AIR LEAKAGE WITHIN MULTI-UNIT RESIDENTIAL BUILDINGS: TESTING AND IMPLICATIONS FOR BUILDING PERFORMANCE

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ABSTRACT

Air leakage testing was performed for six suites within four multi-unit residential buildings in Vancouver BC, to quantify air leakage between adjacent suites, floors, common spaces, and through the exterior building enclosure. In order to measure the leakage across each suite's six surfaces separately, testing was performed using up to four door-fans and an automated fan-control system, precisely controlling the test pressure acting on each surface sequentially.

The primary intent of this work is to provide baseline data and example procedures for users performing similar types of testing in the future. Using data from the six tested suites, air leakage comparisons have been made between different wall and floor assemblies. Lessons learned are reported, and recommendations are made relating to the testing procedure. Conclusions regarding inter-suite leakage and implications on building performance are also discussed. While the data collected here is statistically insignificant to the greater building population, it does provide some baseline values and, with further testing of this type, could be compiled to make air-tightness recommendations and guidelines for multi-unit residential buildings.

Les essais de dépressurisation ont été exécuté pour six appartements dans quatre bâtiments résidentiels multi-unit à Vancouver, C-B, pour quantifier les fuites d'air entre des appartements adjacents, des planchers, des endroits communs, ainsi qu'à travers de l'enveloppe du bâtiment. Afin de déterminer les taux de fuites d'air à travers chacune de six surfaces de chaque appartement séparément, quatre portes-ventilateurs au commande automatique ont été utilisés pour contrôler précisément la pression agissant sur chaque surface séquentiellement.

L'intention principal de cette publication est de fournir des valeurs cibles et des procédures comme exemplaire pour ceux qui poursuivront des essais semblables dans le future. Utilisant les résultats obtenus de ces six appartements, des comparaisons pour les taux de fuites d'air entre les diverses arrangements de murs et planchers ont été effectuée afin d'établir des rapports. Les défis surmontés au cours des essais et des recommandations reliées aux procédures utilisées sont discutés. Des conclusions concernant la nature des fuites d'air entre les appartements et leur implications relatives à la performance du bâtiment sont présentés. Tandis que les résultats rassemblés ici sont statistiquement insignifiants à la population globale des bâtiments, ils fournissent quelques valeurs de base et, avec des essais supplémentaires, pourraient être compiler pour donner des recommandations et des directives d'étanchéité à l'air pour les bâtiments résidentiels multi-unit.

INTRODUCTION

It is essential to control air leakage through the exterior enclosure of multi-unit residential buildings, but also through the interior floors and walls between suites. For several decades, controlling air flow through the exterior building enclosure has been recognized as critical to reducing heat loss/gain and minimizing moisture related problems. In addition, limiting the flow of air between suites and common spaces within the building is equally important, for fire, smoke, odour, contaminant, and sound control. Research has also shown that suite compartmentalization can ensure more reliable suite ventilation and inhibit pollutants (such as odour and tobacco smoke) in one suite from passing into another.

Individual suites in multi-unit residential buildings are not typically designed as separate compartments, to be air-sealed from adjacent suites, corridors, and the exterior. Instead, it is almost the universal practice to supply fresh air to common corridors, allowing it to pass through door undercuts into the suites, and to exhaust stale air with fans in each suite. By pressurizing the corridors, the suites are intended to receive a constant flow of fresh air. Depending on the size of the openings under the doors, the pressures imposed by stack effect, the size of alternative relief paths such as elevators shafts and stairwells, and the strength and operation of the exhaust fan, makeup air for each suite will often be insufficient.

To overcome the demonstrated performance issues with a pressurized corridor supply system, a more effective approach is to duct fresh supply air into each individual suite. This approach works most effectively when the suites are built as air-sealed compartments. Although significant efforts are made to air-seal the exterior building enclosure as well as interior fire-separating walls, small gaps, penetrations, or cracks still exist in practice.

Quantifying air leakage in single-family dwellings or other whole buildings is commonly performed to determine their air-tightness. Quantifying air leakage within suites of a multi-unit building, however, is more complex because air leakage can occur through the adjacent interior walls and floors as well as the exterior building enclosure. Isolating the air leakage of one suite, to the outdoors only, is often of interest – but this cannot be determined without pressure neutralizing all of the potential interior leakage paths for testing. This process is difficult, requiring several door-fans and significant man hours to complete.

Due to the cost and effort required, isolating a single suite for incremental testing is not commonly performed. The work presented here adapts testing methods developed for whole buildings and uses some new techniques to achieve the desired results. There are no generally accepted standards or test procedures for this specific type of work.

Scope

In 2001, a field monitoring program was implemented to measure the performance of rainscreen-clad walls in the coastal climate of Vancouver, BC. As part of the program, exterior walls were instrumented and monitored for five buildings for a period of up to five years. In each building, temperature and relative humidity of one or two suites were also monitored to determine the impact of interior conditions on exterior wall performance. At the conclusion of the program in 2006, the monitored suites in three of the five buildings were accessed to perform air leakage testing. An additional high-rise building (not part of the previous mentioned monitoring program) was also tested as part of this air leakage study. In total, six suites within these four buildings were selected for individual air leakage testing.

The purpose of this testing was to locate and quantify air leakage paths between adjacent suites, floors, common spaces, ultimately determining actual leakage through the exterior building enclosure. Measured air leakage rates, coupled with mechanical system data, can be used to determine approximate ventilation rates in service. These results were correlated with the monitoring data to improve understanding of the performance of these buildings.

Another goal of the field study was to evaluate the feasibility of such intensive testing on occupied buildings in service, and to develop a procedure and reference point for future testing of this type.

Background

Building air-tightness is commonly measured for energy performance quantification, building commissioning, to locate deficiencies in the air barrier system, or to ensure smoke and fire seals are properly installed. Buildings are typically tested as whole units, and while individual suites may be door-fan tested, the accuracy of such tests has been proven questionable due to multiple interior air leakage paths (ASHRAE 2005, Sherman & Chan 2004). To overcome these issues, multiple door-fans are required to neutralize specific surfaces, or other test methods are employed using tracer gases (not discussed further here).

To determine exterior leakage rates in multi-unit buildings, neutralizing interior leakage paths is recommended – but it is not common practice, due to the high cost of equipment and trained technicians required. Testing of this nature is also difficult, requiring multiple operators to set up the system then control fan speeds simultaneously, in order to balance pressures.

Previous Testing of Multi-Unit Residential Buildings

Sherman & Chan (2004) reviewed over 100 publications relating to air tightness research and practice around the world. While thousands of single family dwellings had been tested since the 1970's when blower or fan door testing was introduced, they found that few tests have been performed to measure individual suite air-tightness or leakage paths in multi-unit residential buildings. Sherman & Chan's research presents a range of potential air leakage values and pathways to be expected in multi-unit residential buildings.

Air tightness varies greatly between countries, as well as between dwelling types and construction practices. Few correlations can be made from the large sample set, but typically, newer homes where the builder has considered energy efficiency are more air-tight than older homes. Typical values of air leakage can be found in the ASHRAE Handbook of Fundamentals (2005), which references hundreds of previous studies for single-family dwellings. No such baseline values are provided for multi-unit buildings, particularly residential buildings of the type tested here.

Limited air leakage studies have been performed on multi-unit residential buildings: seven Canadian studies are referenced by Sherman & Chan (2004), representing fewer than 100 units in approximately 40 buildings. Worldwide, less than 500 units have been submitted to this type of testing. The sample set for multi-unit residential buildings is almost negligible compared to more than 100,000 single-family homes documented. The largest air leakage database for single family dwellings is maintained by the Energy Performance of Buildings Group at Lawrence Berkeley National Laboratory (LBNL), with over 73,000 cases. No such database exists for multi-unit residential buildings.

One study, by Gulay et al. (1993), was performed to determine air leakage rates through the building envelope, interior walls and floors for ten multi-unit residential buildings across Canada. During depressurization testing, the leakage rates per suite (normalized to exterior wall area) were in the range of 2.10 to 3.15 $L/s/m^2$ at 50 Pa (3.8 to 5.7 cm^2/m^2 @50 Pa). When the interior corridor walls were not neutralized, the range of air leakage rates increased to 4.56 to 8.33 $L/s/m^2$ at 50 Pa (8.2 to 15.0 cm^2/m^2 @50 Pa). Overall leakage measured through exterior walls during full floor testing was in the range of 0.68 to 10.9 $L/s/m^2$ at 50 Pa (1.2 to 9.6 cm^2/m^2 @50 Pa), where interior surfaces were not neutralized. The study also showed that the air leakage rates measured far exceeded the National Building Code of Canada guidelines of 0.05 to 0.15 $L/s/m^2$ at 75 Pa. It should however be noted that the NBCC requirements are intended for individual enclosure elements (such as window wall or curtain wall systems), not for the air leakage of the entire enclosure.

Studies by Shaw et al (1991), Fang and Persily (1995), Wray et al (1998) and Colliver et al. (1994) present individual component air-leakage area data from testing on several residential buildings. These studies are referenced by Edwards (1999) and provide good reference points for testing.

In a study from Stockholm, Sweden, Levin (1991) found internal leakage paths between apartment units to account for 12% to 33% of the total leakage at 50 Pa. In another study, Bohac et al. (2007) found median leakage to adjacent units to be 27% of the total leakage in six Minnesota apartment buildings. Others have reported similar leakage inter-suite air leakage values for multi-unit residential buildings (Sherman & Chan 2004 and Shaw et al 1991).

These previous studies provide some guidance to the range of air leakage values and flow paths that may be encountered during testing. There is little consistency between the tests, and each building will likely show unique results according to construction practices, details and materials used.

TEST PROCEDURE AND MECHANICS

The air leakage test procedure and equipment setup used are discussed below. The flow mechanics and methodology applied to determine airflow, pressures and equivalent leakage areas are also shown.

Typical Testing Issues

Isolating interior surfaces has proven difficult when testing multi-unit buildings, since multiple fans must be balanced and controlled simultaneously. Tests of this type generally suffer from inaccuracies, because of the impracticality of balancing multiple fans in different areas: since changing one fan speed affects pressures in several zones, simultaneous speed adjustments in each zone are required. Taking twenty minutes or more to balance the fans is not uncommon, assuming that the test is uninterrupted.

Compounding these difficulties, baseline pressure varies with wind speed and with door openings, particularly where plenums such as elevator cores or stairwells cannot be pressure isolated from the test area. If, for example, the elevator door opens at a pressurized hallway then the fans will speed up to compensate for this pressure drop, which means the test must be rebalanced and restarted. Reducing interruptions in an occupied building requires the full cooperation of all residents. Even under ideal testing conditions, results and repeatability depend on several individual operators accurately reading and controlling fan speeds and pressures simultaneously.

To address these issues, the following procedure was adopted. With each fan left subject to its own automatic fan control, the system could come to equilibrium quickly. One operator could control and read pressures simultaneously from a central location, with technicians on hand to set up and manage access and interruptions. Ethernet cable run between each fan control and digital gauge established central control, meaning that operators could complete testing without leaving the immediate area of the suite.

Setup time for door-fan panels is an obstacle to this type of testing, because of the number of door-fans required to isolate a single apartment. The rapid setup panels used here, however, take only a few seconds to place and replace when access is required. These same panels accelerated turnaround time between pressurization and depressurization, since the fan could simply be turned around.

Procedure and Setup

This testing was performed using up to four high-powered door-fans (8500 cfm Retrotec Model 3200 series), automatically controlled from a central location using Retrotec DM-2A gauges (Retrotec 2006).

Neutralizing pressures were applied to incrementally isolate interior surfaces (adjacent walls and floors) of each test suite, to determine the air leakage between specific surfaces. Suite air leakage testing and neutralization of adjacent surfaces was performed using 50 Pa of differential pressure with respect to the exterior. All pressures readings are referenced with respect to the exterior, common to all gauges, and therefore only the relative pressure differences between suites were recorded.

Lower pressures are generally experienced under normal operating conditions; however it has been shown that tests performed at higher differential pressures such as 50 Pa are more accurate to remove environmental noise (i.e. effects of wind and thermal buoyancy/stack effect pressures) (ASHRAE 2005).

A pressurization cycle of the suite and adjacent surfaces, followed by a depressurization cycle, was performed at all suites. Depressurization was performed to offset stack, HVAC, and wind flows and determine average results. The test setup described below is for a pressurization cycle. The depressurization cycle is similar, with fans reversed. This procedure is also shown graphically in the Appendix:

1. Install a fan into the hallway door opening of the test suite, following the manufacturer’s recommended installation guidelines. Position reference pressure tubes at interior of suite and exterior. This fan door will be recording all readings (equivalent leakage area and fan flow), therefore proper calibration prior to use is critical.

Inside the suite, close all exterior windows and doors and open all interior doors and closets, to ensure equalized pressure throughout suite. Leave all mechanical openings open (bathroom and kitchen exhaust).

2. Install a fan door one floor above the suite, so that the suite and common hallway space directly above the test suite can be fully pressurized. This neutralizes the ceiling surface of the test suite. Position reference pressure tubes to the interior of suite and the exterior.

   Note that this fan door can often be installed into a stairwell opening instead of the suite door, so that the suite above will be pressurized by simply opening the suite door. This setup also eliminates any leakage between hallways on adjacent floors. The stairwell, if used, should be open to the exterior so that the reference pressure is to the exterior.

   One 8500 cfm fan was found to be sufficient in the buildings tested, but multiple fans may be required to pressurize entire floors of larger or leaky buildings.
3. Repeat Step 2 one floor below the test suite, to isolate the test suite floor surface.
4. On the test suite floor, install a fan door in the hallway to provide neutralizing pressures. Position reference pressure tubes into the hallway and to the exterior.

   This fan may also be installed into a stairwell opening, provided that the stairwell is open to the exterior (as above). Adjacent suites to left and right of the test suite can therefore be pressurized, by opening or closing their hallway doors as needed. By opening all of the windows in these adjacent suites while their entrance doors are closed, adjoining walls to the test suite will be neutralized to exterior reference pressure.
5. Run reference pressure tubes and fan controls to a central location in the hallway outside the test suite, where the operator can measure and control each unit simultaneously.

   Retrotec DM-2A gauges allow the operator to set the desired pressure drop across each fan. In this case the DM-2A was set to maintain 50 Pa across each doorway, adjusting fan speed automatically. Automatic control speeds up and simplifies the testing procedure.

In these tests, computer software was used to continuously log fan flow, test pressure and calculated equivalent leakage area measurements. Test results can also be displayed directly on the DM-2A gauge in any units of equivalent leakage area, fan flow, flow per unit area, or air changes per hour. One major contributor to the ease of use was the fact that the fans had regulated variable frequency speed controllers that enabled rapid acceleration to speed and ultra stable speed control that was unaffected by changes in pressure drop and voltage.

After the door-fans are set up, they are controlled incrementally to pressurize the spaces adjacent to the test suite. Differential measurements were used throughout this test program as they allow for more accurate readings (by cancelling out most systemic errors) and can isolate individual suite walls with fewer blower doors. For example if one wishes to measure the air leakage between the test suite and the adjoining suite, one would pressurize the test suite, take a reading, then pressurize the adjoining suite and take a second reading. The difference between the two readings is the air leakage between those suites.

This differential procedure is performed in steps to isolate and eliminate each surface until the leakage through the exterior enclosure can be isolated. A six step test procedure to incrementally determine air leakage between suites is illustrated in the Appendix. Large red arrows indicate fan flow direction and small green arrows indicate air leakage paths. The pressurized suites are highlighted in red, and when two pressurized suites are adjacent, the leakage is neutralized between those spaces. The de-pressurization tests are run with the fans turned around to face the opposite direction; however the door-fan setup remains the same.

There is the potential for leakage paths that bypass neutralized suites (ie. A duct or cavity that happens to only be open at the test suite which is not connected to the suite above and below (such as a duct or pipe chase from the first floor running up the entire building and open on the test floor). These leakage paths would be measured as part of the exterior enclosure leakage area. In the four buildings tested, no evidence of such pipe chases or ducts were noted on the drawings or could be observed in the field; however it is something to be aware of when performing this type of testing.

Winds were very calm during the day of the tests, and thus were not seen to have an effect on the readings (minimal pressure fluctuations). If an issue, wind pressures can be dampened by the use of additional exterior reference pressure tubes, positioned around the building.

Additional tests can alternately be performed to determine the impact of intentional exhaust vent openings within the test suite. A test can be performed with and without the exhaust ducts sealed (preferably from the exterior) to determine the portion of air leakage occurs through these openings.

Flow Mechanics

Building air leakage testing is based on the fundamental mechanics of airflow: the amount of flow through an opening is determined by the geometry of the opening and the pressure difference across it. Flow rate is linked to opening area and air pressure via simple mathematical relationships. Typically, air leakage testing results can be described in one of three forms:

1. Fan flow required, in order to create a specified pressure drop across the fan (i.e. 500 L/s flow required to pressurize the test suite to 50 Pa).
2. Equivalent leakage area (ELA), resulting from applied flow and pressures. An equivalent leakage area is a hypothetical rectangular opening (i.e. at 50 Pa, the suite had an equivalent leakage area of 400 cm^2). There are several ELA definitions depending on the analysts' choices of discharge coefficient and the pressure difference.
3. Air exchange rate (often expressed in air changes per hour), or volume of the space being pressurized divided by the fan flow (i.e. the air change rate of the test suite to the exterior was 2.5 ACH, m^3/hr/m^3 at 50 Pa).

The relationship describing airflow through an "equivalent" opening is based on the Bernoulli equation. The general form of the equation is (ASHRAE 2005):

$$Q = C_D \cdot A \cdot \sqrt{\frac{2P}{\rho}} \qquad (1)$$

Where, Q = air flow (m^3/s); A = area of opening (m^2), P = pressure difference (Pa); ρ = density of air (kg/m^3).The discharge coefficient (C_D) is a dimensionless number than depends on the geometry of the opening and the Reynolds number of the flow.

When calculating an equivalent leakage area, all openings through the walls and floor of the suite are combined into an overall opening area and discharge coefficient. Some guidance is provided in ASHRAE (2005), e.g. discharge coefficient $C_D = 0.61$ for a sharp-edged opening. The air leakage area of a building, therefore, is the area of an orifice that would produce the same amount of leakage measured through the building enclosure, at the tested pressure. Unit or normalized leakage area (NLA) can be determined dividing ELA by the surface area leakage is occurring through, i.e. the exterior building enclosure area).

Air leakage measurements are commonly taken at a single test pressure: for the purposes of this test, 50 Pa was used. In practice, however, typical pressures from wind, stack effect, or mechanical systems will be much lower: in the range of 1 to 10 Pa. Using the power law equation, the flow at any pressure can be calculated (ASHRAE 2005):

$$Q = C \cdot (\Delta P)^n \qquad (2)$$

Where, Q = airflow through opening (m^3/s), C = flow coefficient (m^3/s/Pa^n); P = pressure difference between room and exterior (Pa); n = pressure coefficient (dimensionless), usually between 0.5 and 1.0.

Values of c and n can be determined by testing the air leakage over a range of pressures (multipoint airflow tests from 10 to 75 Pa). If a multipoint test is not performed, a typical value of n is 0.65 (ASHRAE 2005, Sherman 2004). If the value of n is assumed to be 0.65, the flow coefficient C can be calculated based on airflow recorded at test pressure.

Units of Measurement & Standards

Air-leakage testing results are presented in a variety of units by the building industry. Perhaps most convenient is an air-leakage measurement in terms of an equivalent leakage area at a common reference test pressure such as 50 Pa (i.e. ELA_{50}). In metric units, equivalent leakage areas of cm^2 normalized per m^2 of pressurized surface are convenient (i.e. 1 cm^2/m^2 @ 50 Pa)

Unit conversions for a typical apartment with a floor area of 112 m^2 and height of 2.44 m are used in the following example to compare several test standards to the measured results. Using a pressure coefficient of 0.65 and equation 2, the following conversions are made assuming 1 cm^2/m^2 normalized air-leakage rate measured at 50 Pa.

1 cm^2/m^2 @ 50 Pa = 0.6 in^2 EfLA/100 ft^2@ 4 Pa
= 0.14 ft3/min/ft2 @ 75 Pa
= 0.73 L/s/m2 @ 75 Pa
= 2.46 ACH @ 50 Pa
= 2.0 $m^3/hr/m^2$ @ 50 Pa

The following standards provide reference normalized effective leakage areas for comparison of the measured results here.

Table 1: Existing Air-tightness Standards and Equivalent Air-Leakage Targets

Standard	Equivalent Air-Leakage Area
LEED v2.2 for New Construction – (EQ2 Pre-requisite 2: Tobacco Smoke Control), Test of all 6 sides of an apartment	1.25 in^2 EfLA @ 4Pa/100 ft^2 = 2.1cm^2/m^2 @50Pa
ASHRAE – tight exterior enclosure	0.1 $ft^3/min/ft^2$ @ 75 Pa = 0.7 cm^2/m^2 @ 50 Pa
ASHRAE – average exterior enclosure	0.3 $ft^3/min/ft^2$ @ 75 Pa = 2.1 cm^2/m^2 @ 50 Pa
ASHRAE – leaky exterior enclosure	0.6 $ft^3/min/ft^2$ @ 75 Pa = 4.3 cm^2/m^2 @ 50 Pa
International Energy Conservation Code (IEEC), Enclosure Leakage	0.4 $ft^3/min/ft^2$ @ 75 Pa = 2.9 cm^2/m^2 @ 50 Pa
National Building Code of Canada 2005, for assemblies (i.e. window/curtain wall)	0.15 L/s/m2 @ 75 Pa = 0.23 cm^2/m^2 @ 50 Pa
Air Tightness Testing and Measurement Association (ATTMA 2007), “best practice” dwelling enclosure air-tightness with mechanical ventilation	3.0 $m^3/hr/m^2$ @50 Pa = 1.5 cm^2/m^2 @ 50 Pa
Typical Range Expected	<1.0 cm^2/m^2 @ 50 Pa for tight building enclosures 2.0 cm^2/m^2 @ 50 Pa average building enclosures >4 cm^2/m^2 @ 50 Pa for leaky building enclosures

Air leakage test results are expressed in this paper in terms of:

- Equivalent Leakage Area at 50 Pa (ELA_{50}): cm^2 @ 50 Pa
- Air Flow at 50 Pa(Q_{50}): l/s @ 50 Pa
- Air Changes per Hour at 50 Pa(ACH_{50}): $m^3/hr/m^3$ @ 50 Pa
- Normalized Leakage Area, over surface area of leakage path (NLA_{50}): cm^2/m^2

BUILDING AND TEST SUITE DESCRIPTION

Three buildings from the monitoring study and one additional high-rise were selected, for a total of four Vancouver, BC buildings. Building reference numbers noted here are consistent with other published reports on this monitoring study (Finch 2007): buildings 2, 3 and 4 were air-leakage tested, while the additional building is referred to as Building ‘A’. Testing was performed between December 5th and 8th, 2006. Weather was overcast with calm winds, and average temperatures were between 5°C and 8°C.

Table 2 provides a summary description of each air-tested suite, with comments pertaining to building construction and noting adjacent suites that were pressurized and depressurized during testing.

Table 2: Building Number, Test Suite and Comments

Building - *Suite*	Description
2 - *401*	Building 2 is a four-storey wood frame of early 1990's construction. Building enclosure rehabilitation was completed in 2001. Exterior walls are rainscreen stucco with taped house-wrap and polyethylene air-barrier at interior. Partition walls and floors are woodframe construction. Suite 401 is a top floor corner unit with cathedral ceiling and skylight, with hallway access (pressurized corridor); a stairwell is to the left; suite 402 is to the right; suite 301 is at floor below.
3 -*608*	Building 3 is a six-storey concrete frame with steel stud and gypsum infill walls of early 1990's construction. Building enclosure rehabilitation was completed in 2002. Rainscreen stucco over exterior insulated and self-adhered membrane air barrier. Roof is 2-ply SBS over concrete. Partition walls are steel stud and gypsum construction. Suite 608 is a top floor unit, with exterior corridor access (this corridor is open to exterior and unconditioned); a lounge is to its left and suite 609 is to its right; suite 508 is at floor below.
3 - *611*	Suite 611 is a top floor unit, with hallway access (pressurized corridor); suite 609 is to the left; a stairwell is to the right; suite 511 is at floor below.
3 - *311*	Suite 311 is a middle floor unit, with hallway access (pressurized corridor); suite 309 is to the left; a stairwell is to the right; suite 211 is at floor below; suite 411 is at floor above.
A - *802*	Building 'A' is a 26-storey concrete frame high-rise of late 1980's construction. Building enclosure rehabilitation was completed in 2006. Rainscreen stucco over exterior insulated and self-adhered membrane air barrier. Partition walls are steel stud and gypsum construction. Suite 802 is a middle floor corner unit, with hallway access (pressurized corridor); suite 801 is to the left; suite 803 is to the right; suite 702 is at floor below; suite 902 is at floor above.
4 - *309*	Building 4 is a four-storey wood frame of early 2000's construction. Exterior walls are rainscreen cement board with a polyethylene air-barrier at the interior. Partition walls and floors are woodframe construction. Suite 309 is a middle floor unit, with hallway access (pressurized corridor); suite 308 is to left; suite 310 is to the right; suite 209 is at floor below; suite 409 is at floor above.

The testing procedure was modified where certain steps were not required, i.e. the test suite was located in a corner of the building, or had only one adjacent suite, or was located at the top floor of the building. Each surface of the suite was isolated as access permitted.

Drawings for each of the tested buildings, as well as further building information and construction details, are provided in the 2007 MASc Thesis by G. Finch (*The Performance of Rainscreen Walls in Coastal British Columbia*). In all four buildings, the intent of the National Building Code in regards to the enclosure air-barrier construction was met.

Buildings 3 and A had previously monitored and reported moisture problems, apparently resulting from insufficient ventilation or fresh-air exchange. Further monitoring in Building 3 by Finch (2007) and testing by Roppel et al. (2007) determined ventilation rates, measuring exhaust fan flow and CO_2 levels within several suites, and found that low ventilation levels were in fact contributing to high interior humidity levels and causing problems. In contrast, monitoring by Finch (2007) showed that buildings 2 and 4 had very low wintertime relative humidity levels. As the buildings have similar mechanical ventilation systems, comparing the air leakage within these buildings would hopefully provide some answers to the different conditions observed.

TEST RESULTS

Measured air leakage results are summarized in Tables 3 through 7, for each of the six suites. A summary of the average equivalent leakage area, normalized leakage area, air exchanges per hour, and relative distribution of air-leakage pathways is provided. The results here provide the average of the pressurization and depressurization value, however typical differences of up to 25% were observed between exfiltration and infiltration air-leakage rates at 50 Pa, largely resulting from different behaviour in air-barrier materials/systems and mechanical exhaust duct dampers. Pressurization tests almost always produced leakier results than depressurization.

Table 3: Equivalent Air-Leakage Area, ELA_{50}

Building – Suite	Equivalent air-leakage area ELA_{50} - cm^2 @ 50 Pa		
	All 6 sides	Exterior Enclosure	Interior Surfaces
2 – 401	1065 cm^2	860 cm^2	206 cm^2
3 – 608	336 cm^2	262 cm^2	74 cm^2
3 – 611	516 cm^2	188 cm^2	328 cm^2
3 – 311	347 cm^2	114 cm^2	233 cm^2
A – 802	319 cm^2	112 cm^2	207 cm^2
4 – 309	415 cm^2	275 cm^2	140cm^2

Table 4: Normalized Air-Leakage Area, NLA_{50}

Building – Suite	Normalized leakage area NLA_{50} - cm^2/m^2 @ 50 Pa		
	All 6 sides	Exterior Enclosure	Interior Surfaces
2 – 401	6.5 cm^2/m^2	12.9 cm^2/m^2	3.0 cm^2/m^2
3 – 608	1.4 cm^2/m^2	4.8 cm^2/m^2	0.4 cm^2/m^2
3 – 611	2.3 cm^2/m^2	4.1 cm^2/m^2	1.8 cm^2/m^2
3 – 311	1.5 cm^2/m^2	2.5 cm^2/m^2	1.3 cm^2/m^2
A – 802	1.0 cm^2/m^2	2.7 cm^2/m^2	0.8 cm^2/m^2
4 – 309	3.1 cm^2/m^2	21.8 cm^2/m^2	1.2 cm^2/m^2

Table 5: Airflow and Air Exchanges per hour

Building – Suite	Flow @50 Pa - L/s & Air Exchanges per Hour @ 50 Pa – ACH_{50}		
	All 6 sides	Exterior Enclosure – *Direct Fresh Air Exchange*	Interior Surfaces – *Mixed Stale Air Exchange*
2 – 401	593 L/s @50 - 13.8 ACH_{50}	479 L/s @50 - 11.1 ACH_{50}	114 L/s @50 - 2.7 ACH_{50}
3 – 608	187 L/s @50 - 4.0 ACH_{50}	146 L/s @50 - 3.1 ACH_{50}	41 L/s @50 – 0.9 ACH_{50}
3 – 611	287 L/s @50 - 6.2 ACH_{50}	104 L/s @50 - 2.2 ACH_{50}	186 L/s @50 - 4.0 ACH_{50}
3 – 311	193 L/s @50 - 4.1 ACH_{50}	64 L/s @50 - 1.4 ACH_{50}	129 L/s @50 - 2.7 ACH_{50}
A – 802	177 L/s @50 - 2.6 ACH_{50}	62 L/s @50 - 0.9 ACH_{50}	115 L/s @50 - 1.7 ACH_{50}
4 – 309	231 L/s @50 - 9.7 ACH_{50}	50 L/s @50 - 6.5 ACH_{50}	181 L/s @50 - 3.2 ACH_{50}

Table 6: Distribution of Air-flow under normal conditions

Building – Suite	Distribution of Airflow to/from Tested Suites			
	Exterior	Adjacent suites	Common areas/halls	All Interior
2 – 401	81%	8%	11%	19%
3 – 608	78%	22%	n/a	22%
3 – 611	36%	17%	46%	64%
3 – 311	33%	15%	52%	67%
A – 802	35%	28%	37%	65%
4 – 309	66%	2%	32%	34%

Table 7: Air Leakage Observations for Each Suite

Building – Suite	Discussion of Probable Air Leakage Pathways within Tested Suites
2 – 401	Possibly more air-leaky due to number of mechanical ducts and questionable cathedral attic space air-sealing between suites/hallway. Suite also had a gas fire-place flue and older leaky windows and skylight. Polyethylene air barrier at ceiling and walls of older, less air-tight construction.

3 – 608	Air-tight to exterior. Unit has exterior corridor access so fresh air-exchange is relatively high compared to 611 and 311. Peel & Stick air barrier membrane at walls, 2 ply SBS roof.
3 – 611	Air-tight to exterior, leaky to interior. Unintentional interior leakage through plumbing/sprinkler penetrations through hallway and poor air-sealing details. Peel & Stick air barrier membrane at exterior walls, 2-ply SBS roof.
3 – 311	Air-tight to exterior, leaky to interior. Unintentional plumbing/sprinkler penetrations through hallway and poor air-sealing details. Peel & Stick air barrier membrane at exterior walls.
A – 802	Air-tight to exterior, leaky to interior. Unintentional plumbing penetrations through hallway and poor air-sealing details between slabs – possibly missing fire-seals. Peel & Stick air barrier membrane and new air-tight windows at exterior walls.
4 – 309	Air-leaky due to mechanical ducts and air-barrier construction. Polyethylene air-barrier membrane at walls. Large difference between pressurization/depressurization testing.

Results show that significant inter-suite leakage occurs within all of these multi-unit residential buildings. Performing air leakage testing within a single unit, with a single door-fan, would have yielded incorrect results - particularly in those buildings which are air-tight.

All of the tests were performed at 50 Pa, to reduce the impacts of wind and building induced pressures. Under normal operating conditions (±4 to 10 Pa), air leakage values would be reduced in the order of 3 to 10 times. Air leakage measurements at 50 Pa can be extrapolated using equation 2, by measuring or assuming an “n” value (typically 0.65), and calculating the “C” value for the suite. These values, including differences between pressurization and depressurization are detailed for each suite in Finch (2007).

IMPLICATIONS FOR BUILDING PERFORMANCE

All of the tested buildings have similarly designed and operating mechanical ventilation systems. Each suite is provided with fresh make-up air via pressurized common corridors, with stale air exhausted through intermittent use of bathroom or kitchen fans. By local building code, these exhaust fans are intended to be programmed to run a minimum number of hours per day, but they do not function this way in normal operation. Historically, mechanical designers have relied on some additional fresh air leakage through the building enclosure to supplement mechanical ventilation. Rehabilitated buildings, however, are much more air-tight than their original construction; therefore this outdoor air-exchange is minimized. Suites are typically heated with electric baseboard heaters, which do little to encourage air movement.

Testing revealed that Buildings 2 and 4 (woodframe construction) are significantly leakier than Buildings 3 and A (steel-stud and gypsum infill walls). In addition, the inter-suite air-leakage in Buildings 2 and 4 made up only 20% of the overall air-exchange within suites. These suites had low winter time relative humidity levels (average <40%) and no reported complaints about condensation or moisture problems.

Overall air leakage at Buildings 3 and ‘A’ was much lower, and moreover inter-suite air-leakage made up approximately two-thirds of the “fresh-air” exchange. As a result, significant stale-air mixing is likely between adjacent suites further contributing to the air quality and humidity issues. During the winter, monitoring suites within Buildings 3 and ‘A’ consistently recorded high interior relative humidity levels (averages of greater than 50-60%). The high humidity levels in these two buildings resulted in condensation on window frames, as well as on/within the surfaces of the exterior walls.

IMPACT OF CONSTRUCTION ON AIR TIGHTNESS

Data from these six suites is summarized and compared to determine if any consistencies can be determined between wall or floor assemblies, from this limited data set. While statistically insignificant, the results confirm predicted differences between assembly types. Figure 1 compares the air leakage between the tested exterior wall assemblies.

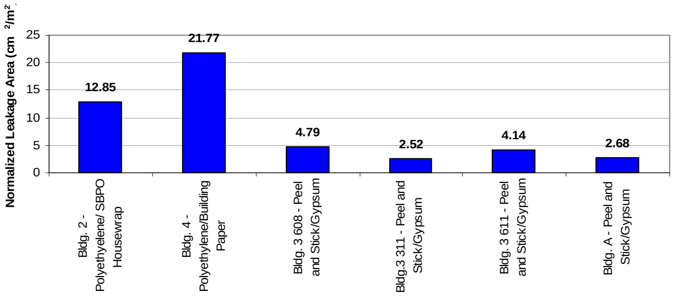


Figure 1: Normalized Leakage Area by Exterior Wall Type

The two wood-frame exterior walls tested here had the highest normalized leakage area - consistently higher than the steel stud and gypsum walls, with peel and stick air barrier membrane.

The differences in air leakage through the different floor assemblies are compared in Figure 2.

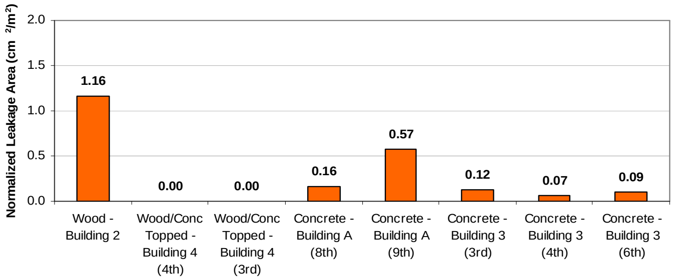


Figure 2: Normalized Leakage Area by Floor Type

The tightest floor systems tested were the concrete-topped wood frame floor, followed by the concrete slab floor. The wood frame floor showed the highest air leakage. Air leakage through a floor slab largely depends on how well the penetrations were fire/smoke sealed. It appears that in Building A one or more of these penetrations was poorly sealed, contributing to the higher-than-average leakage measured through this solid concrete slab. The wood frame floor had a higher leakage area, as could be expected, due to penetrations, gaps, or shrinkage of the plywood and wood joist floor.

The differences of air leakage through the interior suite demising walls are compared in Figure 3.

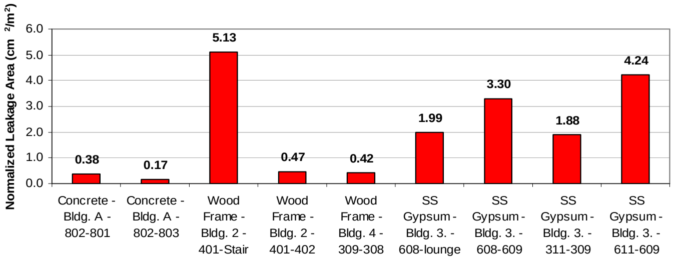


Figure 3: Normalized Leakage Area by Interior Wall Type

The solid concrete walls tested were found to be tightest, followed by the wood frame walls (except one location), and finally the steel-stud and gypsum demising walls. Air leakage differences between solid concrete and framed walls are evident, and it appears that these wood-framed walls were constructed tighter than the steel-stud and gypsum framed walls. Figure 4 compares air leakage for walls between test suites and hallways.

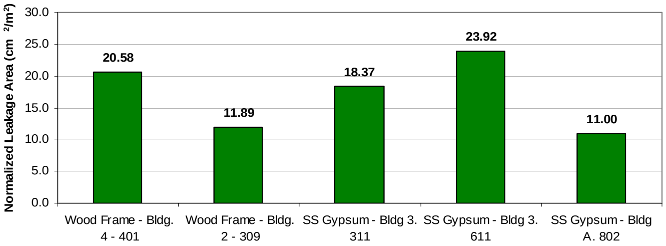


Figure 4: Normalized Leakage Area through Hallway Walls

Hallway door air leakage is excluded from these tests, having an intentional leakage area in the order of 50 cm^2/m^2 for a standard entrance door (including a 1 cm door undercut, normalized over the total area of the door frame). The measured hallway leakage shown here is through unintentional openings such as plumbing penetrations, cracks, gaps, or electrical boxes/switches.

Hallway demising walls were shown to be significantly leakier than the suite demising walls tested, possibly because openings were more frequent or poorly sealed. While this leakage area is unintentional (i.e. not through passive vents or door undercuts), it may be beneficial in cases where suite owners have intentionally blocked the door undercut, inhibiting suite supply air.

LESSONS LEARNED WITH MULTI-UNIT RESIDENTIAL BUILDING TESTING

The minimum setup to effectively test one individual suite within a larger building requires 4 fans, more if the building is very leaky or if one fan cannot provide neutralizing pressures for an entire floor. Four technicians are also required, one with each door-fan, as a safety precaution.

Where the elevator is located off the tested hallway, elevator doors opening and closing will affect pressurization. Curious tenants opening suite doors or going about their daily activities will also impact pressurization. Performing these tests when the building is unoccupied would be ideal, but is not typically possible.

This type of testing is obtrusive, and requires the full cooperation of building management and occupants to complete. Pressurization often requires the temporary blockage of a fire exit. Most multi-unit residential buildings have the minimum two emergency stairwells, which by code should never be blocked. An operator must remain at the door-fan on each floor, to remove the obstruction quickly if a tenant wishes to use the stairwell or in case of emergency.

Access can also be an issue, as several suites must be accessed for each test. Adjacent suites may need to be simultaneously open, or their windows and patio doors may need to be closed. Depressurization times should be minimized in winter, to avoid cold drafts. Ensuring that tenants are aware of the purpose of these tests is generally helpful. Only one or two suites can usually be tested per eight-hour day, allowing for setup, adjustment, interruptions and cleanup.

Despite these limitations, this procedure showed that air leakage testing of individual suites in multi-unit residential buildings is possible, and that consistent results can be achieved using the methods provided.

CONCLUSIONS

Six suites in four multi-unit residential buildings were tested to quantify interior air leakage between adjacent suites, floors and common spaces, as well as through exterior walls.

The following conclusions can be made from the results, which also reflect field experience with these types of assemblies. Solid concrete assemblies were constructed more airtight than wood assemblies and wood assemblies were more airtight than steel stud/gypsum. Suite demising walls and floors were typically constructed more air tight than hallway walls. Exterior walls with peel-and-stick as an air barrier were more air tight than those with polyethylene (at the interior) or taped polyolefin house wrap (to the exterior of the sheathing).

This test method isolated air leakage through the exterior building enclosure, informing the following conclusions. The concrete frame buildings, with an exterior wall construction of peel and stick air/vapour/water barrier membrane over gypsum and steel stud wall, were tightest with a recorded leakage range from 2.5 to 4.8 cm^2/m^2 @50 Pa. The wood-frame walls with polyethylene and/or taped and sealed polyolefin house wrap were considerably leakier, at 12.9 to 21.8 cm^2/m^2 @50 Pa. All measurements were taken with intentional exhaust ducts left open, as they would be in practice and are common to all suites. The leakiest building enclosure, at 21.8 cm^2/m^2 @50 Pa, was tested at a corner unit on the top floor with a fireplace flue. This suite also had the highest enclosure surface area, which may account for its significant variance from the other test results.

Exterior enclosure leakage rates for these four Vancouver buildings ranged from 2.5 to 21.8 cm^2/m^2 @50 Pa, whereas previous testing from Gulay et al. (1993) measured values from 3.8 to 5.7 cm^2/m^2 @50 Pa for ten other Canadian buildings. None of the buildings tested would be considered “air-tight” under ASHRAE, or “best-practice” under ATTMA standards.

Leakage through interior walls and floors becomes more significant as the exterior building enclosure is constructed increasingly airtight. The need for effective ventilation systems is more important with these new tighter building enclosures, otherwise moisture and IAQ problems may develop as a result of insufficient ventilation (natural or mechanical). In those the suites with indoor humidity and moisture problems, interior air leakage accounted for greater than 60% of the net “fresh” air-exchange.

Air-tight building enclosures improve energy efficiency, occupant comfort, and reliable indoor air quality - for all these reasons, the demand for air tightness and suite compartmentalization is likely to increase. However, an air-tight enclosure requires a higher level of ventilation performance. Insufficient mechanical systems can have serious ramifications on building performance, occupant comfort and even health.

Corridor-supply suite-exhaust mechanical systems have historically been sufficient in multi-unit residential buildings, when the building enclosures were leakier and comfort standards less demanding. However, as other research has clearly shown, this approach will often cause problems with today’s air-tight buildings. In addition, air leakage between suites and common spaces becomes more significant as the exterior enclosure becomes tighter.

Ideally, fresh make-up air should be ducted directly into each suite, pressure balanced to minimize inter-suite air pressure differences and resulting air exchange. A schematic of this strategy is provided in the Appendix, although for rehabilitation projects the cost of these upgrades may be prohibitive. Upgrading existing mechanical systems to provide higher ventilation rates would be a less costly alternative. Improvements should include continuous in-line fans with low noise (sone) level for each suite, while heat recovery ventilators (HRVs) could be used for each suite or floor to reduce energy costs.

REFERENCES

ATTMA 2007. The Air Tightness Testing and Measurement Association. Technical Standard 1, Issue 2, July 13 2007.

ASHRAE 2005. ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Bohac, D., Hewett, M., Fitzgerald, J., Grimsrud, D., 2007. Measured Change in Multifamily Unit Air Leakage and Airflow due to Air Sealing and Ventilation Treatments. *Proceedings from ASHRAE/DOE Buildings X*, Clearwater Beach Florida, December 2007.

Colliver, D., Murphy, W., Sun, W. 1994 Development of a Building Component Air Leakage Data Base. *ASHRAE Transaction*, Vol 100 (1): 292-305

Edwards, C. 1999. Modelling of Ventilation and Infiltration Energy Impacts in Mid and High-Rise Apartment Buildings. Canada Mortgage and Housing Corporation.

Fang, J., Persily, A., 1995. Airflow and Radon Transport Modelling in Four Large Buildings, *ASHRAE Transaction,s* Vol 101 (1): 1100-1117.

Finch, G., Straube, J., Hubbs, B. 2006. Building Envelope Performance Monitoring and Modeling of West Coast Rainscreen Enclosures. *Proceedings from the Third International Building Physics Conference*, Montreal, Quebec. August 2006.

Finch, G. 2007. The performance of rainscreen walls in coastal British Columbia. Masters thesis, Department of Civil Engineering, University of Waterloo, Waterloo. Ontario, Canada.

Gulay, B.W., Stewart, C.D., Foley, G.J., 1993. Field Investigation Survey of Air tightness, Air Movement and Indoor Air Quality in High-Rise Apartment Buildings: Summary Report. Canada Mortgage and Housing Corporation, Report 96-220.

Levin, P. 1991. Building Technology and Air Flow Control in Housing, Report D16, Swedish Council for Building Research, Stockholm.

Persily, A. 1999. Myths About Building Envelopes. *ASHRAE Journal*, Vol. 41 (3), March 1999, pp. 39-47.

Retrotec. 2006. 2000/3000 Door-fan Manual for Energy, Scientific and Commercial Users. Retrotec Energy Innovations Ltd.

Roppel, P., Lawton, M., Hubbs, B. 2007. Balancing the Control of Heat, Air, Moisture, and Competing Interests. *Proceedings from the 11th Canadian Building Science and Technology Conference*. Banff, Alberta. March 2007.

Shaw, C.Y., Magee, R.J., Rousseau, J. 1991. Overall and Component Airtightness Values of a Five-Storey Apartment Building, *ASHRAE Transactions*, Vol. 97 (2), 1991, pp. 347-353.

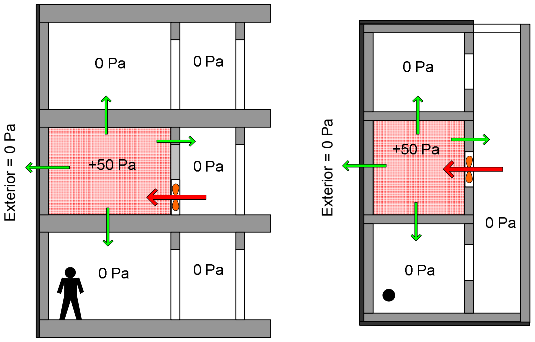
Sherman, M.H., Dickerhoff, D. 1998. Airtightness of U.S. Dwellings. *ASHRAE Transactions*, 1998. V. 104 Part 2.

Sherman, M.H., Chan, R. 2004. Building Airtightness: Research and Practice. Lawrence Berkeley National Laboratory Report No. LBNL-53356. Draft, February 19, 2004.

Wray, C., Theather, I., Moffat, P., 1998. Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High-Rise Residential Buildings, Canada Mortgage and Housing Corporation.

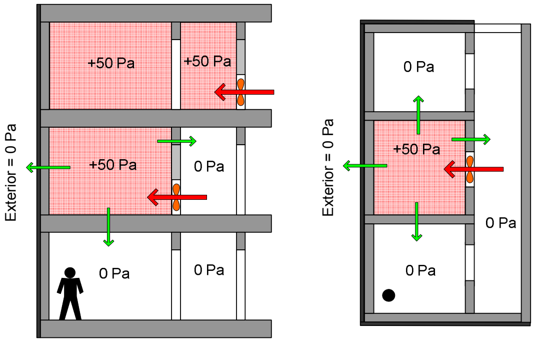
APPENDIX - Six Step Neutralizing Pressure Method

Test # 1 – Pressurize Suite (Adjacent Suites Open to Exterior)



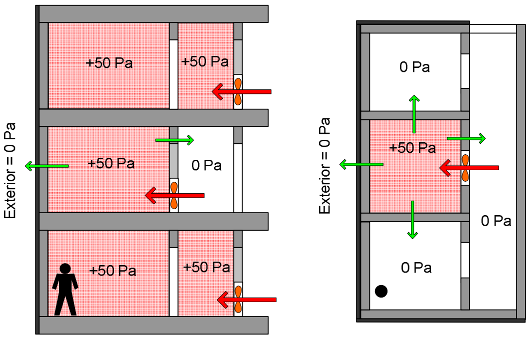
Section View – Floor Above and Below *Plan View – Test Floor*

Test # 2 – Pressurize Suite and Floor Above



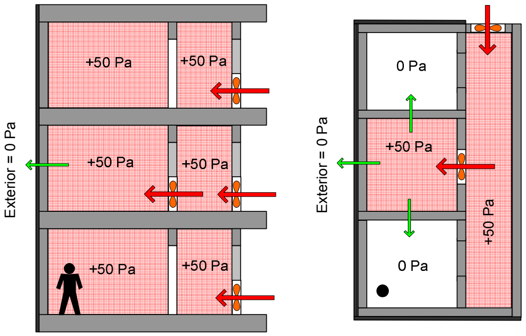
Section View – Floor Above and Below *Plan View – Test Floor*

Test # 3 – Pressurize Suite, Floors Above and Below



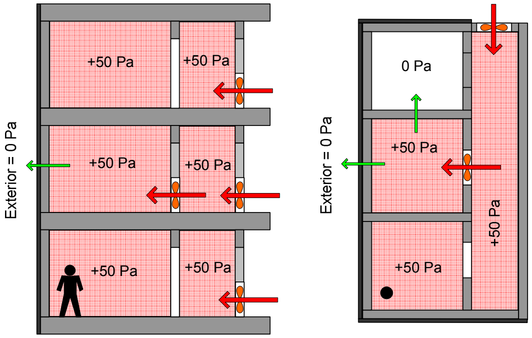
Section View – Floor Above and Below *Plan View – Test Floor*

Test # 4 – Pressurize Suite, Floors Above and Below, and Hallway



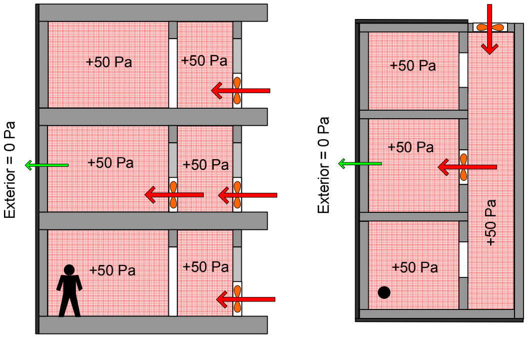
Section View – Floor Above and Below *Plan View – Test Floor*

Test # 5 – Pressurize Suite, Floor Above and Below, Hallway and Left Suite



Section View – Floor Above and Below *Plan View – Test Floor*

Test # 6 – Pressurize Suite and All Adjacent Interior Surfaces

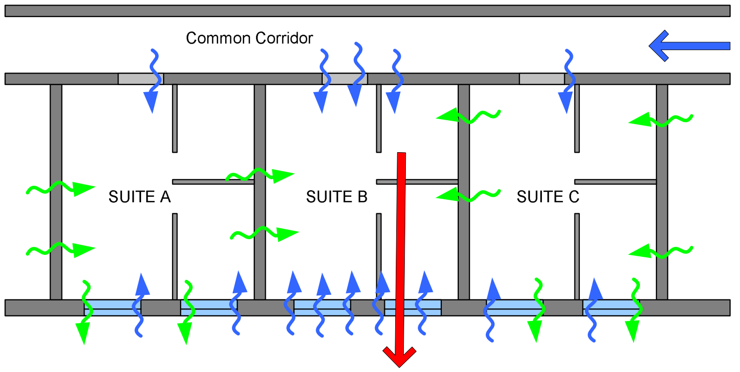


Section View – Floor Above and Below *Plan View – Test Floor*

APPENDIX -

Rehabilitation Strategy Schematic for Suite Ventilation in Multi-Unit Residential Buildings

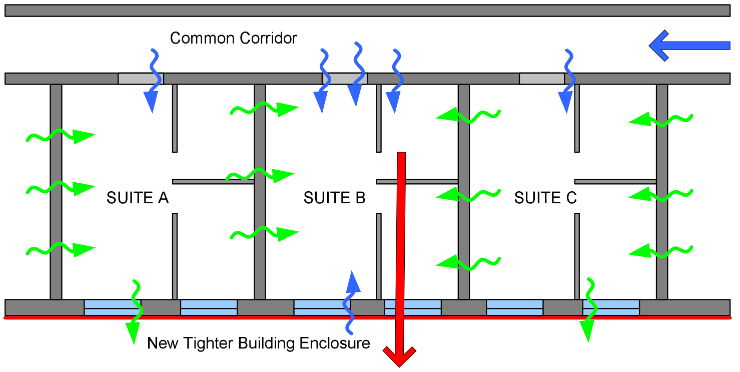
PLAN VIEW – PORTION OF MULTI-UNIT RESIDENTIAL BUILDING FLOOR



Un-balanced Pressurized Corridor/Suite Point Exhaust System – Prior to Rehabilitation

Prior to Rehabilitation – Exhaust in one suite as controlled by occupants, which pulls small amounts of stale air from neighbouring suites, and fresh air from hallway and exterior. Exterior wall makes up majority of leakage area, inter-suite leakage is small

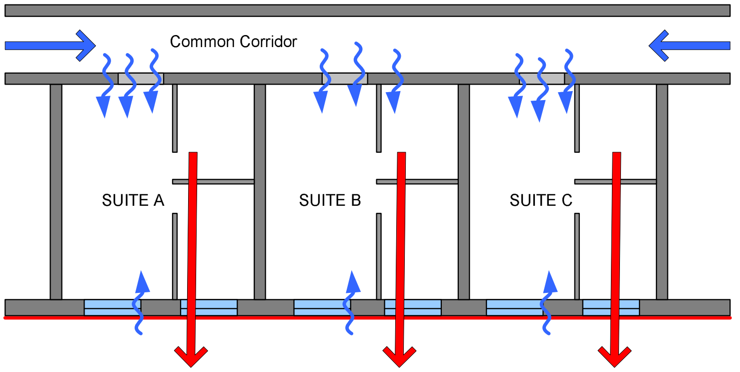
PLAN VIEW – PORTION OF MULTI-UNIT RESIDENTIAL BUILDING FLOOR



Un-balanced Pressurized Corridor/Suite Point Exhaust System – After Rehabilitation

After Rehabilitation – Exhaust in one suite as controlled by occupants, which pulls larger amounts of stale air from neighbouring suites, and fresh air from hallway. Leakage through the exterior which used to be dominant is reduced and therefore makes up a small portion of the air exchange

PLAN VIEW – PORTION OF MULTI-UNIT RESIDENTIAL BUILDING FLOOR



Balanced Pressurized Corridor/Suite Point Exhaust System – After Rehabilitation

Balanced System – Continual exhaust or controlled simultaneous exhaust at each suite. Balanced hallway flows to ensure sufficient suite fresh air supply. Balanced pressure ensures only fresh air is transferred to suites from controlled locations, not stale air from adjacent suites