sufficient leakage between the corridor and suite for the transfer of makeup air from the corridor into the suite. Even if there was sufficient leakage, Figure 2 shows that many of the corridor supply systems cannot provide all the makeup air that is required if more than half the exhaust devices on a floor are operating at any given time.

This point is significant, because it means that additional makeup air for suite exhaust devices must be provided by another source: uncontrolled infiltration of outdoor air through the building envelope. However, using direct infiltration for makeup air is undesirable during cold weather, unless this makeup air is heated before entering the suite or it enters the suite at low flow rates away from the occupants. For some test suites, this means of providing makeup air does not work. As Figure 4 shows, the test suites in Buildings 4 and 9 were pressurized relative to outdoors, even with all the exhaust equipment in the suite operating. This means that makeup air cannot flow into these suites from outdoors.

Another possible but also undesirable source of makeup air is transfer airflows from adjoining suites and shafts. The ultimate source of these transfer airflows is outdoor air flowing into other areas of the building through leakage openings in the building envelope. These airflows can sometimes be significantly contaminated. This practice is specifically prohibited by the National Building Code of Canada (NBCC 1990).

## Leakage Areas of Suite Access Doors

With the exception of the leakiest door, the measured ELAs shown in Figure 5 were all within the ranges reported in the literature. Tamura and Shaw (1976) reported ELAs of 140 to 374 cm² (22 to 58 in²) for similarly configured stair doors. Colliver et al. (1994) reported ELAs of 79 to 326 cm² (12 to 51 in²) for residential doors without weather-stripping.

The magnitudes of the suite access door ELAs shown in Figure 5 were highly dependent on the fit between the door and its frame (particularly at the latch side), on the size of the door undercut, and on the presence and fit of weather-stripping between the door and its frame. All of these factors are highly variable and can change over the life-cycle of the building.

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

The leakiest suite access door (Building 9) was unlike the other doors tested. It had a very poor latch fit (with significant light transmission at this side of the door), large gaps between the door and frame (except on the hinge side), and a large undercut (19 mm, 0.75 in). In this building, occupants had expressed complaints of drafts and excessive air velocity near suite access doors. In particular, the building manager reported that there were instances when pamphlets left under these doors were being blown into the suites and along their interior hallways. The large undercut for this suite access door may be an indication that the corridor supply air system was intended to supply ventilation air to the suites in this building.

NFPA Standard 80 (1992) specifies maximum allowable clearances between a "swinging fire door with builders hardware", its frame, the floor, and the door sill (if any). This type of fire door includes suite access doors. The maximum allowable clearances were converted to equivalent leakage areas using the theoretical method of Gross and Haberman and using a reference pressure difference of 10 Pa (0.04 in w.c.) with a discharge coefficient of 0.611. Excluding the leakiest door, all of the measured leakage areas were within the corresponding ELA limits based on the NFPA Standard 80 clearances (470 cm², 73 in²). The leakiest door (798 cm², 124 in²) considerably exceeded this limit.

NFPA Standard 105 (1985) specifies allowable air leakage rates for smoke-control doors. This Standard recommends that air leakage through doors between rooms and corridors should not exceed 5 L/s per m$^2$ of door opening. Although the Standard does not specify a pressure exponent for the gaps around these doors, assuming a pressure exponent of 0.5 is reasonable, based on the range of exponents determined from the door leakage tests (average of 0.53). Therefore, the air leakage rate recommendation of NFPA Standard 105 corresponds to an ELA of 13 cm$^2$ (2 in²) for an average-sized suite access door (1.81 m$^2$, 19.5 ft²). This ELA is at 10 Pa (0.04 in w.c.) with a discharge coefficient of 0.611. Consequently, this means that none of the suite access doors can be considered to be smoke-control doors according to this Standard. It also means that the ELA of suite access doors needs to be considerably reduced to meet this recommendation.

The theoretical ELAs shown in Figure 5 generally followed a similar pattern compared to the measured ELAs. For Building 7, there was excellent agreement between the theoretical and measured ELAs. However, the theoretical and measured ELAs sometimes differed significantly for the other buildings. The deviations were due to several factors. The suite access doors in Buildings 3, 4, and 8 had weather-stripping, which was not accounted for in the theoretical method. In Building 9, the suite access door had a poor latch fit, which also was not accounted for by the theoretical method. The reasons for the discrepancies in Buildings 5, 6, and 10 are unknown. Based on the differences observed, it appears that further investigations are needed before theoretical calculations can be reliably substituted for measured leakage areas of suite access doors.

## Suite Access Door Flows

Figure 6 shows that the airflows through the suite access doors during the one-day test period were generally from the corridor to the adjoining test suite (positive flows). However, in two buildings (6 and 7), the airflows through the suite access door were reversed (negative flows).

For Building 7, the reversal was due to continuous exhaust outside the test suite and an inoperative corridor supply air system. However, flow was into the test suite from the corridor when the exhaust systems were off, such as during the overnight tracer gas tests.

In Building 6, the reversal was due to combined stack and wind effects that exceeded the tendency of the corridor supply air system to pressurize the corridor relative to the test suite. Figure 4 shows that the depressurization of the test suite in this building relative to outdoors ranged from 8 to 15 Pa (0.03 to 0.06 in w.c.) during the one-day test period when there was no mechanical exhaust operating in the test suite. The associated pressurization of the exterior wall from outside occurred due to stack effect, because the suite was located below the neutral pressure level. It also occurred due to wind effects, because the exterior wall of the test suite was on the windward side of the building. As a result, air tended to flow into the test suite from outdoors. As there was no mechanical exhaust operating in the suite, the continuity of airflows required that this air then exit the suite into the corridor through the suite access door.

## Suite Air Exchange

For the eight buildings with positive door flows (Buildings 1 through 5 and 8 through 10), it appears in Figure 7 that these door flows were primarily responsible for the air exchange in most of the test suites, based on comparisons of the air exchange rates derived from these door flows with the measured room air exchange rates. In six of these eight buildings (Buildings 1 through 5 and 9), Figure 4 shows that the test suites were pressurized relative to outdoors. This means that air could not flow into the suite directly from outdoors through the envelope. It also means that any air that was involved in the air exchange and that was not coming from the corridor into these six test suites must have been transfer air from other suites. Buildings 8 and 10 had complex flows, including flows directly from outdoors into the test suite. As a result, it is less clear what fraction of the air exchange in these two test suites was attributable to the airflow through the suite access door.

Figure 7 also shows that, within experimental error bounds, all of the test suite rooms except in Building 4 and the bedroom in Building 7 met or exceeded the associated air exchange requirement of ASHRAE Standard 62 (1990b). The requirements shown in Figure 7 are based on 7.5 L/s per person, which is more stringent than the 0.35 ach requirement commonly used for lower population density spaces.

## Transfer Air

The pressure difference across the suite access doors was not measured at the time of the corridor supply airflow tests. However, based on the variability of stack- and wind-induced pressure differences that were estimated using measured weather data collected on-site, it is likely that the "measured" airflows across the suite access doors at the time of the corridor supply airflow tests were in the ranges shown in Figure 6.

In some suites, the differences between the corridor supply and suite access door flows shown in Figure 6 were significant. Compared to the corresponding door flows, the measured supply flows ranged from 14 to 100% of these flows, with an average of 59% (excluding Buildings 6 and 7). This indicates that a significant fraction of the airflow through the suite access door for some test suites must be transfer air from the remainder of the building, although not necessarily from any of the suites. The comparison assumes that none of the corridor air supply on the test story exits the corridor through paths other than the suite access doors. If there are other exits, then the transfer airflows could be higher fractions of the suite access door flows.

The data in Table 4 also indicate there is transfer air movement in the test buildings. These data show that inter-suite transfer air fractions for the test suites varied from 0 to 45% with an average of 19%. The uncertainty associated with the calculated transfer air fractions ranged from 2 to 75% with an average of 18%. Considering the uncertainty bounds in each case, half the test suites had non-zero transfer air fractions (Buildings 3, 5, 6, 7, and 10). This means that these suites had transfer air flowing into them directly or indirectly from occupied suites elsewhere in the building. The other five test suites tested had or could have had a zero inter-suite transfer air fraction (Buildings 1, 2, 4, 8 and 9). However, due to the low occupancy rate in Building 1 (about 30%), the fraction for Building 1 does not indicate that the test suite was not exposed to transfer air from other suites. Different results might be obtained when the building is fully occupied.

The highest uncertainty occurred in Building 9, where the air change rate in the suite was unusually high (2.62 ach in the living room compared to an average for all other test suites of 0.94 ach). The effect of the high air change rate in Building 9 can be explained as follows. Based on the $CO_2$ concentrations listed in Table 4 for that building, there was a relatively small but uncertain difference (56 ppm) between the concentrations outdoors and in the suites other than the test suite, because the suites were very-well ventilated. Most of the uncertainty in this difference was due to uncertainty associated with the average concentrations in the other suites (±100 ppm). At the same time, there was also a small difference (22 ppm) between the equilibrium concentration in the test suite and the outdoor concentration. As the equilibrium concentration in the test suite approaches the average concentration in other suites, the uncertainty in the transfer air fraction becomes more dependent on the larger uncertainty associated with the larger average concentration and the uncertainty in the transfer fraction increases.

In five of the nine test buildings with an operative corridor supply system (1, 2, 3, 9, 10), this system was able to pressurize the corridors on every story at the time of the tests. Consequently, the corridor supply air system in each of these buildings prevented air from flowing from the suites into the corridors. Table 4 shows that these five buildings tended to have similar $CO_2$ concentrations outdoors and in the corridors. However, it is important to recognize that these systems by their nature cannot prevent direct transfer airflows through partition walls, floors, and ceilings between adjoining suites. Although the cause of the non-zero transfer fractions in Buildings 2, 3, 9, and 10 is unknown, these transport paths may have been the reason. It is also possible that there was no transfer air from other suites entering the test suites in Buildings 2 and 9, based on the uncertainties associated with the inter-suite transfer fractions for these two suites.

In the other four buildings with an operative corridor supply system (4, 5, 6, and 8), this system failed to prevent transfer airflows from suites to the corridors on lower stories, or from windward suites to the corridors. This was not a problem for the test suite in Building 4, which was located below the neutral pressure level and had a zero transfer air fraction. As Table 4 shows, the $CO_2$ concentration in the corridor of the test floor in Building 4 was only about 5 ppm greater than outdoors. This latter difference was within the $CO_2$ measurement uncertainty (±10 ppm).

There was a problem that could be related to the transfer airflows through the corridors in Building 5. In this building, the test story was located above the neutral pressure level. Flows in this building were upward in the stair and elevator shafts from the lower stories toward the test story. Flows were also from the stair and elevator shafts into the corridors on the upper stories, including the test story. As a result, elevated $CO_2$ concentrations in the vertical shafts affected these concentrations in the corridor on the test story. Specifically, Table 4 shows that the $CO_2$ concentrations in the corridor of the test story in Building 5 were about 130 ppm greater than outdoors.

A similar problem occurred in Building 7, where the test story was also located above the neutral pressure level. For this building, Table 4 shows that the $CO_2$ concentrations in the corridor of the test story were about 260 ppm greater than outdoors. Unlike Building 5, contamination of suites by transfer air was expected in Building 7, because the corridor supply system in Building 7 was inoperative.

Reasons for the non-zero transfer air fractions in Buildings 6 and 8 could not be identified. However, because the $CO_2$ concentrations in the corridor adjoining each of these test suites were about the same as the concentrations outdoors, it is expected that direct transfer airflows through partition walls, floors, or ceilings between adjoining suites was the cause.

## CONCLUSIONS

The key findings from field performance tests of these buildings were:

1. Corridor supply airflows usually did not meet design flows.
2. Makeup air paths for suite exhaust were not properly designed.
3. Suite access door leakage was highly variable and usually did not meet smoke control requirements.
4. Airflow from the corridor through the suite access door leakage appeared to be the primary ventilation air supply for suites.
5. Suites were usually well-ventilated, but some were marginally- or under-ventilated.
6. Poor pressure control often allowed transfer air from one suite to another. Inter-suite transfer air fractions ranged from 0 to 45%, with an average of 19%.

In summary, this work showed suite ventilation can be highly influenced by corridor supply flows, by the treatment of corridor access doors, and by transfer airflows. As a result, suite ventilation at any given time in current mid- and high-rise residential buildings is very difficult to predict.

To ensure suite ventilation performs as intended under all operating conditions, the building industry needs to address the identified problems through improved ventilation design, operation, and maintenance practices.

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## REFERENCES

ASHRAE. 1990a. *ANSI/ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1990b. *ASHRAE Guideline 2-1986 (RA 90), Engineering analysis of experimental data*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1992. Design of Smoke Management Systems, Chapter 4. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1993a. *ANSI/ASHRAE Standard 136-1993, A method of determining air change rates in detached dwellings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1993b. 1993 Handbook - Fundamentals, Chapters 14, 23, and 32. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1983. *ASTM E741-83, Standard test method for determining air leakage rate by tracer dilution*. Philadelphia: American Society for Testing and Materials.

ASTM. 1984. *ASTM E783-84, Standard method for field measurement of air leakage through installed exterior windows and doors*. Philadelphia: American Society for Testing and Materials.

CGSB. 1986. *CAN/CGSB Standard 149.10-M86, Determination of the airtightness of building envelopes by the fan depressurization method*. Ottawa: Canadian General Standards Board, Supply and Services Canada.

Colliver, D.G., W.E. Murphy, , and W. Sun. 1994. “Development of a building component air leakage data base”. ASHRAE Transactions, V.100, Part 1, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Sikorski, B. and S. Moffatt. 1996. “FANalyzer: An automated portable test bench for analyzing the performance of fractional horsepower fan-motor sets”. Report of Sheltair Scientific Ltd. to Canada Mortgage and Housing Corporation, February.

NBCC. 1990. *National Building Code of Canada*. Ottawa: Associate Committee on the National Building Code, National Research Council Canada.

NBCC. 1995. *National Building Code of Canada*. Ottawa: Canadian Commission on Building and Fire Codes, National Research Council Canada.

NFPA. 1985. *ANSI/NFPA 105: Installation of smoke- and draft-control door assemblies*. Quincy: National Fire Protection Association. August 12.

NFPA. 1992. *ANSI/NFPA 80: Fire doors and fire windows*. Quincy: National Fire Protection Association. August 14.

Sheltair Scientific. 1998. “Field testing to characterize suite ventilation in recently constructed mid- and high-rise residential buildings”. Report of Sheltair Scientific Ltd. to Canada Mortgage and Housing Corporation, November.

Sherman, M.H. 1980. Air infiltration in buildings. Ph.D. Thesis, University of California, Berkeley.

Tamura, G.T. and C.Y. Shaw. 1976. “Air leakage data for the design of elevator and stair shaft pressurization systems”. ASHRAE Transactions, V.82, Part 2, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Theaker, I.G. and C.P. Wray. 2000. "Ventilation system design of recent Canadian multi-unit residential buildings". ASHRAE Transactions, V.106, Part 2, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.