1 AIR LEAKAGE TESTING OF INDIVIDUAL SUITES IN MULTI-UNIT RESIDENTIAL BUILDINGS

Air leakage testing of six suites in four multi-unit residential buildings in Vancouver, BC was performed to quantify air leakage between adjacent suites, floors, common spaces and through the exterior building enclosure.

Testing was performed using up to four high power door-fans and an automated fan-control system that precisely controlled the test pressure across each wall sequentially in order to measure the leakage of the six sides of the suite separately.

Air leakage and flow path test results are expressed in terms of:

- Equivalent Leakage Area at 50 Pa (ELA_{50}): cm^2 @ 50 Pa & in^2 @ 50 Pa
- Air-Flow at 50 Pa(Q_{50}): l/s @ 50 Pa & ft^3/min @ 50 Pa (CFM_{50})
- Air-Changes per Hour at 50 Pa(ACH_{50}): $m^3/hr/m^3$ @ 50 Pa & $ft^3/hr/ft^3$ @ 50 Pa (CFM_{50})
- Normalized Leakage Area, over surface area of leakage path (NLA_{50}): cm^2/m^2 @ 50 Pa & $in^2/100\ ft^2$ @ 50 Pa.

This provides some baseline data for users performing similar type of testing in the future. Comparisons between different wall and floor assemblies are made using data from the six tested suites.

Three of the buildings tested were part of a larger study which monitored the hygrothermal performance of the exterior walls over the past five years. The fourth building was recently rehabilitated and was tested for this study as a result of complaints of high interior humidity during the wintertime. The air leakage testing results combined with the previous data and observations is used to better understand past performance and make conclusions regarding the interior air quality and ventilation rates within these buildings.

The impact of air-tightness on the existing mechanical systems and suite ventilation of the four buildings is shown. Recommendations to avoid ventilation and humidity problems within multiunit residential buildings, particularly with air-tight exterior enclosures are discussed.

1.1 INTRODUCTION

Control of air leakage in multi-unit residential buildings is important through the exterior enclosure but also through interior floors and walls between suites. Controlling the flow of air through the exterior building enclosure has been realized as critical for several decades to reduce heat loss/gain and minimize moisture related problems. Controlling the flow of air between suites and common spaces within the building is equally as important for fire, smoke, odour, contaminant, and sound control.

Individual suites in multiunit residential buildings are typically designed as separate compartments which are air-sealed from adjacent suites and to the exterior. Ventilation supply and exhaust air is controlled by mechanical means in most modern buildings. In multi-unit residential buildings it is common 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, a constant flow of air exfiltrates into the suites provided there is a path to the suite. Depending on the size of the opening, and strength of the exhaust fan, makeup air for the suite may or may not be sufficient. A more suitable approach to duct fresh supply air into each individual suite may alternately be used and can overcome some of the issues with a pressurized corridor supply system.

Significant effort is also made to air-seal the exterior building enclosure and interior fire-separating walls; however small gaps, penetrations, or cracks may still exist in practice. Therefore understanding the source of the makeup air in these suites is critical to the understanding of problems in multi-unit buildings with insufficient ventilation, which can result in high interior humidity and air quality issues.

Quantifying air leakage in single-family dwellings or other whole buildings is commonly performed to determine the air-tightness. However quantifying air leakage within suites of a multi-unit building is difficult, as air leakage can occur through the adjacent interior walls, floors, and exterior building enclosure. Often it is of interest to isolate the air leakage of one suite to the outdoors only. This cannot be determined without pressure neutralizing all of the potential interior leakage paths while testing. This process is difficult and requires the use of several door-fans and man hours to complete the task.

Isolating a singular suite within a building and performing incremental air leakage testing to quantify the relative air leakage between adjacent suites, floors, common spaces and the exterior is not commonly performed due to the cost and effort required. The work presented here adapts testing methods developed for single buildings and uses some new techniques to achieve the desired results. There are no applicable standards or test procedures for this specific type of work.

Lessons learned and recommendations are made as to the testing procedure. Conclusions regarding inter-suite leakage and implications on performance of the building are also discussed. Concrete frame buildings are compared to wood-frame buildings and the differences in interior air leakage pathways between wall and floor assemblies. While the data collected here is statistically insignificant to the greater building population, it provides some baseline values and with further testing of this type, could be compiled to make recommendations as to normal/leaky/tight air-tightness guidelines for multi-unit residential buildings.

1.1.1 Scope

A field monitoring program was implemented in 2001 to measure the performance of rainscreen clad walls in the coastal climate of Vancouver, BC. As part of the program, the exterior walls of five buildings were instrumented and monitored for a period of up to five years. In each building the temperature and relative humidity of one or two suites were also monitored to determine the impact of the interior conditions on the exterior wall performance.

At the conclusion of the wall monitoring program in 2006, access was provided to three of the five buildings to perform the air leakage testing of the monitored suites. In addition, one high-rise building (not part of the previous mentioned monitoring program) was also tested as part of this air leakage study. Six suites in these four buildings were selected for individual air leakage testing.

The purpose of the air leakage testing was to quantify air leakage paths between adjacent suites, floors, common spaces, and ultimately determine 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. The air leakage testing results in combination with the data collected from the past five years is used to improve the understanding of the performance of these buildings.

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

1.1.2 Background

Air leakage testing of buildings is commonly performed to measure air-tightness 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 often tested as whole units, and while individual suites within a larger building may be door-fan tested, the accuracy of such tests has been shown to be questionable due to multiple interior air leakage paths (ASHRAE 2005, Sherman & Chan 2004). To overcome these issues, the use of multiple door-fans are required to neutralize specific surfaces, or other test methods are employed using tracer gases (not discussed further here).

While the practice of neutralizing interior leakage paths to determine exterior leakage is recommended when testing individual units in multi-unit buildings it is not common practice due to the high cost of the required equipment and trained technicians. Testing of this type is also difficult because of the inherent nature of the test setup, requiring multiple operators to simultaneously control and balance pressures quickly.

Issues with testing of multi-unit buildings with multiple fans are discussed and techniques used to overcome them. Results from previous tests of multi-unit residential buildings are also presented.

1.1.2.1 Test Procedure and Issues

When testing multi-unit buildings it has been found to be difficult to balance and control multiple fans simultaneously to isolate interior surfaces. Tests of this type suffer from inaccuracies caused by the impractical nature of trying to control 2, 3 or 4 fans that are interacting with each other such that changing one fan speed causes pressures to change in several zones requiring simultaneous speed adjustments in each zone. Add to this the fact that the baseline pressure can be changing with wind speed and door openings and you have 4 fans chasing each other. It is not uncommon to take 20 minutes to balance the fans out using this method, provided the test is uninterrupted. Reducing interruptions in an occupied building during the tests requires the full cooperation of all residents, and can be an issue, particularly where plenums such as elevator cores or stairwells adjacent to the test area cannot be pressure isolated from the test area. A relatively common occurrence is for the elevator door to open at a pressurized hallway, requiring the fans to speed-up to compensate for the pressure drop, often requiring the restart of the test. Further the test results and repeatability are subjective and rely on several individual operators to accurately read and control fan speeds and pressures simultaneously.

To overcome some of these issues, the approach taken here was to let each fan be controlled by its own automatic fan control so that the system of compartments, leaks and pressure would come to equilibrium quickly. One operator will control and read pressures simultaneously from a central location and technicians will be on hand to setup and assist with potential issues that come up with access and residents. Central control was accomplished by running ethernet cable between each fan control and digital gauge so that the entire test could be performed without moving from the close proximity of the tested apartment.

Set-up time for panels has been an obstacle to this type of testing since many set ups are required to complete test on a single apartment. Rapid set up panels were used that allowed them to be set up in a few seconds and also allowed people to pass through them for access when required.

These same panels allowed for rapid testing in the depressurisation direction, since the fan merely had to be turned around. Being able to test in both directions allowed for more accurate readings since testing in both directions and averaging the results can be shown to be much more accurate than testing in one direction where offset pressures can throw result off a lot. The data shows results in both direction and it is apparent that neither pressurization nor depressurization alone was representative of the actual leakage.

1.1.2.2 Previous Testing of Multi-Unit Residential Buildings

Sherman & Chan (2004) performed a review of over 100 publications relating to air tightness research and practice across the world. They found that while thousands of single family dwellings have been tested since the 1970's when blower or fan door testing was introduced, few tests have been performed to measure individual suite air-tightness or leakage paths in multi-unit residential buildings. A few cases are presented which provide some insight into the range of potential results for this test.

Air tightness varies greatly among dwellings, across countries, and by construction type. Few correlations can be made from the large sample set, however typically newer more energy efficient homes where air-tightness was a consideration of the builder, are more air-tight than older homes. Typical values of air leakage can be found in the ASHRAE Handbook of Fundamentals (2005) referencing hundreds of previous studies for single-family dwellings. No such baseline values are provided for multi-unit buildings, particularly residential buildings which were tested here.

Few studies have been performed in the past on multi-unit residential buildings. Seven Canadian studies are referenced by Sherman & Chan (2004) which tested fewer than 100 units in approximately 40 buildings. Worldwide, less than 500 units have been tested. The sample set for multi-unit residential buildings is practically insignificant in comparison to the >100,000 single-family homes tested and documented. The largest database of single family dwellings is maintained by the Energy Performance of Buildings Group at LBNL which has over 73,000 from over the US. No such database exists for multi-unit residential buildings.

One study by Gulay et al. (1993) (of Wardrop Engineering in other literature) was performed for CMHC to determine air leakage rates through the building envelope, inter-floor, and inter-suite leakage rates in ten buildings investigated across Canada. The results indicated that leakage rates per unit of exterior wall area were found to be 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) during suite fan depressurization testing. When testing was conducted such that the corridor wall could not be isolated from leakage through the exterior wall, 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 rates per unit of exterior wall area found during full floor testing was 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 isolated. It was also noted that these air leakage rates far exceeded the National Building Code of Canada guidelines of 0.05 to 0.15 L/s/m^2 at 75 Pa.

In a study from Sweden, Levin (1991) found internal leakage paths between apartment units in Stockholm to account for 12% to 33% of the total leakage at 50

Pa. Similar leakage values have been reported by others for other multi-unit residential buildings (Sherman & Chan 2004).

In another Canadian study, Shaw et al. (1991) found exterior wall air tightness values by be nine times greater that those of the floor/ceiling, and leakage to the left and right partitions (adjacent units) in between the two extremes. In the same study, they observed that the overall airtightness values of four buildings with different wall constructions were similar.

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

1.2 TEST PROCEDURE AND MECHANICS

The test procedure and setup which was developed for the tests is discussed, as well as the flow mechanics and calculations performed to determine the flows, pressures and equivalent leakage areas.

1.2.1 Procedure and Setup

Testing was performed using up to four high-powered door-fans (Retrotec Model 3200 series, each providing up to 8500 cfm) which were automatically controlled from a central location using Retrotec DM-2A gauges. All fans were precisely controlled to maintain 50 Pa between the tested space and outdoors.

Neutralizing pressures were applied to incrementally isolate interior surfaces (adjacent walls, floors) of a 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 pressure with respect to the exterior. Lower pressures would be experienced under normal operating conditions; however it has been shown that tests performed at higher pressures such as 50 Pa are more accurate to remove environmental noise (effects of wind and thermal buoyancy (stack effect) pressures) (ASHRAE 2005).

The fans and digital pressure/control gauges were calibrated prior to testing to ensure accuracy of the readings. All pressures readings are referenced with respect to the exterior, common to all gauges, and as such the relative pressure differences between suites are only recorded.

Pressurization of the suite, followed by depressurization was performed for all suites tested. Depressurization in addition to pressurization was performed to offset stack, HVAC, and wind flows and determine average results. Test setup is described for a pressurization setup; depressurization is similar however the fans are reversed within the same door frame setup. The basic test setup used for each suite is as follows, and shown graphically in Figure 1-1:

1. Install door-fan in suite of interest as per manufacturer's installation guidelines. Reference pressure tubes located in suite and to exterior. Close all exterior windows and doors. Open interior room doors/closets to ensure equalized pressure throughout suite. Leave all intentional openings open (bathroom and kitchen exhaust fans). This fan will be taking all of the readings (equivalent leakage area and fan flow) therefore should be properly calibrated prior to use.
2. Install door-fan at the floor above such that the suite and common hallway space directly below the test suite can be pressurized. Often the door-fan can be installed in one of the stairwells instead of the actual suite door. The suite will be pressurized if the hallway door is opened at the time of hallway pressurization. This setup also eliminates any inter-hallway leakage between floors. The stairwell should be opened to the exterior to prevent the fan from depressurizing it. Reference pressure tubes to the suite/hallway and exterior. High powered fans or multiple fans may be required to pressurize entire floors of some larger or leaky buildings. In the buildings which were tested, one 8500 cfm fan was found to be sufficient in every case. This fan was only neutralizing the leakage across one of the 6 sides of the apartment.
3. Repeat Step 2 for floor below test suite.
4. Install door-fan in hallway on the same floor of the suite of interest. Often the door-fan can also be installed in one of the stairwell doors (open to the exterior). Reference pressure tubes to hallway and exterior. By installing the door-fan in the hallway, the two adjacent suites (left and right) can be pressurized by opening and closing suite hallway doors of those suites as needed. Opening the windows in those adjacent suites while the entrance door is closed will neutralize the suite to zero reference pressure. This fan will only be providing neutralizing pressures.

Reference pressure tubes and fan controls are run to a central location in hallway outside the test suite to allow the user to measure and control each unit simultaneously. The Retrotec DM-2A gauges allow the user to set the desired pressure drop across each fan to any desired pressure. In this case the fan speed was adjusted automatically by the DM-2A to maintain 50 Pa across the doorway ion which it was mounted. Automatic control speeds up and simplifies the testing procedure and as anyone who has tried this before knows, manually balancing four fans simultaneously can be quite difficult in the field.

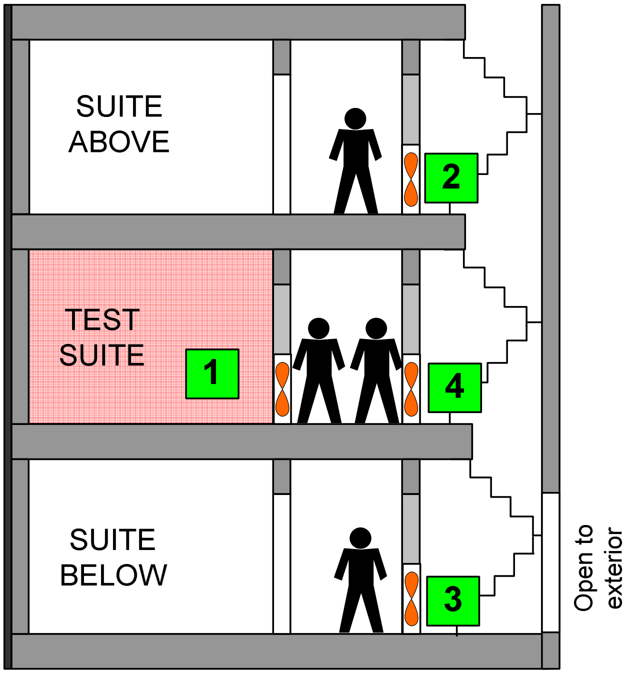


Figure 1-1: Door-fan test setup for isolation of individual test suite.

Computer software was used to continuously data-log the fan flow, test pressure and calculated equivalent leakage area measurements. Figure 1-2 shows the DM-2A speed controlling gauges interfaced with a laptop for data-logging and a door-fan installed in a hallway door. Test results can be displayed directly on the DM-2A in any units of equivalent leakage area, fan flow, flow per unit area, or air changes per hour.

Even though the data logged looked good on paper, it was shown to be unnecessary since the gauges read out directly in the results needed and appeared very stable. The added time to set up the laptop was found to be unnecessary although it did prove that the system balanced itself out quickly after 1 or 2 minutes and was stable enough that readings could be taken in confidence. One major contributor 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.

Figure 1-2: Control Equipment and Door-Fan Installed in Hallway Doorway.

The accuracy of the ELA/flow measurements is dependent on the operator taking the readings when neutralizing pressures are at equal to the test suite pressure (50 ±1 Pa). Accuracy is improved by using the @50 Pa function on the DM-2A gauge. In effect if the test pressure is say 50.5 Pa, the DM-2A extrapolates to exactly to 50 Pa mathematically and displays that result.

It was discovered that watching the leakage area across the suite settle down while monitoring the pressures across each surface worked well. After a short while the leakage area would stabilize as the controllers brought each fan up to the correct speed to maintain the 50 Pa test pressure.

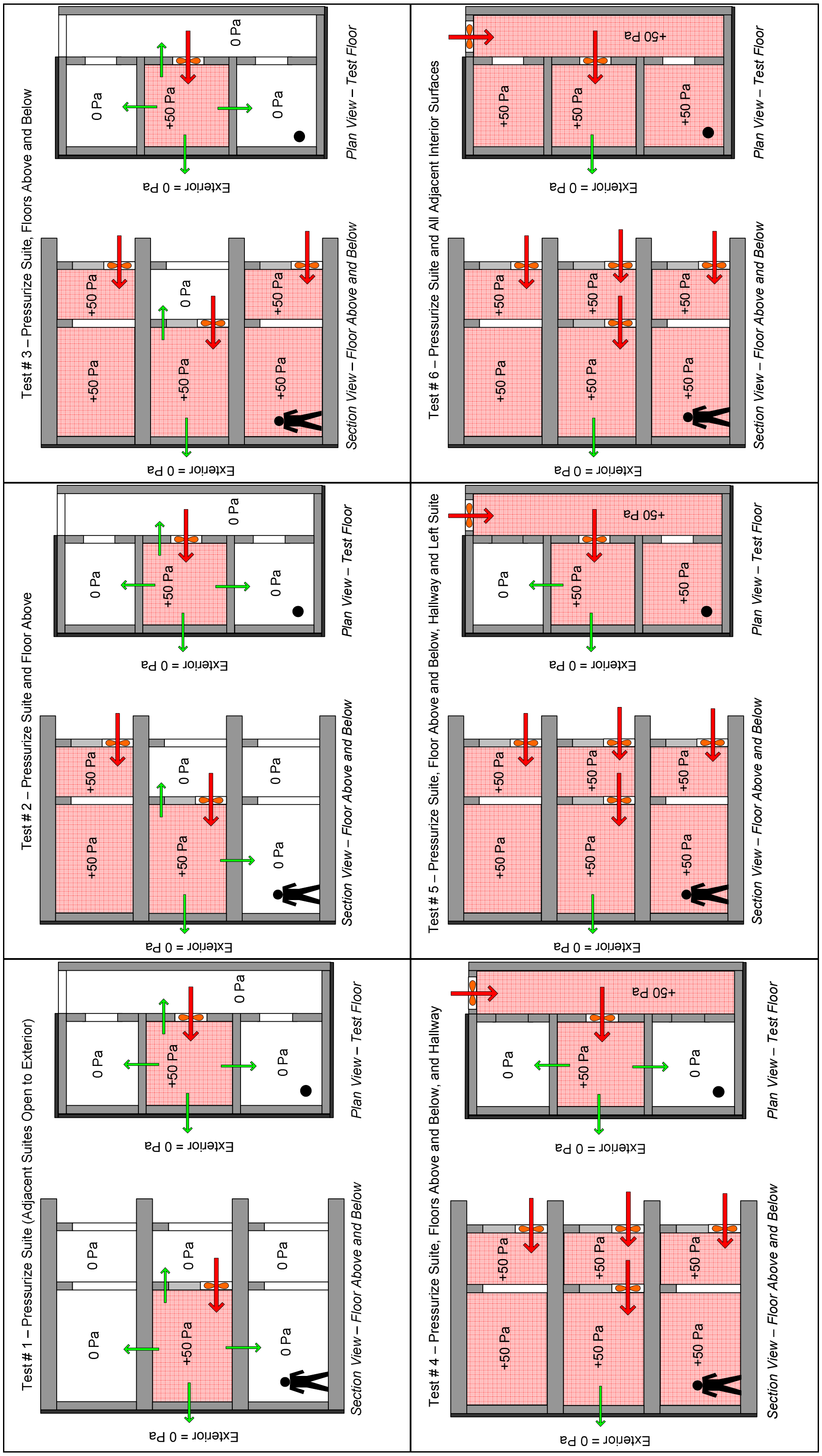
Winds were very calm during the day of the tests, and thus were not seen to have an effect on the readings (minimal pressure fluctuations). Had high winds been encountered, Retrotec has wind-dampening kits available that can dampen wind speeds up to 32 km/hr (20 mph) which could have been used had this been a problem.

After the door-fans are setup, they are controlled incrementally to pressurize surfaces adjacent to the test suite. For example if you wish to know the air leakage between the test suite and the one next door, you would pressurize the test suite, take a reading, then pressurize the one next door and take a second reading. The difference between the two readings is the air leakage between those suites.

This procedure is performed in steps to isolate and eliminate each surface until the leakage through the exterior enclosure can be isolated. The six step test procedure to incrementally determine air leakage between suites is illustrated on the following page. 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 to exist in the field (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 show up 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.

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.


Test # 1 – Pressurize Suite (Adjacent Suites Open to Exterior)
Section View – Floor Above and Below
Plan View – Test Floor
+50 Pa
0 Pa
Exterior = 0 Pa
Test # 2 – Pressurize Suite and Floor Above
Section View – Floor Above and Below
Plan View – Test Floor
+50 Pa
0 Pa
Exterior = 0 Pa
Test # 3 – Pressurize Suite, Floors Above and Below
Section View – Floor Above and Below
Plan View – Test Floor
+50 Pa
0 Pa
Exterior = 0 Pa
Test # 4 – Pressurize Suite, Floors Above and Below, and Hallway
Section View – Floor Above and Below
Plan View – Test Floor
+50 Pa
0 Pa
Exterior = 0 Pa
Test # 5 – Pressurize Suite, Floor Above and Below, Hallway and Left Suite
Section View – Floor Above and Below
Plan View – Test Floor
+50 Pa
0 Pa
Exterior = 0 Pa
Test # 6 – Pressurize Suite and All Adjacent Interior Surfaces
Section View – Floor Above and Below
Plan View – Test Floor
+50 Pa
Exterior = 0 Pa

1.2.2 Flow Mechanics

Air leakage testing of buildings is based on the fundamental mechanics of air flow through openings. The amount of flow through an opening is determined by the geometry of the opening and pressure difference across it. Air flow, opening area and air pressure are related to each other using simple mathematical relationships.

Typically in air leakage testing the results can be described in one of three forms:

1. Fan flow required to create a specified pressure drop across the fan (ie. 500 cfm flow was required to pressurize the suite to 50 Pa).
2. Equivalent leakage area which is result of the applied flow and pressures. An "equivalent" leakage area is the size of fictitious rectangular opening. (ie. At 50 Pa, the suite had an equivalent leakage area of 400 cm^2).
3. Air exchange rate, often expressed in hourly air changes per hour, which is simply volume of the space being pressurized, divided by the fan flow. (ie. The air change rate of the suite to the exterior was 2.5 ACH at 50 Pa).

The relationship describing the airflow through an "equivalent" intentional 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 the equivalent leakage area, all of the openings through the walls/floor of the suite are combined into an overall opening area and discharge coefficient. Some guidance is provide in ASHRAE (2005) to select a discharge coefficient, C_D, however can be assumed to be 0.61 for a sharp edged orifice opening. The air leakage area of a building is, therefore, the area of an orifice (equivalent area) that would produce the same amount of leakage as the building enclosure at the tested pressure.

The relationship can be simplified to typical test units (imperial areas and metric pressures) as follows (Retrotec 2006).

$$Q = 1.0755 \cdot A \cdot \sqrt{P} \tag{2}$$

Where, Q = room supply flow (cfm),
A = equivalent leakage area, ELA (in^2)
P = pressure difference between room and exterior (Pa)
1.0755 = constant, including conversions for mix of metric/imperial units commonly used in practice

Unit or normalized leakage areas can be determined by dividing the equivalent leakage area over the surface area which the leakage occurs through (ie. exterior building enclosure area).

Air leakage measurements are commonly taken at a single test pressure, and for purposes of this test 50 Pa was used. However in practice typical pressures as a result of 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):

$$Q = C \cdot (\Delta P)^n \tag{3}$$

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)

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

1.3 BUILDING AND TEST SUITE DESCRIPTION

Four buildings in Vancouver, BC were air leakage tested. A plan view of each building highlighting the tested suites is provided in *Appendix G: Air Leakage Testing* and should be referred in conjunction with the test procedure.

Building numbering is consistent with previous reports from the monitoring study (Buildings 2, 3 and 4), and the additional building is referred to as Building 'A' for purposes of this report.

Table 1-1 provides a summary the tested suite number in each building, and comments pertaining to adjacent suites which were pressurized and depressurized during testing to quantify the air leakage of individual surfaces.

Table 1-1: Building Number, Test Suite and Comments

Building	Suite	Comments
2	401	Top floor, corner, 3rd floor below, stairwell (left), suite 402 (right), hallway access
3	608	Top floor, 5th floor below, Lounge (Left), suite 609 (right), hallway access (open hallway to exterior)
3	611	Top floor, 5th floor below, suite 609 (left), stairwell (right), hallway access
3	311	Middle floor, 2nd floor below, 4th floor above, suite 309 (left), stairwell (right), hallway access
A	802	Middle floor, 7th floor below, 9th floor above, suite 801 (left), suite 803 (right), hallway access
4	309	Middle floor, 2nd floor below, 4th floor above, suite 308 (left), suite 310 (right), hallway access

The testing procedure was modified (ie. test steps were omitted) where the test suite was located in a corner of the building or had only one adjacent suite or at the top floor of the building. Each surface of the suite was isolated where at all possible and interior access was provided.

Each of the Buildings is described in more detail in the following sections and supplemental information is provided in *Appendix G: Air Leakage Testing*.

1.3.1 <u>Building 2</u>

Building 2 is a four-storey wood-frame condominium building which was constructed in the early 1990's. In 2001, the exterior walls and roof were rehabilitated as a result of widespread moisture related damage to the exterior walls. The exterior cladding and plywood sheathing was replaced with a stucco rainscreen clad system as shown in Figure 1-3. The SBPO house-wrap was taped and sealed during the rehabilitation and forms an integral portion of the exterior wall air barrier system. The polyethylene membrane was left intact from original construction and forms a portion of the air barrier system. Air sealing details between suites are unknown.

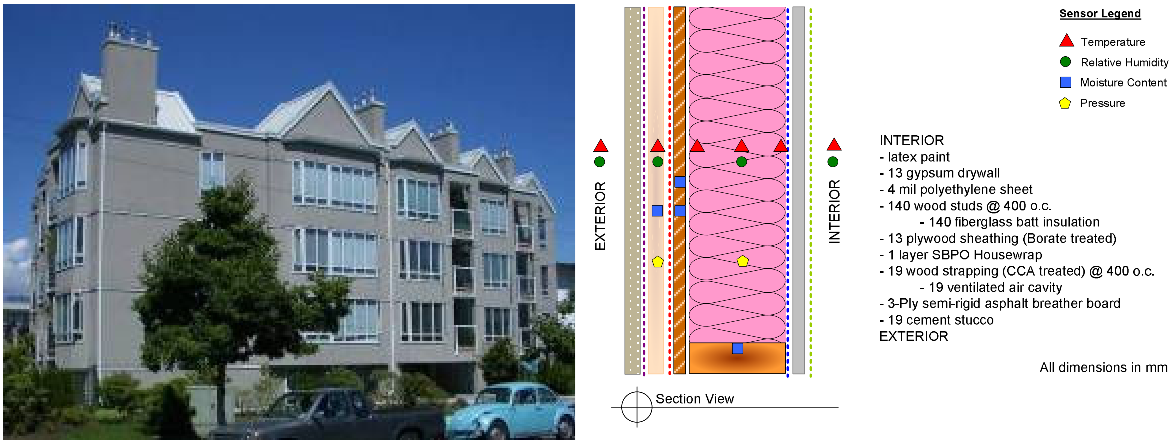


Figure 1-3: Building 2 – Overview and Wall Assembly Details.

Suite 401, highlighted in Figure 1-4 was tested as the interior conditions were monitored there for the past five years. A plan view of the 4th floor is shown in *Appendix G: Air Leakage Testing* showing the adjacent suites which were neutralized during the test.

Figure 1-4: Building 2 – Suite 401 Highlighted at Southeast Corner

The fourth floor suites have a vaulted cathedral ceiling and skylights over the living room as shown in the figure. Metal roof deck is used at these steep sloped sections and a two-ply modified bitumen roofing assembly is used at low-slope areas over the remainder of the suites.

Each suite has a gas fireplace with a 6" diameter flue exhausting through common chimney build-outs at the roof (ie. 1st through 4th floor stacked suites use same chimney build-out). The fireplace dampers were closed during the testing of this suite, and the fireplace was off. A bathroom exhaust fan and kitchen range hood exhaust fan are located in this suite as the primary exhaust, however neither is continuously used. The occupant also has a portable humidifier and several large trees/plants. Two interior views of the suite are shown in Figure 1-5.

Figure 1-5: Building 2 – Suite 401 Interior at Living Room (left), Bedroom (right)

Suite 401 has a gross floor area of 684 ft^2, and a gross volume of 5472 ft^3. The exterior wall area is 720 ft^2 which includes four large windows and one sliding glass door.

1.3.2 <u>Building 3</u>

Building 3 is a six-storey concrete-frame residential building which was constructed in the early 1990's. In 2002, the exterior walls were rehabilitated and windows replaced as a result of widespread moisture related damage to the steel-stud and gypsum exterior walls. The exterior cladding was replaced with a stucco rainscreen clad system as shown in Figure 1-6. The exterior wall air barrier system consists of a self-adhered modified bitumen layer to the exterior of the gypsum sheathing (Figure 1-7). The roof consists of a two-ply modified bitumen roofing assembly. Air sealing details between suites are unknown.

Figure 1-6: Building 3 – Overview and Wall Assembly Details

Figure 1-7: Building 3 – Air Barrier Membrane over Gypsum Sheathing

Moisture problems within the rehabilitated exterior walls of Building 3 were noted by Finch et al. (2006) and found to be correlated with humid interior conditions and condensation at the gypsum sheathing during the winter.

Further monitoring and testing by Roppel et al. (2007) determined ventilation rates by measuring exhaust fan flow and CO_2 levels within several suites and found that the low ventilation levels were contributing to the high interior humidity levels.

The current VBBL and BCBC have similar minimum requirements as ASHRAE Standard 62 which recommends 15 cfm per person. Table 9.32.3.3.A requires a minimum ventilation rate for the principal exhaust, which may be the bathroom exhaust fan, based on the number of bedrooms.

The VBBL requires that the principal exhaust fan be controlled by an adjustable time control device to provide a minimum of two 4-hour operating periods per day, or be designed to run continuously. A separate requirement states that the bathroom fan should have a capacity of 50 CFM if run intermittently or 20 CFM if run continuously.

The primary exhaust fans (bathroom) were measured in fourteen of the suites by Roppel et al. (2007) and found a range of 20 to 61 cfm (average 43 cfm). While the fans were supposedly installed on timers, occupants reported that the fans were not all on the same time nor ran for the four hours twice per day as required by Vancouver Building Code.

The source of make-up supply air to the suites was also questioned as several door undercuts were missing or blocked with weather-stripping.

Suite 311, 611, and 608 highlighted in Figure 1-8 were tested. Interior conditions were monitored in suites 311 and 611 for the past five years and 608 for a period of 6 months during the past year. A plan view of the 3rd and 6th floors highlighting these suites is shown in *Appendix G: Air Leakage Testing*.

Figure 1-8: Building 3 – Suites 311, 611 and 608 Highlighted.

Suite 611 has a gross floor area of 742 ft^2, and a gross volume of 5936 ft^3. The exterior wall area is 488 ft^2 which includes three windows and one insulated metal panel glazed swing door.

Suite 611 is located off of conditioned hallway space. The entrance door is almost flush to the floor and weather-stripped therefore provisions for makeup air to this suite is unknown and likely through unintentional openings.

Suite 311 has a gross floor area of 742 ft^2, and a gross volume of 5936 ft^3. The exterior wall area is 488 ft^2 which includes three windows and one insulated metal panel glazed swing door.

Suite 311 is located off of conditioned hallway space. Supply or makeup air is partially provided to this suite via door undercut (13 mm).

Suite 608 has a gross floor area of 742 ft^2, and a gross volume of 5936 ft^3. The exterior wall area is 588 ft^2 which includes three windows, one insulated metal panel glazed swing door and one insulated metal swing door.

Suite 608 is located at the exterior exposed hallway, unlike the majority of the suites in the building which are located off of conditioned space. No provisions for supply or makeup air are provided to this suite. The doorway is fitted with weather stripping and makeup air is assumed to find its way through unintentional openings in the building enclosure. The exterior walls (except at the covered hallway) were retrofit in 2003 with a more airtight wall assembly than originally in was in place.

The interior conditions of suite 608 were monitored for a period of six months in 2005 and were found to be elevated to levels similar to suites 311 and 611 (monitored continuously from 2002 to 2006).

1.3.3 <u>Building 4</u>

Building 4 is a four-storey wood-frame residential building which was constructed in 2002. The exterior wall assembly is shown in Figure 1-9. The polyethylene is taped and sealed at penetrations and forms an integral part of the air barrier system.

The wood-frame floors are topped with a 2″ concrete topping which accommodates radiant heating pipes. As such the floor slab is expected to be relatively air-tight compared to a typical plywood floor. Air sealing details between suites are unknown.

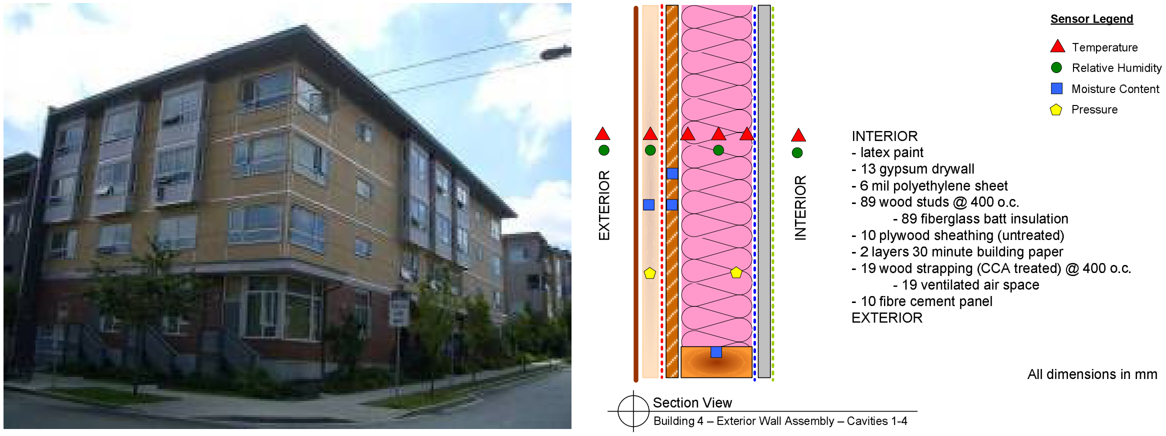


Figure 1-9: Building 4– Overview and Wall Assembly Details

Suite 309, highlighted in Figure 1-4 was tested as the interior conditions were monitored there in this suite past five years. A plan view of the 4th floor is shown in *Appendix G: Air Leakage Testing*.

Figure 1-10: Building 4 – Suite 309, view of Northwest corner.

Suite 309 has a gross floor area of 378 ft^2, and a gross volume of 3024 ft^3. The exterior wall area is 136 ft^2 which includes one large bay window.

1.3.4 Building A

Building 'A' is a 26 storey concrete-frame condominium building which was constructed in the 1987. In 2006-2007, the exterior walls were rehabilitated in as a result of widespread moisture related damage to the exterior steel stud and gypsum infill walls. The exterior cladding was replaced with a stucco rainscreen clad system and new windows. The exterior wall air barrier system consists of a self-adhered modified bitumen layer to the exterior of the gypsum sheathing, similar to Building 3. An exterior overview of the building is shown in Figure 1-11.

Figure 1-11: Building A – Overview of South Elevation

Suite 802 in the building was chosen for air leakage testing as the occupant had complained of high humidity and condensation on the windows during the winter months. It was suspected that insufficient ventilation was occurring in this suite (and others) in this recently rehabilitated building. The air leakage testing was performed to determine the source of the makeup air, and the air tightness of the exterior building enclosure which had recently been rehabilitated.

Suite 802 has a gross floor area of 1085 ft^2, and a gross volume of 8680 ft^3. The exterior wall area is 450 ft^2 which consists of approximately 53% glazing.

1.3.5 Test Dates

The air leakage testing of the four buildings was performed from December 5th through 8th. One building was tested per day, and one to three suites in each building was tested. The weather and exterior temperature during the tests are summarized in Table 1-2. Fortunately winds were calm and temperatures mild during the testing.

Table 1-2: Summary of Building Test Date and Weather/Temperature

Date	**Building #**	**Floor #**	**Suite #**	**Weather**
Dec. 5/06	2	4th	401	Cloudy, calm winds 5°C
Dec. 6/06	3	6th	608	Cloudy, calm winds, 6-8°C
Dec. 6/06	3	6th	611	Cloudy, calm winds, 6-8°C
Dec. 6/06	3	3rd	311	Cloudy, calm winds, 6-8°C
Dec. 7/06	A	8th	802	Overcast, calm winds, 8°C
Dec. 8/06	4	3rd	309	Overcast, calm winds, 8°C

1.4 TEST RESULTS

The test results are tabulated for each suite in the following sections. In addition, the results are compared by building type, wall/floor assembly to show the impact of construction on the relative air tightness. Raw data and supplemental building information is provided in *Appendix G: Air Leakage Testing*.

1.4.1 Building 2

Air leakage testing data for Suite #401 in Building 2 is presented in Table 1-3.

Table 1-3: Suite 401 – Building 2, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA$_{50}$)**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA$_{50}$)**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *165 m^2* *(1778 ft^2)*	1070 cm^2 (166 in^2)	1060 cm^2 (164 in^2)	1065 cm^2 (165 in^2)	100%	1257 cfm (593 L/s)	13.8	6.5 cm^2/m^2 (9.3 in^2/100 sq.ft)
3rd floor + suite 301 *64 m^2* *(684 ft^2)*	64 cm^2 (10 in^2)	84 cm^2 (13 in^2)	74 cm^2 (11.5 in^2)	7%	87 cfm (41 L/s)	1.0	1.2 cm^2/m^2 (1.7 in^2/100 sq.ft)
hallway 4th floor *8 m^2* *(82 ft^2)*	116 cm^2 (18 in^2)	66 cm^2 (10 in^2)	91 cm^2 (14 in^2)	9%	107 cfm (51 L/s)	1.2	11.9 cm^2/m^2 (23.8 in^2/100 sq.ft)
left wall stairwell *6 m^2* *(64 ft^2)*	40 cm^2 (6 in^2)	21 cm^2 (3 in^2)	31 cm^2 (5 in^2)	3%	36 cfm (17 L/s)	0.4	5.1 cm^2/m^2 (7.4 in^2/100 sq.ft)
right wall suite 402 *21 m^2* *(227ft^2)*	10 cm^2 (2 in^2)	10 cm^2 (2 in^2)	10 cm^2 (2 in^2)	1%	12 cfm (6 L/s)	0.1	0.5 cm^2/m^2 (0.7 in^2/100 sq.ft)
exterior walls + roof *67 m^2* *(720 ft^2)*	840 cm^2 (130 in^2)	879 cm^2 (136 in^2)	860 cm^2 (133 in^2)	81%	1014 cfm (479 L/s)	11.1	12.9 cm^2/m^2 (18.5 in^2/100 sq.ft)

The normalizing area for the exterior walls and roof above is taken at the exterior wall area only, excluding the roof area. Leakage through the roof could not be isolated from the exterior walls in this case however is assumed to be small. If the area of the roof was included the normalized equivalent leakage area would be 6.6 cm^2/m^2 (9.9 in^2/100 sq.ft) through the exterior building enclosure instead of 12.9 cm^2/m^2 (18.5 in^2/100 sq.ft).

It is shown that a relatively large percentage of the air leakage through this suite is through the exterior walls, roof, and exhaust ducts. The suite demising walls and floors are relatively well sealed. A high percentage of the interior air leakage is through the hallway through unintentional openings, potentially through the attic/cathedral ceiling space of this suite. Several penetrations through the gypsum drywall which are typically unsealed were observed in the hallway (sprinkler heads, lights, switches, receptacles etc.).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 1-12).

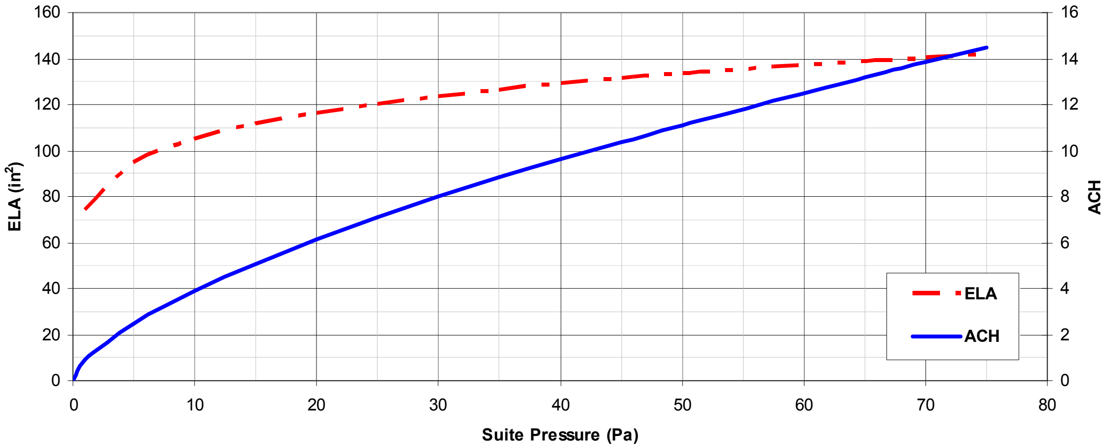


Figure 1-12: Exterior Wall ELA and ACH Relationships for Suite 401, Building 2

1.4.2 <u>Building 3</u>

Three suites in Building 3 were individually air leakage tested: 608, 611, and 311.

1.4.2.1 Suite 608

Air leakage testing data for Suite #608 in Building 3 is presented in Table 1-4. The floor below was not isolated from the testing due to access restrictions, however as shown by the tests of 611 and 311, inter-floor leakage between suites in this building was found to be insignificant.

Table 1-4: Suite 608 – Building 3, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA$_{50}$)**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA$_{50}$)**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *235 m^2* *(2532 ft^2)*	341 cm^2 (53 in^2)	330 cm^2 (51 in^2)	336 cm^2 (52 in^2)	100%	396 cfm (187 L/s)	4.0	1.4 cm^2/m^2 (2.1 in^2/100 sq.ft)
left wall lounge *10 m^2* *(108 ft^2)*	18 cm^2 (3 in^2)	22 cm^2 (3 in^2)	20 cm^2 (3 in^2)	6%	24 cfm (11 L/s)	0.2	2.0 cm^2/m^2 (2.9 in^2/100 sq.ft)
right wall suite 609 *16 m^2* *(176ft^2)*	43 cm^2 (7 in^2)	65 cm^2 (10 in^2)	54 cm^2 (2 in^2)	16%	64 cfm (30 L/s)	0.6	3.3 cm^2/m^2 (4.8 in^2/100 sq.ft)
exterior walls + roof *55 m^2* *(588 ft^2)*	280 cm^2 (43 in^2)	243 cm^2 (38 in^2)	262 cm^2 (41 in^2)	78%	309 cfm (146 L/s)	3.1	4.8 cm^2/m^2 (6.7 in^2/100 sq.ft)

The normalizing area for the exterior walls and roof is taken at the exterior wall area only, not including the roof or floor below. As shown for suites 311 and 611, air leakage between floors in this building is negligible and is assumed to be so for this suite. Leakage through the roof could not be isolated from the exterior walls and is assumed to be negligible. If the area of the roof was included, the normalized equivalent leakage area would be 2.1 cm^2/m^2 (3.1 in^2/100 sq.ft) through the exterior building enclosure instead of 4.8 cm^2/m^2 (6.7 in^2/100 sq.ft).

While the majority of air leakage occurs through the exterior building enclosure (which is beneficial for this suite as no provisions were made for makeup air), some leakage occurs between adjacent suites (22%).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 1-13).

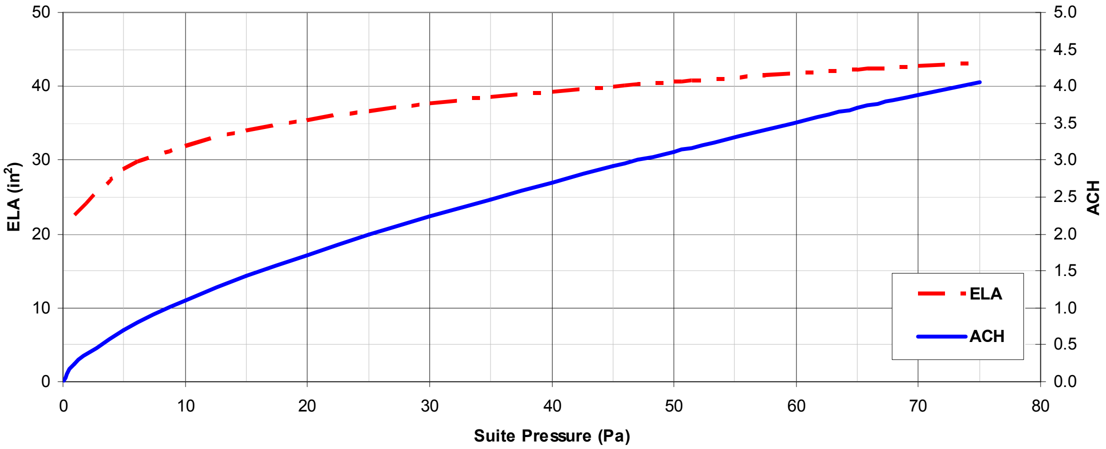


Figure 1-13: Exterior Wall ELA and ACH Relationships for Suite 608, Building 3

The impact of taping the bathroom and kitchen exhaust fan inlets was tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage area dropped by 26 cm², when both bathroom and kitchen ducts were sealed this dropped to 32 cm² from a total of 280 cm².

The exhaust ducts were cast into the concrete floor slab and have an unknown area, however typical 2.5 cm x 250 cm (1" x 10") ducts would have only an area of 63 cm² and something similar was likely used here. It is also possible that the ducts were damaged or partially constricted during installation reducing the area. Sealing the bathroom/kitchen fans may also only have a minimal impact, as air may be drawn from other openings (electrical outlets) which are attached to the pressurized plenum created by the fan. The remainder of the leakage to the exterior is assumed to occur around windows, and penetrations through the building enclosure.

1.4.2.2 Suite 611

Air leakage testing data for Suite #611 in Building 3 is presented in Table 1-5.

Table 1-5: Suite 611 – Building 3, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA_{50})**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *225 m^2* *(2423 ft^2)*	540 cm^2 (84 in^2)	492 cm^2 (77 in^2)	516 cm^2 (80 in^2)	100%	609 cfm (287 L/s)	6.2	2.3 cm^2/m^2 3.3 in^2/100 sq.ft)
5th floor + suite 511 *69 m^2* *(742 ft^2)*	8 cm^2 (1in^2)	5cm^2 (1 in^2)	7cm^2 (1in^2)	1%	8 cfm (4 L/s)	0.1	0.1 cm^2/m^2 (0.1 in^2/100 sq.ft)
hallway 6th floor *10 m^2* *(107 ft^2)*	204 cm^2 (32 in^2)	270 cm^2 (42 in^2)	237 cm^2 (37 in^2)	46%	280 cfm (132 L/s)	2.8	23.9 cm^2/m^2 34.4 in^2/100 sq.ft)
left wall suite 609 *20 m^2* *(216ft^2)*	88 cm^2 (14 in^2)	82 cm^2 (12 in^2)	85 cm^2 (13 in^2)	16%	100 cfm (47 L/s)	1.0	4.2 cm^2/m^2 (6.1 in^2/100 sq.ft)
exterior walls + roof *45 m^2* *(488 ft^2)*	240 cm^2 (37 in^2)	135 cm^2 (21 in^2)	188 cm^2 (29 in^2)	36%	221 cfm (104 L/s)	2.2	4.1 cm^2/m^2 (6.0 in^2/100 sq.ft)

The normalizing area for the exterior walls and roof is taken at the exterior wall area only, not including the roof or stairway wall. Leakage through the roof or stairwell could not be isolated from the exterior walls in this case however is assumed to be small (solid concrete with no penetrations). If the area of the roof and stairwell wall was included, the normalized equivalent leakage area would be 1.5 cm^2/m^2 (2.1 in^2/100 sq.ft) instead of 4.1 cm^2/m^2 (6.0 in^2/100 sq.ft).

The majority of air leakage into this suite occurs through unintentional openings in the hallway wall (46%) and adjacent suite (16%). A negligible amount of leakage is through the floor slab (<1%) and the remainder is through the exterior walls and roof (36%).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 1-14).

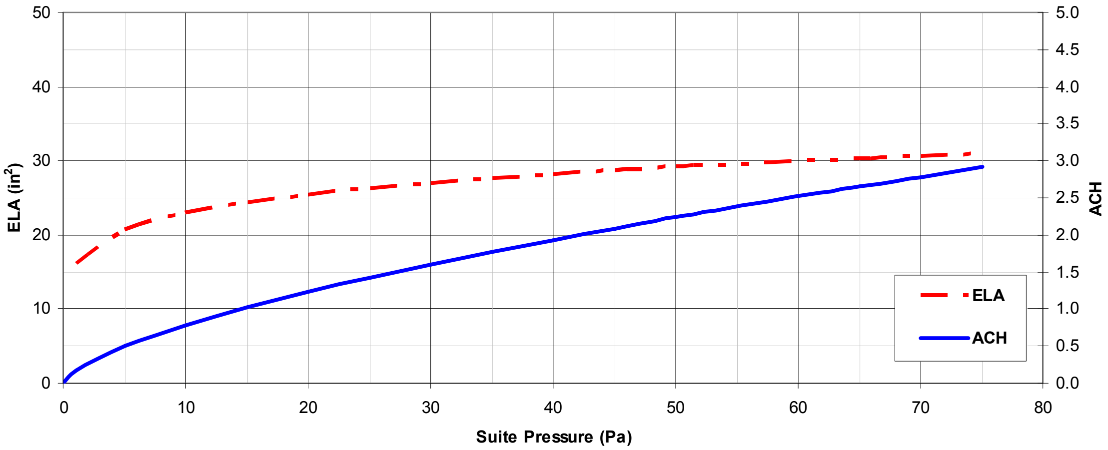


Figure 1-14: Exterior Wall ELA and ACH Relationships for Suite 611, Building 3

Like suite 608 the area of in-slab ducts make up approximately 50 cm^2 to 100 cm^2 of the exterior leakage area. The remainder of the leakage to the exterior is assumed to occur around windows, and penetrations through the building enclosure.

1.4.2.3 Suite 311

Air leakage testing data for Suite #311 in Building 3 is presented in Table 1-6.

Table 1-6: Suite 311 – Building 3, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA$_{50}$)**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA$_{50}$)**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *225 m^2* *(2423 ft^2)*	392 cm^2 (61 in^2)	302 cm^2 (47 in^2)	347 cm^2 (54 in^2)	100%	409 cfm (193 L/s)	4.1	1.5 cm^2/m^2 (3.1 in^2/100 sq.ft)
4th floor + suite 411 *69 m^2* *(742 ft^2)*	3 cm^2 (1 in^2)	6 cm^2 (1 in^2)	5 cm^2 (1 in^2)	1%	5 cfm (2 L/s)	0.1	0.1 cm^2/m^2 (0.1 in^2/100 sq.ft)
2nd floor + suite 211 *69 m^2* *(742 ft^2)*	9 cm^2 (1 in^2)	8 cm^2 (1 in^2)	9 cm^2 (1 in^2)	2%	10 cfm (5 L/s)	0.1	0.1 cm^2/m^2 (0.2 in^2/100 sq.ft)
hallway 4th floor *10 m^2* *(107 ft^2)*	169 cm^2 (26 in^2)	195 cm^2 (30 in^2)	182 cm^2 (28 in^2)	52%	215 cfm (101 L/s)	2.2	18.0 cm^2/m^2 (26 in^2/100 sq.ft)
left wall suite 309 *20 m^2* *(216 ft^2)*	46 cm^2 (7 in^2)	30 cm^2 (5 in^2)	38 cm^2 (6 in^2)	11%	45 cfm (21 L/s)	0.5	1.9cm^2/m^2 (2.7 in^2/100 sq.ft)
exterior wall *45 m^2* *(488 ft^2)*	165 cm^2 (26 in^2)	64 cm^2 (10 in^2)	114 cm^2 (18 in^2)	33%	135 cfm (64 L/s)	1.4	2.5 cm^2/m^2 (3.6 in^2/100 sq.ft)

The normalizing area for the exterior walls is taken as the exterior wall area only, not including stairway wall. Leakage through stairwell could not be isolated from the exterior walls in this case however is assumed to be small (solid concrete with no penetrations). If the area of the stairwell wall was included, the normalized equivalent leakage area would be 2.0 cm^2/m^2 (2.9 in^2/100 sq.ft).

The majority of air leakage into this suite occurs through unintentional openings in the hallway wall (52%) and adjacent suite (11%). A negligible amount of leakage is through the floor slabs (3%) and the remainder is through the exterior walls (33%).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 1-15).

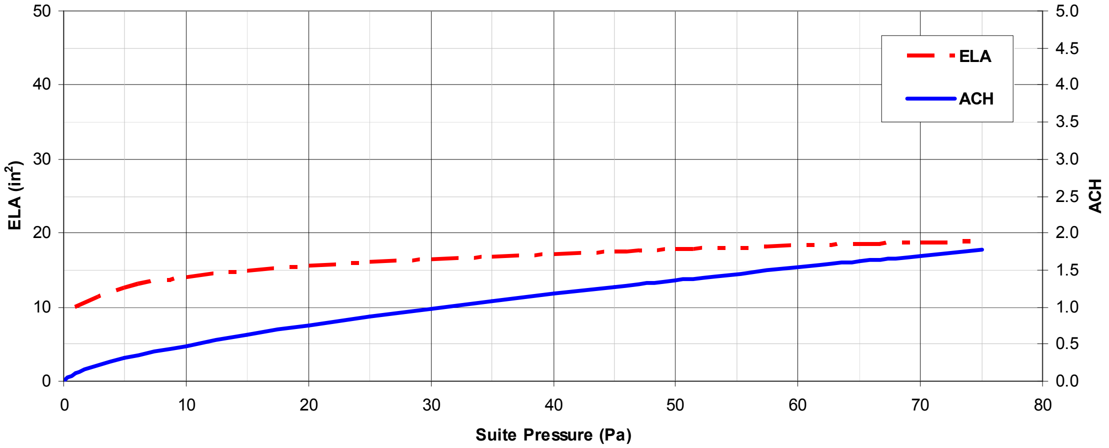


Figure 1-15: Exterior Wall ELA and ACH Relationships for Suite 311, Building 3

The impact of taping the bathroom and kitchen exhaust fan inlets were tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage area remained the same, indicating air was potentially bypassing the inlet grille, possibly at other penetrations in the wall or ceiling.

The three suites tested in Building 3 show similar air leakage results, particularly 311 and 611 which are of similar configuration. The building enclosures are relatively tight in all suites; however significant inter-suite and unintentional hallway to suite leakage is occurring.

1.4.3 Building A

Air leakage testing data for Suite #802 in Building 'A' is presented in Table 1-7.

Table 1-7: Suite 802 – Building A, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA$_{50}$)**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA$_{50}$)**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *314 m^2* *(3381 ft^2)*	347 cm^2 (54 in^2)	290 cm^2 (45 in^2)	319 cm^2 (49 in^2)	100%	376 cfm (177 L/s)	2.6	1.0 cm^2/m^2 (1.5 in^2/100 sq.ft)
9th floor + suite 902 *101 m^2* *(1085 ft^2)*	61 cm^2 (9 in^2)	54 cm^2 (8 in^2)	58 cm^2 (9 in^2)	18%	68 cfm (32 L/s)	0.5	0.6 cm^2/m^2 (0.8 in^2/100 sq.ft)
7th floor + suite 702 *101 m^2* *(1085 ft^2)*	16 cm^2 (3 in^2)	16 cm^2 (3 in^2)	16 cm^2 (3 in^2)	5%	19 cfm (9 L/s)	0.1	0.2 cm^2/m^2 (0.2 in^2/100 sq.ft)
hallway 8th floor *11 m^2* *(114 ft^2)*	145 cm^2 (22 in^2)	88cm^2 (14 in^2)	117 cm^2 (18 in^2)	37%	138 cfm (21 L/s)	1.0	11.0 cm^2/m^2 (16.0 in^2/100 sq.ft)
left wall suite 801 *33 m^2* *(359 ft^2)*	5 cm^2 (1 in^2)	20 cm^2 (3 in^2)	13 cm^2 (2 in^2)	4%	15 cfm (7 L/s)	0.1	0.4 cm^2/m^2 (0.5 in^2/100 sq.ft)
right wall suite 803 *27 m^2* *(288 ft^2)*	5 cm^2 (1 in^2)	4cm^2 (1 in^2)	5 cm^2 (1 in^2)	1%	5 cfm (2 L/s)	<0.1	0.2 cm^2/m^2 (0.2 in^2/100 sq.ft)
exterior walls *42 m^2* *(450 ft^2)*	115 cm^2 (18 in^2)	108 cm^2 (17 in^2)	112 cm^2 (17 in^2)	35%	132 cfm (62 L/s)	0.9	2.7 cm^2/m^2 (3.9 in^2/100 sq.ft)

It was possible to neutralize all adjacent surfaces of the suite (unlike other Building 3, 2, or 4), therefore normalized values are accurate for the surfaces which were measured as no assumptions were made.

The majority of air leakage into this suite occurs through unintentional openings in the hallway wall (37%). Leakage between suites is small (solid concrete walls) at 5%, however significant leakage occurs between floors (23% total). The remainder (35%) is through the exterior walls.

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 1-16).

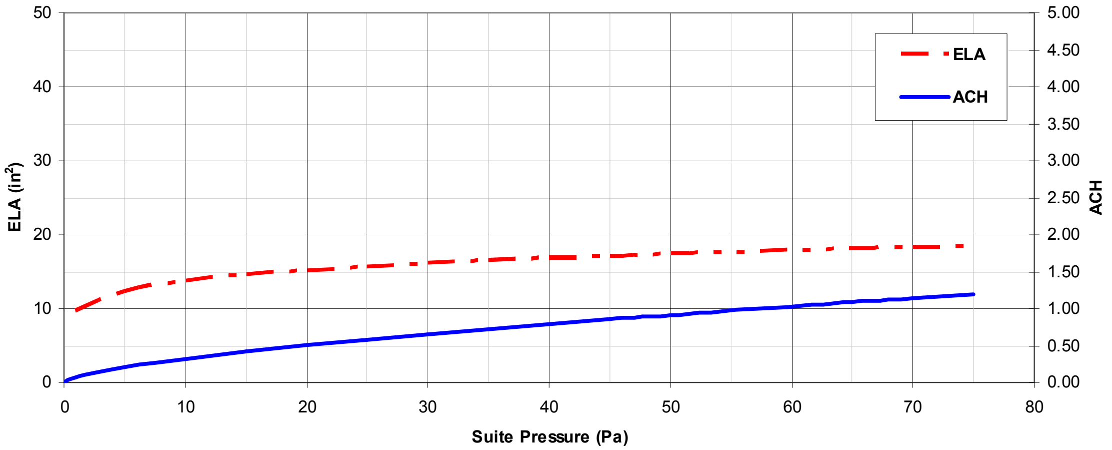


Figure 1-16: Exterior Wall ELA and ACH Relationships for Suite 802, Building A

The impact of taping the bathroom and kitchen exhaust fan inlets was tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage area dropped by 18 cm^2, when both bathroom and kitchen ducts were sealed this total dropped to 29 cm^2 from a total exterior enclosure leakage of 115 cm^2.

The exhaust ducts were cast into the concrete floor slab and have an unknown area, however typical 2.5 cm x 250 cm (1" x 10") ducts would have only an area of 63 cm^2 each (126 cm^2 total) and something similar was likely used here. It is also possible that the ducts were damaged or partially constricted during installation reducing the area. Sealing the bathroom/kitchen fans may also only have a minimal impact, as air may be drawn from other openings (electrical outlets) which are attached to the pressurized plenum created by the fan. The remainder of the leakage to the exterior is assumed to occur around windows, and penetrations through the building enclosure, which was the tightest of the six tests performed.

Air leakage values through the exterior walls measured for this suite are similar in range to those from Building 3 (which has similar construction). Plotted to the same scale, both buildings have approximately the same exterior wall leakage characteristics (Figure 1-16 versus Figure 1-14 and Figure 1-15).

1.4.4 Building 4

Air leakage testing data for Suite #309 in Building 4 is presented in Table 1-8.

Table 1-8: Suite 309 – Building 4, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA_{50})**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *133 m²* *(1428 ft²)*	470 cm² (73 in²)	360 cm² (56 in²)	415 cm² (64 in²)	100%	490 cfm (231 L/s)	9.7	3.1 cm²/m² (4.5 in²/100 sq.ft)
4th floor + suite 902 *35 m²* *(378 ft²)*	0 cm² (0 in²)	0 cm² (0 in²)	0cm² (0 in²)	0%	0 cfm (0 L/s)	0	0 cm²/m² (0 in²/100 sq.ft)
2nd floor + suite 702 *35 m²* *(378 ft²)*	0 cm² (0 in²)	0 cm² (0 in²)	0 cm² (0 in²)	0%	0 cfm (0 L/s)	0	0 cm²/m² (0 in²/100 sq.ft)
hallway 3rd floor *6 m²* *(68 ft²)*	120 cm² (19 in²)	140cm² (22 in²)	130 cm² (20 in²)	31%	153 cfm (72 L/s)	3.0	20.6 cm²/m² (30.0 in²/100 sq.ft)
left wall suite 308 *24 m²* *(256 ft²)*	15 cm² (2 in²)	5 cm² (1 in²)	10 cm² (2 in²)	2%	12 cfm (6 L/s)	0.2	0.4 cm²/m² (0.6 in²/100 sq.ft)
exterior walls *13 m²* *(136 ft²)*	335 cm² (52 in²)	215 cm² (33 in²)	275 cm² (43 in²)	35%	325 cfm (50 L/s)	6.5	21.8 cm²/m² (31.3 in²/100 sq.ft)

Access was not provided to the adjacent suite 310; therefore the right wall could not be isolated from the total air leakage to the exterior. However as shown the leakage between adjacent suites (308 on left side) was found to be minimal (2%). Therefore it is assumed that the leakage between suites 309 and 310 would also be small. As a check during testing, the pressure difference across the door of suite 310 when the hallway was pressurized was approximately 50 Pa, therefore the door undercut and any incidental leakage was balancing this suite.

It is shown that a relatively large percentage of the air leakage through this suite is through the exterior walls and exhaust ducts. The suite demising walls and floors are relatively well sealed. A high percentage of the interior air leakage is from the hallway through unintentional openings. Several penetrations through the gypsum drywall which are typically unsealed were observed in the hallway (sprinkler heads, lights, switches, receptacles etc.).

A consistent air leakage difference was observed between pressurizing and depressurizing this suite. Unlike the other buildings, this difference was consistent and can likely be attributed to use of polyethylene as the air barrier. While pressurizing the suite, the polyethylene is pushed out into insulation of the stud bays, increasing the size of any openings. When depressurizing the suite the polyethylene would be pulled against the solid gypsum drywall and thus any openings would be partially restricted and smaller. The average difference is consistently 110 to 130 cm^2 through the tests and an average of 116 cm^2 (18 in^2).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 1-17).

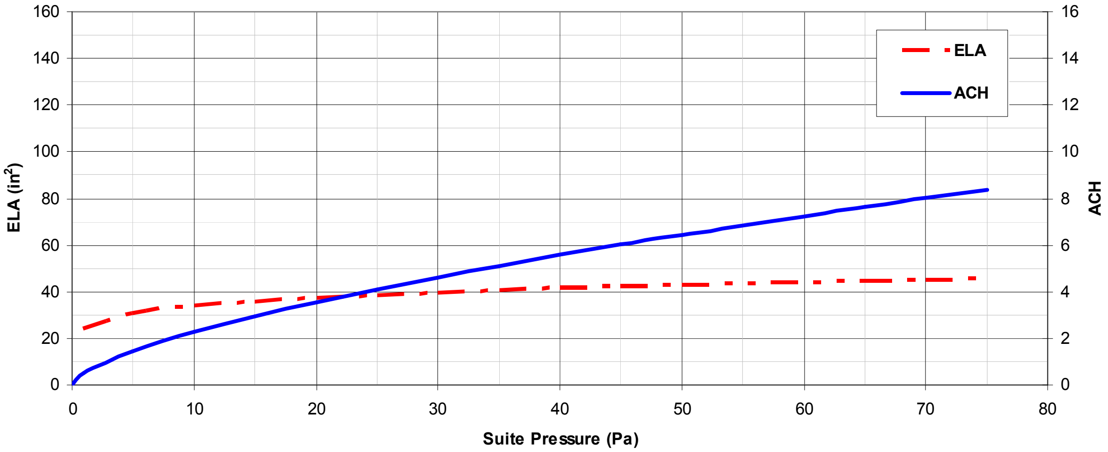


Figure 1-17: Exterior Wall ELA and ACH Relationships for Suite 309, Building 4

The impact of taping the bathroom and kitchen exhaust fan inlets was tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage remained the same. Sealing the bathroom/kitchen fans may also only have a minimal impact, as air may be drawn from other openings (electrical outlets) which are attached to the pressurized plenum created by the fan.

Air leakage values measured for this suite are similar in range to those from Building 2 (similar wood-frame construction). Figure 1-17 is plotted to the same scale as Figure 1-12 for comparison of the two buildings.

1.4.5 Summary

The air leakage through the exterior building enclosure from the six tests is summarized in Table 1-9.

Table 1-9: Summary of Air Leakage to Exterior for all Tested Buildings

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA$_{50}$)**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA$_{50}$)**
	Pressurize	**Depressurize**	**Average**				
BLDG 2 - 401 exterior walls *67 m^2* *(720 ft^2)*	840 cm^2 (130 in^2)	879 cm^2 (136 in^2)	860 cm^2 (133 in^2)	81%	1014 cfm (479 L/s)	11.1	12.9 cm^2/m^2 (18.5 in^2/100 sq.ft)
BLDG 3 - 608 exterior walls *55 m^2* *(588 ft^2)*	280 cm^2 (43 in^2)	243 cm^2 (38 in^2)	262 cm^2 (41 in^2)	78%	309 cfm (146 L/s)	3.1	4.8 cm^2/m^2 (6.7 in^2/100 sq.ft)
BLDG 3 - 611 exterior walls *45 m^2* *(488 ft^2)*	240 cm^2 (37 in^2)	135 cm^2 (21 in^2)	188 cm^2 (29 in^2)	36%	221 cfm (104 L/s)	2.2	4.1 cm^2/m^2 (6.0 in^2/100 sq.ft)
BLDG 3 - 311 exterior wall *45 m^2* *(488 ft^2)*	165 cm^2 (26 in^2)	64 cm^2 (10 in^2)	114 cm^2 (18 in^2)	33%	135 cfm (64 L/s)	1.4	2.5 cm^2/m^2 (3.6 in^2/100 sq.ft)
BLDG A - 802 exterior walls *42 m^2* *(450 ft^2)*	115 cm^2 (18 in^2)	108 cm^2 (17 in^2)	112 cm^2 (17 in^2)	35%	132 cfm (62 L/s)	0.9	2.7 cm^2/m^2 (3.9 in^2/100 sq.ft)
BLDG 4 – 309 exterior walls *13 m^2* *(136 ft^2)*	335 cm^2 (52 in^2)	215 cm^2 (33 in^2)	275 cm^2 (43 in^2)	35%	325 cfm (50 L/s)	6.5	21.8 cm^2/m^2 (31.3 in^2/100 sq.ft)

Comparison to Previous Published Values

The air leakage results for the six tested suites in Vancouver are compared to the previous results from five other Canadian buildings (Gulay et al. 1993), in normalized units of L/s/m^2 at 50 Pa. These are further compared to the NBCC 2005 requirements for building enclosure air tightness.

Table 1-10: Summary of Individual Suite Air Leakage – L/s/m^2 @ 50 Pa

Test Suite/Building	**Entire Suite Leakage, normalized to total surface area (L/s/m^2 @ 50 Pa)**	**Exterior Wall Leakage normalized to wall surface area (L/s/m^2 @ 50 Pa)**
Gulay et al (1993) – Range of 10 buildings	4.56 to 8.33 (normalizing area unknown)	2.10 to 3.15
NBCC 2005 Requirements	No Standard	0.05 to 0.15 (@ 75 Pa)
401/Building 2	3.59	7.16
608/Building 3	0.56	1.49
611/Building 3	0.79	2.67
311/Building 3	0.86	1.40
802/Building A	1.28	2.30
309/Building 4	1.74	12.12

The previous test results are similar in range to those measured in the four Vancouver buildings, with the two wood-frame buildings having higher leakage rates than the concrete frame buildings. However, both tests show results that are significantly higher than the NBCC 2005 requirements for building enclosure air tightness. The NBCC values however exclude the impact of intentional openings such as exhaust ducts which were not isolated in the Vancouver or other previous tests.

Impact of Construction on Air Tightness

The data from the six suites is summarized and compared to determine if any consistencies between wall or floor assemblies can be determined from the limited data set. While statistically insignificant, the results confirm predicted differences between assembly types.

Figure 1-18 compares the air leakage between wall exterior building enclosure assemblies.

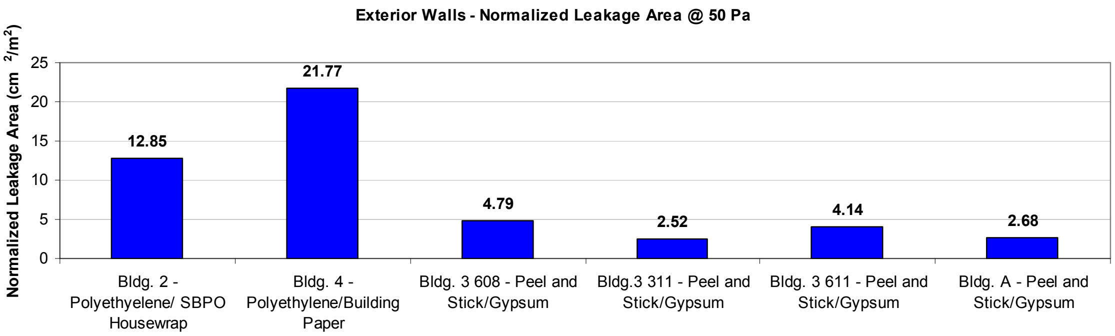


Figure 1-18: Comparison of Normalized Air Leakage through Exterior Walls

Here the two wood-frame exterior walls had the highest normalized leakage area, consistently higher than the steel stud and gypsum walls with the peel and stick air barrier. Suites 608 and 611 at the top floor of Building 3 had higher leakage areas than the other two of this set as likely some air leakage through the roof was measured but could not be isolated from the results.

The differences in air leakage through the floor assembly by type are compared in Figure 1-19.

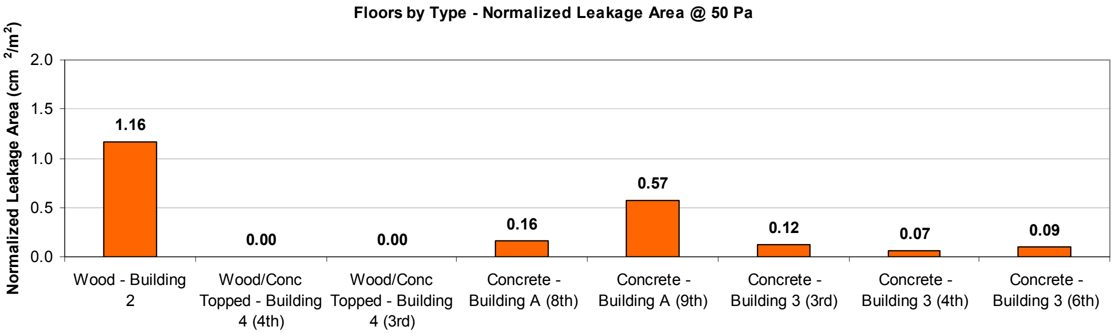


Figure 1-19: Comparison of Normalized Air Leakage through Floors by Type

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

The differences in air leakage through suite demising walls by type are compared in Figure 1-20.

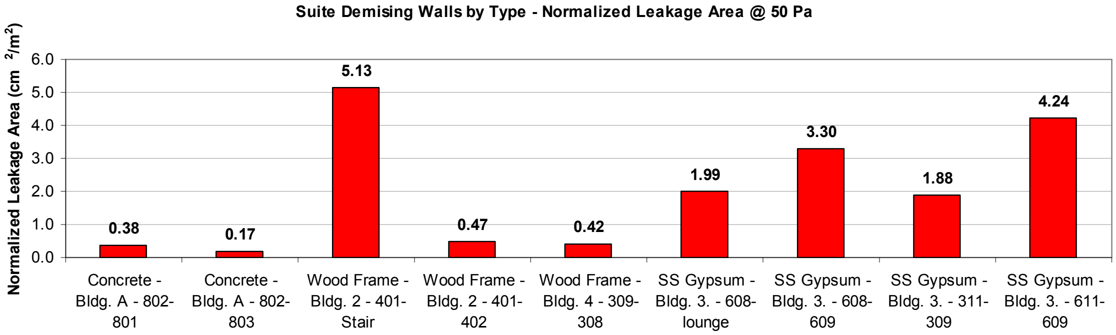


Figure 1-20: Comparison of Normalized Air Leakage through Demising Walls

The solid concrete walls were the tightest, followed by the wood frame walls (with exception of one location), and finally the steel-stud and gypsum demising walls. The differences between solid concrete and the framed walls are obvious, however it appears that wood-framed walls were constructed tighter than steel-stud and gypsum framed walls.

The differences in air leakage through the walls between the common hallway and suite are compared in Figure 1-21.

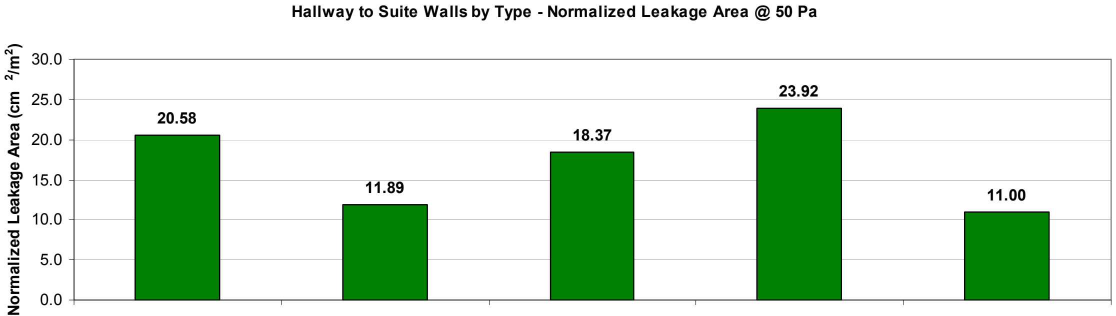


Figure 1-21: Comparison of Normalized Air Leakage through Hallway Walls

Air leakage through the hallway door is excluded from these tests, which has a leakage area is in the order of 50 cm^2/m^2 for a standard entrance door with a 1 cm door undercut normalized over the total area of the door frame. Therefore the measured leakage here is potentially through unintentional openings such as plumbing penetrations, cracks, gaps, or electrical boxes/switches.

The hallway demising walls were significantly leakier than the suite demising walls, possibly as openings were more frequent or poorly sealed. While the leakage area is unintentional (not through passive vents or door undercuts) it may be beneficial for suite supply air in cases where suite owners intentionally block the door undercut.

The following conclusions can be drawn from the results, which also reflect field experience with these types of assemblies. Solid concrete assemblies are less leaky than wood, however wood assemblies are less leaky than steel stud/gypsum. Suite demising walls and floors are more air tight than hallway walls. Exterior walls with peel-and-stick as an air barrier are more air tight than those with polyethylene or sealed taped house-wrap.

Leakage through interior walls and floors becomes increasingly significant as the exterior building enclosure becomes increasingly more air-tight. As shown in the next section, this has implications on building performance if not addressed, particularly during rehabilitations where the exterior walls are replaced and constructed more air-tight than the original walls and existing mechanical systems remain in place.

1.4.6 Lessons Learned With Multi-Unit Residential Building Testing

The minimum test setup to test and neutralize one individual suite within a larger building requires 4 fans, more if the building is very leaky or one fan cannot pressurize an entire floor (for neutralizing pressures). A total of four technicians are also required, one for each fan as a safety precaution and remain with each fan during testing should a problem occur.

When the elevator core is also located off of the tested hallway, the elevator doors opening and closing will affect pressurization. Curious tenants opening suite doors or going about their daily activities will also impact the pressurization. Performing the testing when the building is unoccupied would be ideal, however is not typically possible unless a new construction job.

The testing is by all means obtrusive and requires full cooperation of building manager and occupants to run smoothly. The testing requires the temporary blockage of an emergency fire exit. Modern and most older buildings have a minimum of two stairwells, and by no means can both be blocked. The door-fan operator must remain at the door-fan on each floor and be able to quickly take down and remove door-fan in an emergency or if a tenant wishes to use the stairwell.

Access can also be an issue, several suites to be simultaneously open, but also require access to open or close windows and doors within suites. Depressurization times should be minimized in winter. Ensuring the tenants are aware of the purpose generally helps to smooth the process out. Plan to test 1 or 2 suites per 8 hour day allowing for setup, adjustment, and cleanup.

The 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.

1.5 DISCUSSION OF BUILDING PERFORMANCE

A discussion of the interior performance of the tested suites is discussed followed by a review of the mechanical systems and ventilation strategies for the four buildings.

1.5.1 Past Performance

Temperature and relative humidity (RH) data has been collected for the past five years from the interior of the tested suites in Buildings 2, 3 and 4, and spot measured during the past year in Building A. The impact of air-tightness can be shown, as all suites had similar occupancy loads, and similar mechanical ventilation systems (exhaust by bathroom fan occupant controlled or on timers with makeup air provided by door undercuts from pressurized hallways).

Monthly average suite dewpoint temperatures are plotted in Figure 1-22 for five suites in Buildings 2, 3, and 4 from January 2002 to January 2005. Figure 1-23 plots the corresponding relative humidity within the suites over the same time period.

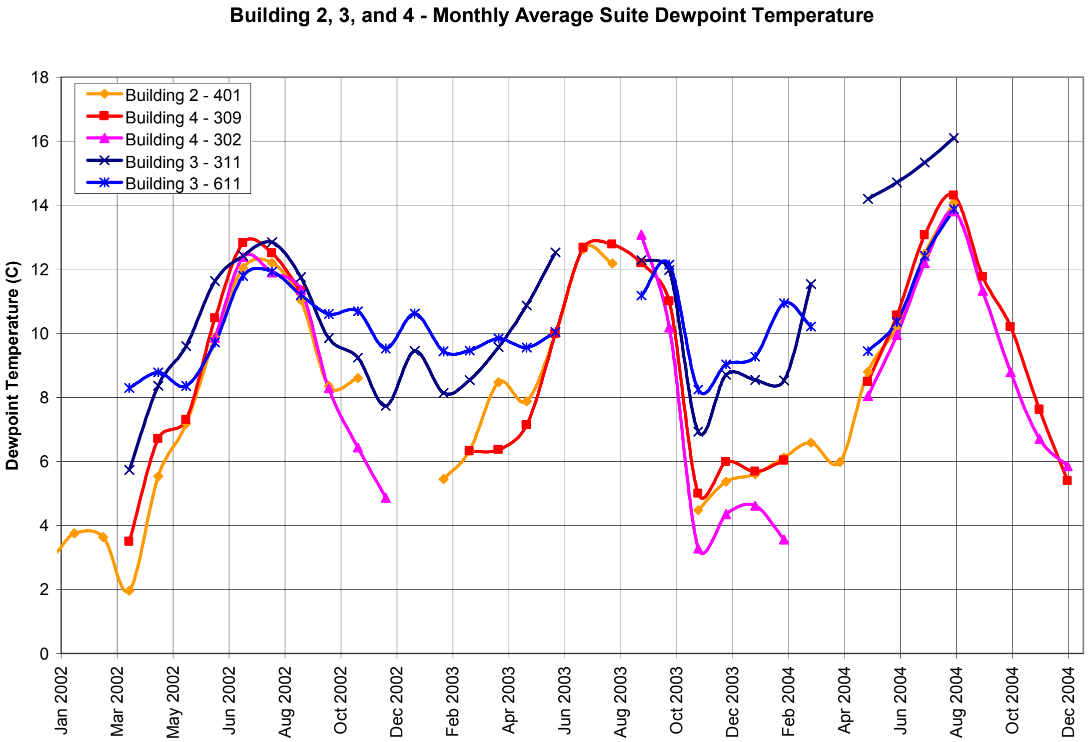


Figure 1-22: Building 2, 3 and 4 – Monthly Average Suite Dewpoint Temperature

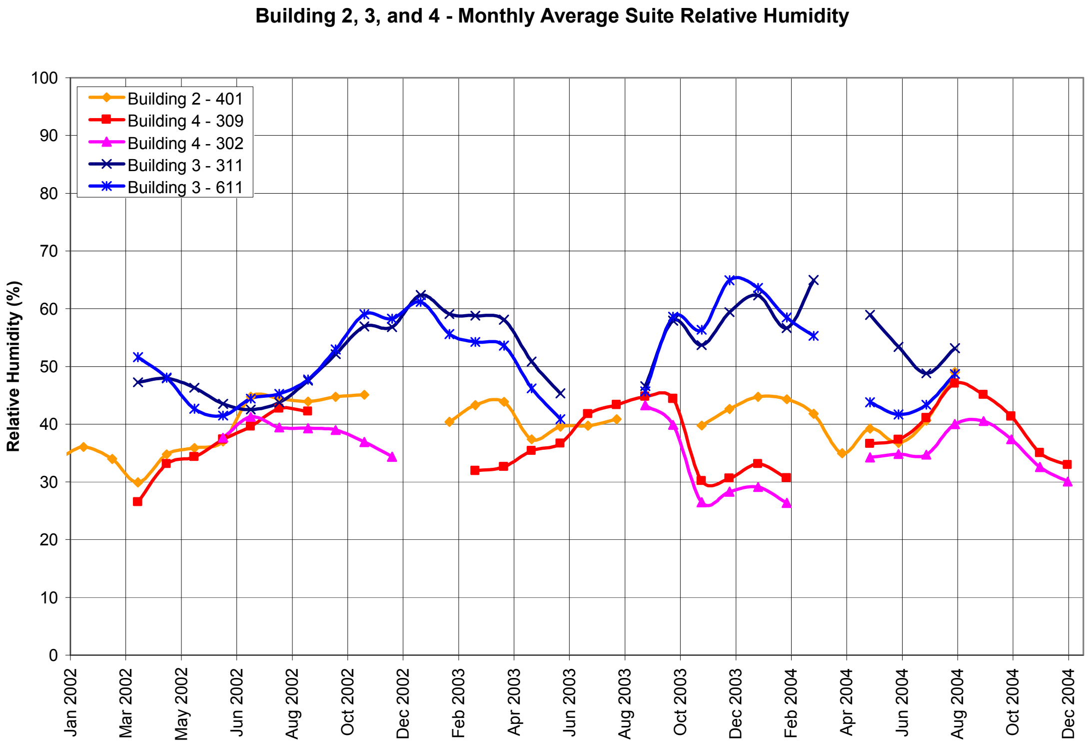


Figure 1-23: Building 2, 3 and 4 – Monthly Average Suite Relative Humidity

The interior dewpoint and relative humidity within suites of Buildings 2 and 4 remain relatively close over the three years, showing similar seasonal trends which are average for Vancouver. Building 2 is slightly more humid than Building 4, however the occupant in Building 2 uses a humidifier during the winter and has a number of large plants which would increase wintertime humidity.

During the same period the two monitored suites in Building 3 show a significantly different trend. Average wintertime dewpoint temperatures are elevated (8-10°C) as are the relative humidities which approach unsafe levels (average of 60-70% for several months). As previously discussed, Building 3 has moisture problems within the exterior walls, and condensation and mildew on interior surfaces during the winter months which correlate with the elevated interior dewpoint/humidity levels in this building.

Building A was not monitored during this period; however the interior temperature and relative humidity in several suites in Building 'A' were measured in November and December 2006. A summary of average readings taken during field reviews are as follows:

- Suite 802 was measured at 24°C and 65% RH when exterior conditions were 5°C and >80% RH.
- Suite 902 was measured at 17°C and 61% RH while hallway conditions were 21°C and 25% RH during an exceptional cold period in Vancouver when the exterior temperature was -8°C and 50% RH.
- Suite 1107 was measured at 19°C and 63% RH while hallway conditions were 22°C and 30%, exterior conditions were 3°C and >80% RH.

Complaints of condensation on window sills and glazing were also reported in Building A, which has occurred post-rehabilitation.

1.5.2 Impact of Air-Tightness on Mechanical Systems

The mechanical systems within the four tested buildings are similar. A pressurized corridor supplies make-up air into the suites (typically through 13 mm (½") door undercuts). Air is exhausted through bathroom fans (50 to 90 cfm rated) on timers and/or humidistat/occupant controlled. Additional exhaust fans are provided in the kitchen however used only when cooking and are occupant controlled. Therefore the ventilation rate of the suite is dependent on the supply of makeup air, exhaust fan flow, windows if used, and potentially additional air leakage through a leaky exterior enclosure. Ventilation efficiency is reduced when stale makeup air is drawn in from adjacent suites, which can be significant depending on the distribution and percentage of the total suite leakage area. Heating in all of the buildings investigated consists of electrical base-board heaters at the perimeter walls below windows which is set by an occupant controlled thermostat.

The four tested suites in Buildings 3 and 'A' were found to be relatively air-tight compared to the other Buildings 2 and 4. Wintertime elevated humidity and moisture problems are evident and have lead to damage in Building 3 and condensation and humidity problems have been reported in Building A. In contrast, the two tested suites in Buildings 2 and 4 were found to be relatively air-leaky. Elevated humidity or moisture problems have not been reported within Building 2 and 4 over the past four years.

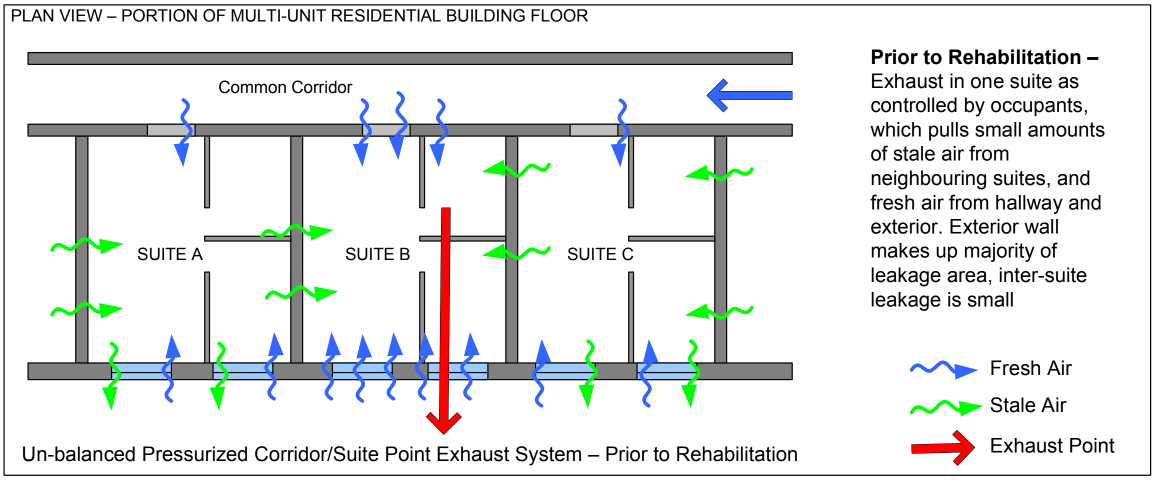
Buildings 3 and 'A' were rehabilitated in 2002 and 2006 with similar air-tight exterior wall assemblies with an air-tight peel and stick membrane over gypsum sheathing-steel stud wall and new air-tight windows. Testing has confirmed the relative air-tightness of these assemblies as constructed. Subsequently a large percentage of the air leakage into these suites is through adjacent suites and common areas and one-third of the total suite air leakage is through the exterior building enclosure. In both of these buildings the existing mechanical systems remained in place after the exterior wall rehabilitation. In both buildings, the height of the door-undercut varies from tightly sealed up to a 13 mm (1/2") open gap.

With the existing mechanical system, there is no provision to deliver fresh make-up air directly to the suites in any of these buildings. Therefore, make-up air will be drawn from a combination of the corridors, adjacent suites, and the exterior walls/roof. The path of air exchange is dependent on leakage area and pressure differentials between the suite and adjacent zones (corridor, adjacent suites, and exterior environment). If a suite is tight to the exterior, but relatively leaky to the adjacent suite or common spaces, the majority of makeup air will come from these leakier locations. Drawing stale, moisture laden air from adjacent suites will increase the relative humidity within the suites as the effective ventilation rate is significantly reduced.

Air-tightness combined with the existing mechanical system is a contributing factor in the interior performance of Buildings 3 and 'A'. Additional mechanical ventilation is required for these tighter buildings as opposed to the leakier wood-frame enclosures (Buildings 2 and 4) which were tested. This by no means implies that airtight buildings with peel and stick will have interior moisture problems, or wood-frame buildings will not have problems. A number of factors contribute to interior moisture problems, and air tightness coupled with deficient mechanical ventilation is the most significant issue.

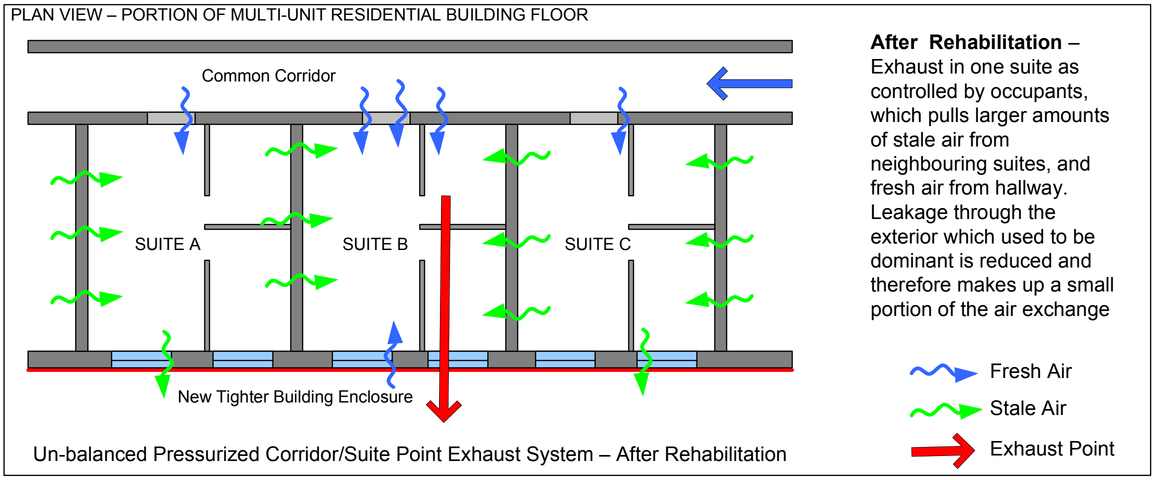
Mechanical systems must be designed for each individual building and assumptions as to base air leakage rates through the building enclosure are no longer valid with modern wall assemblies.

Figure 1-24 graphically shows the impact of air tightening the exterior wall of a building (such as during a rehabilitation) on suite ventilation and how problems could be avoided by using a balanced system, with continual or controlled exhaust in each suite, while ensuring sufficient makeup air reaches each suite.



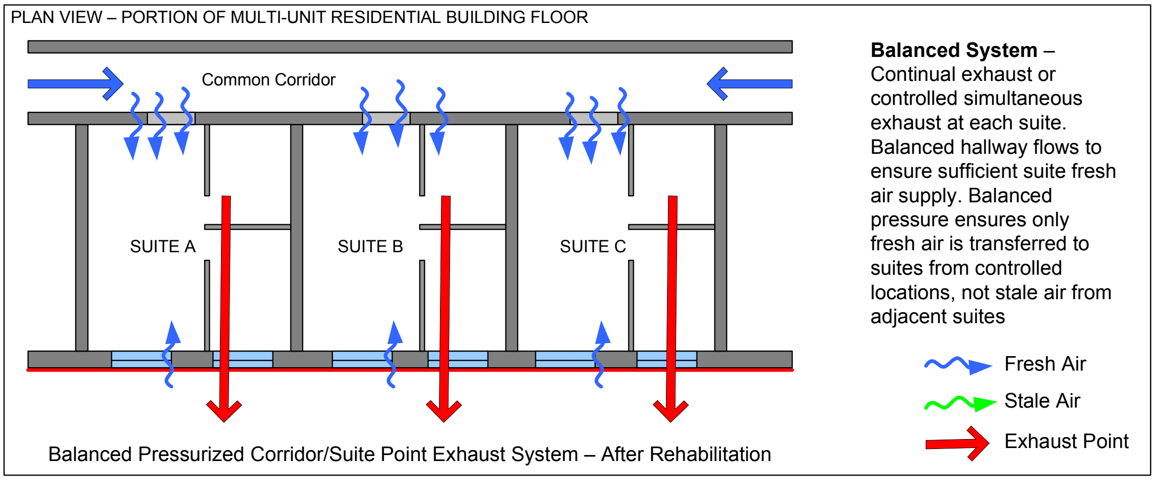
Prior to Rehabilitation – Exhaust in one suite as controlled by occupants, which pulls small amounts of stale air from neighbouring suites, and fresh air from hallway and exterior. Exterior wall makes up majority of leakage area, inter-suite leakage is small

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

Un-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

Balanced Pressurized Corridor/Suite Point Exhaust System – After Rehabilitation

Figure 1-24: Impact of Air Tightness of Walls on Mechanical Systems

1.6 CONCLUSIONS

Air leakage testing of six suites in four multi-unit residential buildings was performed to quantify air leakage between adjacent suites, floors, common spaces and through the 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).

The test method allowed the air leakage through the exterior building enclosure to be isolated. The concrete frame buildings with exterior walls constructed with a peel and stick air/vapour/water barrier membrane over gypsum and steel stud wall were the tightest and had a range of leakage 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 as they would be in practice and would be common to all measurements. The leakiest building at 21.8 cm^2/m^2 @50 Pa of exterior enclosure leakage included a fireplace and was a corner unit on the top floor, which had the highest enclosure surface area which may explain its difference from the other buildings.

The leakage rates for the six Vancouver buildings ranged from 1.40 to 12.1 $L/s/m^2$ at 50 Pa (2.5 to 21.8 cm^2/m^2 @50 Pa) whereas previous testing from Gulay et al. (1993) measured values from 2.10 to 3.15 $L/s/m^2$ (3.8 to 5.7 cm^2/m^2 @50 Pa) for ten buildings across Canada.

Leakage through interior walls and floors becomes more significant and cannot be ignored, especially as the exterior building enclosure is increasingly constructed more air-tight. The need for balanced mechanical systems is more important with these new tighter building enclosures, otherwise moisture problems may develop as a result of insufficient ventilation (natural or mechanical).

Corridor supply and suite exhaust mechanical systems may have worked in the past in multi-unit residential buildings when the building enclosures were leakier, however may not work with today's modern air-tight buildings. In addition, air leakage between suites and common spaces will increasingly become more important as the exterior enclosure increasingly becomes tighter. While the air-tightness of these interior partition walls/floors should be improved, it will not make up for insufficient mechanical ventilation. Preferably, fresh make-up air would be ducted and supplied to each suite and pressures balanced to eliminate inter suite leakage (as is done in many new buildings). For rehabilitation projects, the cost of such an option may be prohibitive and the existing mechanical systems may have to be upgraded to accommodate higher mechanical ventilation rates. This can include the use of continuous in-line fans with low noise (sone) level and possibly the use of heat recovery ventilators (HRVs) within each suite or floor to reduce energy costs.

While air-tight buildings are desirable for energy efficiency and thermal and occupant comfort, a higher level of performance is required from the mechanical and ventilation systems. Air-tight buildings put a higher demand on the mechanical ventilation systems to actually perform in service and deficient systems can have serious ramifications on building performance and occupant comfort. While consideration in design for the integration of all building components (structural, mechanical, building enclosure, etc) has been called upon by practitioners for years, and as we strive to achieve higher performance buildings it becomes an absolute necessity.

1.7 <u>ACKNOWLEDGEMENTS</u>

Performing such large scale testing requires the assistance of several people in the field and the use of specialized test equipment. I would like to thank first of all Colin Genge at Retrotec for his guidance and assistance with the testing and to Retrotec for providing all of the required test equipment for the week. Also to Hua Ge and Wendy Ye at BCIT, Matthew Mulleray, Shen Huang, and Chris Black at RDH Building Engineering, Mark Lawton and Anik Teasdale St-Hilaire at Morrison Hershfield for their assistance in the field with the setup, testing, and cleanup on site. In addition Brian Simpson at BC Housing (Building 3), Jim McKenzie at Building 2, Ed Starkins, Patrick Snowolf, and Don Driedger at Building 4 for providing access to the suites, and to all of the building tenants for their understanding during the testing.

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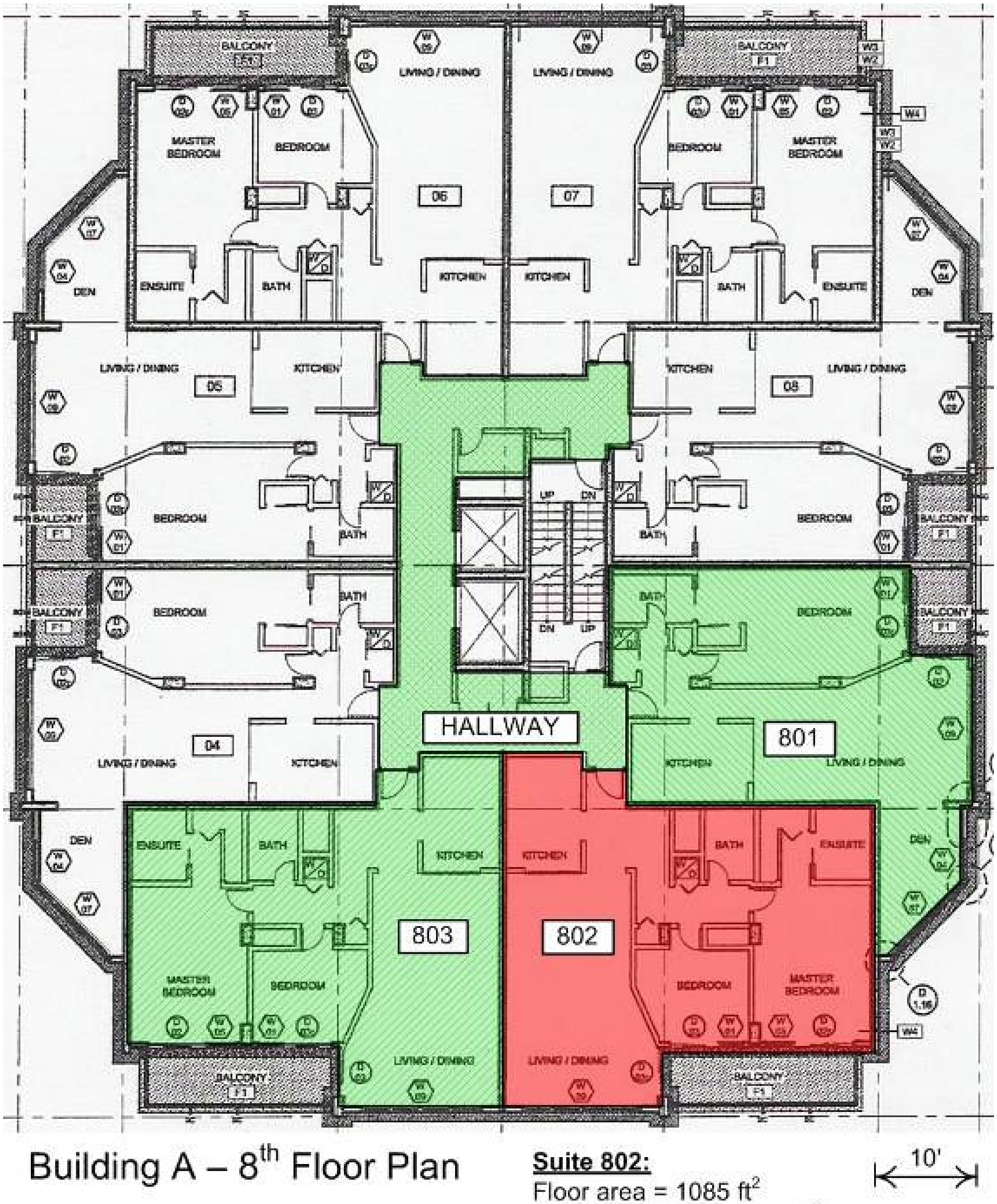
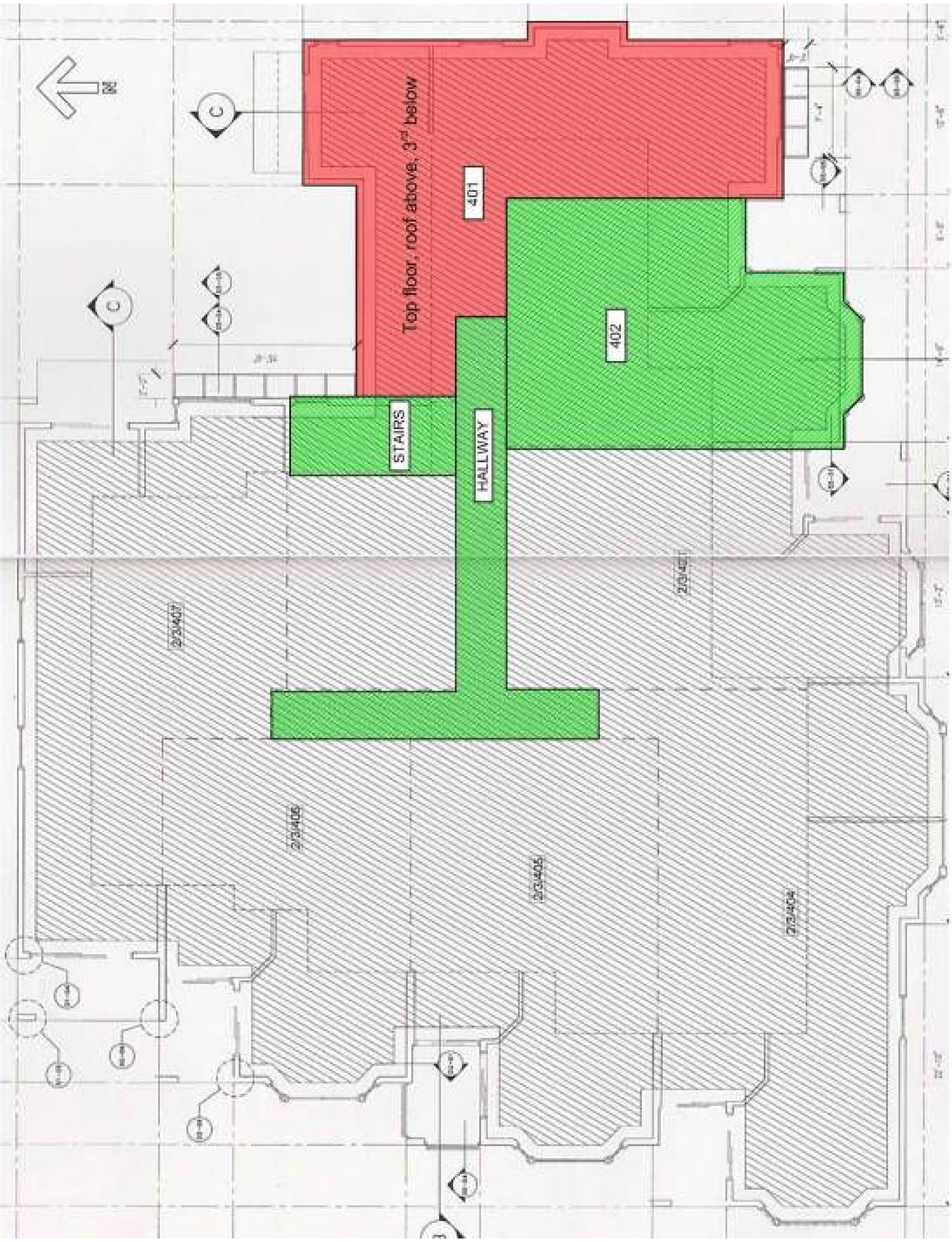
1.9 BUILDING PLANS

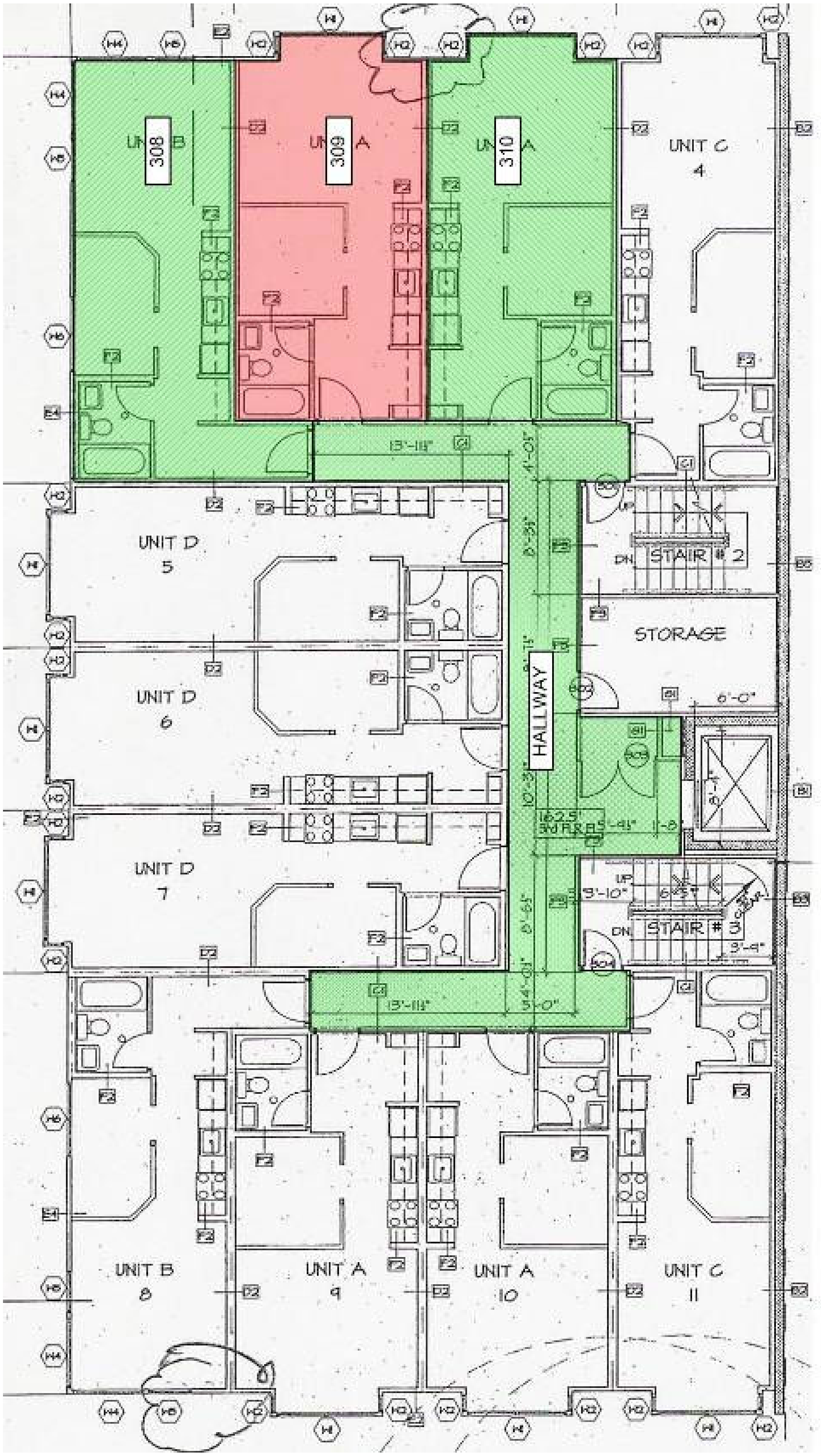


Building A – 8th Floor Plan

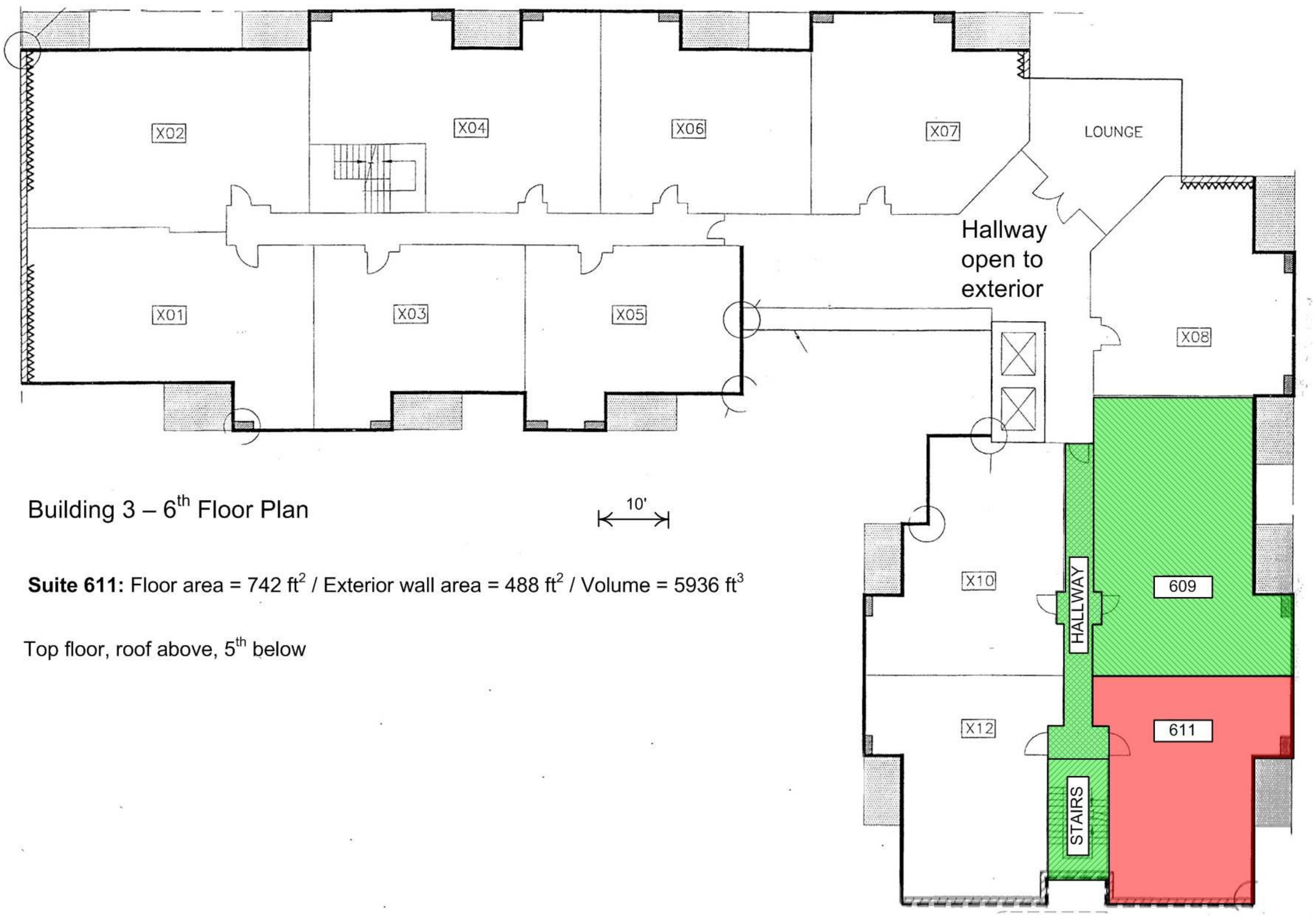
Suite 802:
Floor area = 1085 ft^2
Exterior wall area = 450 ft^2
Volume = 8680 ft^3



Building 2 – 4th Floor Plan   **Suite 401**: Floor area = 684 ft^2 / Exterior wall area = 720 ft^2 / Volume = 5472 ft^3



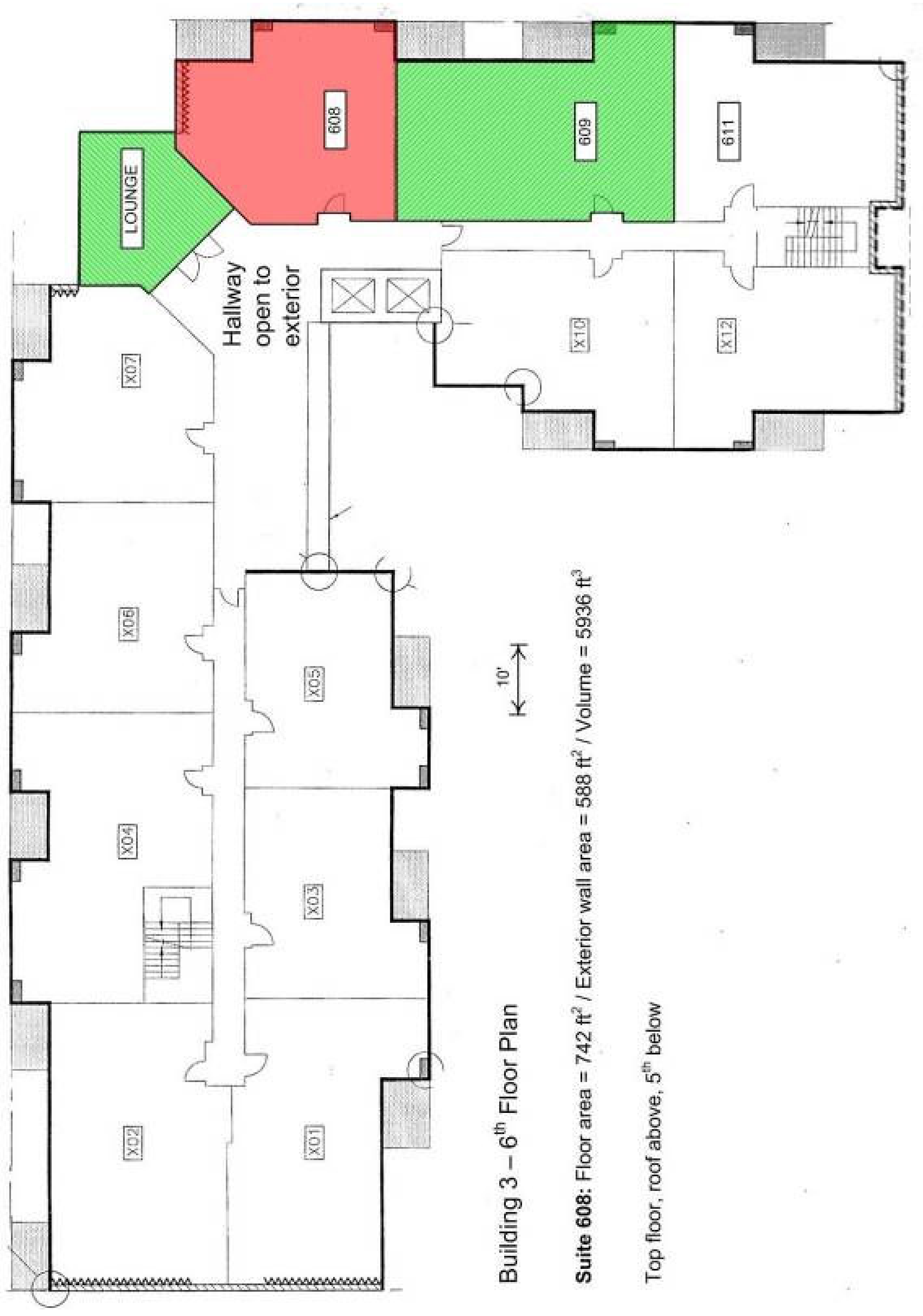
Building 4 – 3rd Floor Plan **Suite 301:** Floor area = 378 ft^2 / Exterior wall area = 136 ft^2 / Volume = 3024 ft^3



Building 3 – 6th Floor Plan

Suite 611: Floor area = 742 ft^2 / Exterior wall area = 488 ft^2 / Volume = 5936 ft^3

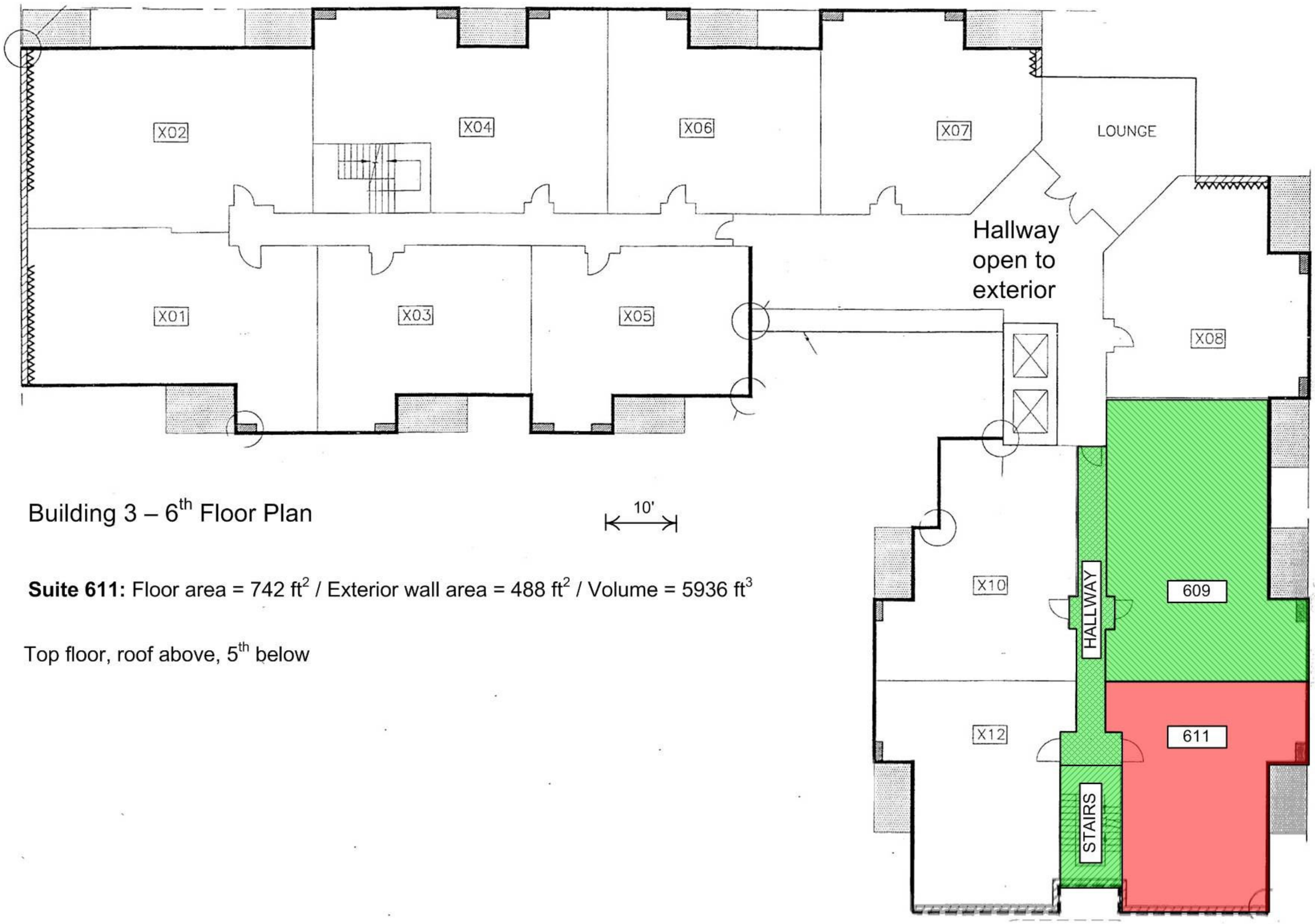
Top floor, roof above, 5th below



Building 3 – 6th Floor Plan

Suite 608: Floor area = 742 ft^2 / Exterior wall area = 588 ft^2 / Volume = 5936 ft^3

Top floor, roof above, 5th below



Building 3 – 6th Floor Plan

Suite 611: Floor area = 742 ft^2 / Exterior wall area = 488 ft^2 / Volume = 5936 ft^3

Top floor, roof above, 5th below