THE EFFECT OF ENCLOSURE RETROFIT ON AIR LEAKAGE RATES FOR A MULTI-UNIT RESIDENTIAL BUILDING: SINGLE CASE STUDY

by

ROBIN URQUHART

BA HONOURS, QUEEN'S UNIVERSITY, 2005

MA, UNIVERSITY OF NORTHERN BRITISH COLUMBIA, 2009

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Abstract

The Effect of an Enclosure Retrofit on a Multi-Unit Residential Building: Case Study
Robin Urquhart
Master of Building Science (MBSc.), 2013
Ryerson University, Department of Architectural Science

This case study examines the effect of an enclosure retrofit on a high-rise, multi-unit residential building (MURB). Literature on fan pressurization test methodologies and MURB air leakage rates is reviewed. The enclosure for the case study building was tested using the guarded-zone fan pressurization method. Results of the air leakage testing show significant improvement in the enclosure tightness and compare well to measured data for other MURBs across North America. There is recognition of a need to standardize both testing methods and presentation of data for air leakage in MURBs. The issue of abnormal flow exponent values is discussed and recommendations for future research are made.

Acknowledgments

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1 Introduction

A recent report produced by the University of British Columbia highlights the need for energy retrofits to current building stock in Vancouver in order to meet energy demand and greenhouse gas reduction targets by 2030 (ISIS Research Centre, 2011). A large proportion of that building stock is mid and high-rise (5 to 33 story) multi-unit residential buildings (MURBs) (CMHC, 2013). Many of these MURBs are currently undergoing or will be undergoing exterior retrofits due to a variety of issues. Most retrofits focus on energy saving measures such as improving insulation values and increasing air tightness of the building enclosure (Finch, 2007; CMHC, 2013).

Studies tend to focus on the energy savings of retrofits, and to omit data on air leakage improvements. However, air leakage has an effect on many aspects of a building, principally; energy efficiency, indoor air quality, HVAC efficiency and enclosure durability (CMHC, 2001). It is important to understand how air leakage rates are influenced by enclosure retrofits as this will directly affect other important health, safety and financial aspects of the built environment.

There is currently no industry standard for air leakage testing MURBs (Finch, 2009). The complexity of multiple zones makes traditional, single-zone depressurization methods inadequate. Studies have proposed a variety of techniques for testing large, multi-unit buildings, some of which are discussed in this paper. Additionally, air leakage rates are measured in many different ways making direct comparisons between different buildings difficult (Sherman and Palmiter, 1995).

It is important to understand how enclosure retrofits affect air leakage rates in MURBs and also to be able to directly compare values between buildings. This paper presents a relatively new, simple and robust, method for air leakage testing. A thirteen-story MURB was tested before and after an enclosure retrofit. Data is presented in a variety of units to ensure comparability between other studies. The Normalized Leakage Area metric (NLA) was selected with which to present data (see Section 5.4.2). The effect of the retrofit on air leakage rates will be assessed and compared to other MURBs across Canada and the U.S.

The results will be described in four unit forms (refer to Section 5.4 for more information on metric types):

1. ELA_{50}, Equivalent Leakage Area (cm^2 @50Pa) - relates overall enclosure leakage to the cross-sectional area of an equivalent tubular hole.
2. NLA_{50}, Normalized Leakage Area (cm^2/m^2 @50Pa) – relates ELA to the area across which the pressure difference occurs (i.e., enclosure area).
3. Q_{norm50}, Normalized flow rate (L/s-m^2 @50Pa) – relates the flow rate (L/s) to the area across which the pressure difference occurs (i.e., enclosure area).
4. ACH_{50}, Air Changes per Hour (@50Pa) – the rate per hour at which the volume of the test space will have been displaced by new air.

There are many standards and targets for air leakage in high-rise and commercial buildings. The Table below shows examples of the more common target levels for various standards in Canada. The values are listed in normalized air leakage at 50Pa (NLA_{50}) (Finch, 2009).

Table 1 – MURB air leakage targets (Finch, 2009)[1]

Standard	**Requirement**	**NLA_{50} equivalent**
LEED v2.2 for New Construction	1.25 in^2 EfLA @4Pa/100ft^2	2.1 cm^2/m^2 @ 50Pa
ASHRAE – tight exterior enclosure	0.1 $ft^3/min/ft^2$ @75Pa	0.7 cm^2/m^2 @ 50 Pa
ASHRAE – average exterior enclosure	0.3 $ft^3/min/ft^2$ @75Pa	2.1 cm^2/m^2 @ 50 Pa
ASHRAE – leaky exterior enclosure	0.6 $ft^3/min/ft^2$ @75Pa	4.3 cm^2/m^2 @ 50 Pa
International Energy Conservation Code (IEEC)	0.4 $ft^3/min/ft^2$ @75Pa	2.9 cm^2/m^2 @ 50 Pa
National Building Code of Canada (2005)	0.15 $L/s/m^2$	0.23 cm^2/m^2 @ 50 Pa
Air Tightness Testing and Measurement Association (ATTMA 2007)	3.0 $m^3/hr/m^2$	1.5 cm^2/m^2 @ 50 Pa

[1] Conversions between metrics were accomplished using the power law equation (refer to Equation 1) and an assumed flow exponent value of 0.65. A typical apartment with a floor area of 112 m^2 and height of 2.44 m was also used for purposes of comparison (Finch, 2009).

2 Objectives

This study will assess the effectiveness of an enclosure retrofit on air leakage for a thirteen-storey MURB in Vancouver, Canada.

The study is designed to answer the following research questions:

1. What is the effect on air infiltration and exfiltration rates of an enclosure retrofit for a MURB?
2. How does this effect compare to extant data for infiltration and exfiltration rates for other MURBs in North America?

Specific research objectives are listed below:

1. Establish appropriate air leakage test methodology and presentation metric
2. Measure uncontrolled air flow (infiltration/exfiltration) rates through the enclosure pre- and post-retrofit.
3. Compare and analyse the pre- and post-retrofit air leakage testing results
4. Examine potential influence of enclosure retrofit on air leakage results
5. Analyze flow exponent values for potential effect on data
6. Compare air leakage differences to existing data for enclosure air leakage of MURBS in North America

3 Literature Review

The literature review is divided into two sections: (1) fan (de)pressurisation methods and (2) MURB leakage rates. It is also important to review the literature on fan pressurisation methods in order to justify the methodological approach during field testing. There are many methods available and the most appropriate for the given case study and context was selected. There is a lack of literature for air leakage rates of high-rise, multi-unit buildings. The available literature was reviewed to give preliminary indication of air leakage rates through the enclosure of MURBs and to justify adding more to the limited data set.

3.1 Fan (de)pressurization methods for multi-unit buildings

All buildings allow air to move through the enclosure to some degree. A ventilation system moves air in a controlled manner. Air that moves in an uncontrolled manner is known as infiltration/exfiltration or leakage. The majority of leakage through a building enclosure is pressure driven by wind, stack effect and differences in relative humidity (Hutcheon & Handegord, 1995; Younes et al. 2011). Due to the variability of conditions, it can be difficult to measure the rate of air movement in the natural setting of a building (Michalski 1994).

One of the most common methods for testing enclosure leakage is through fan pressurization or depressurization (Jeong et al. 2008). Fan depressurisation relies on creating an artificial pressure difference between the interior and exterior environments of a building enclosure through the use of fans. Fans are beneficial in that they accurately measure the flow across a controlled pressure difference. Creating this pressure difference, however, may induce elements of the building enclosure to change.

For example, seals may tighten or passive exhaust vents may open, depending on the pressure difference. The test is relatively simple for a small, single-zone building and becomes more difficult as building size increases (Finch et al. 2009). The size and nature of mid-rise to high-rise MURBs requires fan sizes in excess of conventionally produced models in order to (de)pressurize the entire building. Additionally, it is important to be able to separate leakage between suites from leakage through the enclosure to get an accurate enclosure tightness value. There are currently no universally accepted methods for air tightness testing multi-unit buildings (Walthier & Rosenthal, 2009; Younes et al., 2011) making standardization and comparison difficult.

The American Society for Testing and Materials has outlined a method for testing building enclosure tightness of single unit, low-rise buildings (ASTM 779-10, ASTM 1827-12). The method cannot account for stack effect, temperature differentials and requires the test be conducted under specific circumstances. The method uses a single fan and requires all interior spaces to be interconnected. The building is pressurised and depressurised in 5-10Pa increments between 10Pa and 60Pa. Air flow rates are recorded for every pressure difference (a minimum of 5 data points are required) and analysed. The method is accurate for small, single-zone buildings, but due to fan power and construction limitations, is not directly applicable to larger, multi-unit buildings. As yet, ASTM has not set a standard for high-rise or multi-unit buildings (ASTM 1827-12).

The US Army Corps has developed a fan depressurisation method by which to test its barrack buildings and ensure its mandated air leakage rates (USACE, 2012). The method is relatively simple and somewhat similar to the ASTM 779 standard. Units that are self-contained (i.e., openings only to the exterior) must be tested individually and simultaneously using multiple fans. Units that have openings to a common space (i.e., a corridor) must be tested collectively using one fan. All units, except the test unit are brought to exterior pressure by opening doors and windows to the exterior. The test unit is then (de)pressurised to 75Pa and air leakage rates recorded.

There are two major problems with the Army Corps test method. First, large buildings with many self-contained units require many fans to run simultaneously. This can present significant logistical difficulties and be prohibitively expensive (Genge 2009). The second problem involves the scenario of testing a single unit. The method of testing cannot separate internal air leakage from enclosure leakage. As Genge (2009) notes, the Army Corps method is a good starting point, but further development of the method to ensure more reliable and complete results would involve neutralising pressure between adjacent suites and the test suite to ensure that the only leakage pathway is through the enclosure.

The German “Fachverband Luftdichtheit im Bauwesen e.V.” (Association for Air Tightness in the Building Industry) has proposed a similar method to the US Army Corps for testing a multi-unit building enclosure (Erhorn-Kluttig et al., 2009). They advocate fan (de)pressurisation testing of 20% of individual units in a multi-unit building, including at least one apartment on the top floor, one on the ground floor and one at the building’s mid-height. The air leakage values include air movement between floors as well as air leakage through the enclosure. The data extrapolation takes the internal leakage pathways into account by allowing an individual unit’s air leakage rate to exceed the minimum whole-building leakage rate by 30%. If any unit exceeds the 30% threshold the building does not pass the test. The significant disadvantage of this test method is that there is little allowance for considerable leakage in untested zones, such as elevators, corridors and ventilation systems (Walthier & Rosenthal, 2009).

Proskiw and Parekh (2001) propose a method for separating leakage between internal partitions from leakage through the building enclosure by installing the door fan between the zones. Zone A is of primary interest and Zone B is of secondary interest. The fan is used to pressurise Zone B and the air flow rate recorded. Zone B is then equalised with ambient outdoor pressure by opening a window or door. The pressure across the fan is maintained at the pressure of the original measurement. The new air flow rate is recorded. The difference in air flow rates shows the amount of leakage between Zone B and Zone A. The method is mathematically quite simple and yields robust data. However, it is a one-dimensional method and does not take into account leakage pathways from other units adjacent to (above, below and sides) the test unit.

Modera et al. (1989) developed a ‘guarded-zone’ method, whereby the test unit is guarded from pressure differential between adjacent spaces, leaving the only pressure differential across the envelope. The method requires six blower door fans to equalize pressures throughout the building and create a pressure in the test unit. Once the enclosure leakage is recorded, the adjacent spaces can be pressure equalized with the ambient outdoor pressure and the increase in airflow shows the air leakage to those areas. The method determines the permeability coefficient of the enclosure directly. As Feustel (1990) notes, the method relies on keeping the adjacent zones at exactly the same pressure as the guarded zone, which can be difficult. The other limitation is that the method provides only two values; air leakage through internal partitions and air leakage through the enclosure. It does not give an idea as to where air leakage problem areas exist.

The deduction method was sought as an alternative to the logistical difficulties of the guarded-zone method (Feustel 1990). There are different incarnations of the deduction method, but the most recent and applicable comes from Finch et al. (2009). The method relies on up to four, high-powered, door fans. The premise of the method is similar to the guarded-zone method in that pressure is neutralized between adjacent spaces and the test unit. The test unit is first measured with adjacent spaces at ambient temperature. One by one the adjacent spaces are brought to the same pressure as the test unit, thereby eliminating leakage between the unit and that space. By eliminating all spaces one by one, the tester can determine leakage values through internal partitions and the building enclosure. The major benefit of this method is in separating the leakage through internal partitions from the leakage through the building enclosure. Another benefit is the ability to test a large scale, multi-unit building with a maximum of four door fans.

In terms of testing only the building enclosure, the guarded zone method and deduction method differ very little if at all. Both rely on the neutralisation of pressure between the test unit and adjacent units. This ensures that air leakage is occurring only through the exterior wall area, as that is only area across which a pressure difference exists.

Feustel (1990) argues that the enclosure air leakage data from the guarded-zone method is not as robust as data from the deduction method. He uses a variety of field studies to compare the accuracy of each method. It is surprising that there would be a difference in results as the methods, as far as enclosure leakage is concerned, rely on the same principle: the neutralisation of pressure across the test suite and adjacent areas. The reason given by Feustel (1990) for the relative inaccuracy of the guarded-zone method is the difficulty in keeping pressurised areas at constant pressures. Stack effect, wind and relative humidity differences may affect pressure differences. The technology for door fans has come a long way in the last two decades. The new technology allows for better and easier control of fans and the recording of multiple time averaged data points for a given pressure difference. Finch et al. (2009) argue that by recording multiple data point, which are then put through linear regression, and pressurizing each unit at varying intervals, the 'noise' of stack effect, wind and humidity can be negated. This study is only interested in the effect of the retrofit on enclosure leakage rates and as such internal leakage pathways will not be taken into account.

3.2 Air Leakage Rates for MURBs

Existing studies repeatedly mention the scarcity of measured data relating to leakage rates of MURBs (Diamond et al. 1996; Sherman and Dickerhoff, 1998; Sherman and Chan, 2004; Finch et al., 2009; Price, 2011). The vast majority of air leakage measurements have been conducted on houses (e.g. single family detached or semi-detached dwellings). Price et al. (2011), in their study of North American buildings, stated, "as for apartment data, we were (unpleasantly) surprised at the paucity of information in this area." They were able to find information for only 20 buildings since the completed by Diamond et al (1996).

Gulay et al. (1993) published one of the first comprehensive MURB air leakage studies in Canada. The study found that air leakage rates (normalized to enclosure wall area) were between 2.10 and 3.15 L/s-m^2 at 50Pa. The study used a neutralized, guarded-zone method to account for interior partition leakage. When the suites were tested without pressure neutralisation across suites, the leakage rates more than doubled.

Proskiw and Phillips (2001) collected data from literature related to air leakage rates for twenty-three, multi-unit residential buildings in Canada. The data was analysed according to building type; namely, reinforced concrete, brick, wood and steel. Reinforced concrete had the lowest leakage rate, while brick was approximately four times leakier. The average leakage rate was determined to be 3.2 L/s-m^2 @75Pa. It should be noted that due to the low numbers of buildings examined in each category (e.g. in the case of concrete only 2 buildings were examined) the results showed an indication of potential leakage rates and did not set a benchmark.

Proskiw and Phillips (2001) also noted three buildings in the data set that received envelope retrofits. Air leakage data collected pre and post-retrofit indicate an average air tightness increase of 15%, ranging from 7% to 24%. Proskiw and Phillips stated that the sample size is too low to indicate a benchmark, and more data is needed, but that it provides an early indication of potential increases in airtightness due to envelope retrofits.

Price et al. (2006) noted air leakage from a variety of techniques and conditions. Air change rate (ACH) is often used under ambient conditions to indicate the leakage rate of a given volume. The data showed a range of leakage rates from 0.5 to 2 ACH_{NAT}. Due to the fact that ACH_{NAT} measurement relies on specific, but often unstated volume of the test space, comparisons between buildings are tenuous if not impossible. Fan pressurization measurements were also found in the data set and showed a geometric mean leakage rate of 4.8L/s-m^2 @50Pa. ACH_{NAT} is dependent on characteristics such as buoyancy and wind direction and speed, meaning that direct comparisons to leakage parameters (i.e., L/s@50Pa) are impossible. From the data available, Price et al. (2006) found little systematic variation between building leakage and construction type, location, function, height or size.

A CMHC (2006) report focused on air leakage control in MURBS and detailed two case studies of MURBS that received air leakage control retrofits. Air leakage values were not measured specifically; however, analysis of energy usage shows that improvement of enclosure tightness accounted for a 12% and 6.5% improvement in energy savings respectively. It is very difficult to draw a correlation between energy improvement savings and air leakage rates. It is recommended that studies examining the effect of enclosure upgrades on energy efficiency also include data on leakage rates.

Canadian House and Mortgage Corporation commissioned a report focusing on air leakage control in multi-unit residential buildings (CMHC 2013). The report examines 40 MURBS across Canada (91%) and the U.S. (9%), ranging in age, construction type, height and location.

The study found the mean air tightness to be 3.66 L/s-m^2 @75P.a Particular trends were also noted in the data. Air tightness was correlated to the age of the building; the newer the building the tighter it was. Similarly, the age of the air barrier correlated to building tightness, including retrofits that may have been done to the air barrier. A very slight trend was noted suggesting that building height positively correlates to air tightness; suggesting a bias to leakier roofs and ground floors and/or proficiency in repetitive construction.

A section of the report detailed the effectiveness of airtightness retrofits on six MURBs in Canada. The pre-retrofit measurements showed an average air leakage of 4.99 L/s-m^2 @75Pa. Post-retrofit measurements showed an improvement of 31% to 3.20 L/s-m^2 @75Pa. It can also be noted from the data that the leakier buildings showed the greatest improvement, which may be an indication to help direct retrofit decision/planning in the future (i.e. direct cash and resources to the 'lowest hanging fruit').

It is apparent that a deficiency in the literature exists generally regarding air leakage rates in MURBs and especially in air leakage improvements due to retrofits. The data that exists is difficult to compare as there is no current standardization of measurement or reporting practices for commercial buildings. A standard should be established to ensure comparison amongst data sets and to ensure accurate and robust data during testing. In the absence of a standard, it is recommended that measurements are provided in a variety of units and/or that all relevant data is included in the published reports (ie. wind direction and speed, geometry, volume, flow exponent, etc.).

4 The Case Study Building

4.1 Description of the building

The case study building is a 13-story, multi-unit residential building located in Vancouver, BC. The building was constructed in 1985/86 as a residence for senior citizens (RDH "Case Study 4, The case study building", 2012). The building is comprised of four distinct floor types.

1. Ground floor – Uniquely includes the floor area into total enclosure area. The floor plan is similar to the Thirteenth floor in terms of suite size and placement (refer to Figure 1)
2. Floors two to eight – Identical floor plans for all suites on these floors (refer to Figure 2).
3. Floors nine to twelve – Uniquely feature gas fireplaces with 6" diameter flue. The floor plan is identical to floors two to eight (refer to Figure 2).
4. Floor thirteen – Uniquely features skylights and operable balcony doors. The floor plan is similar to the First floor in terms of suite size and placement (refer to Figure 3).

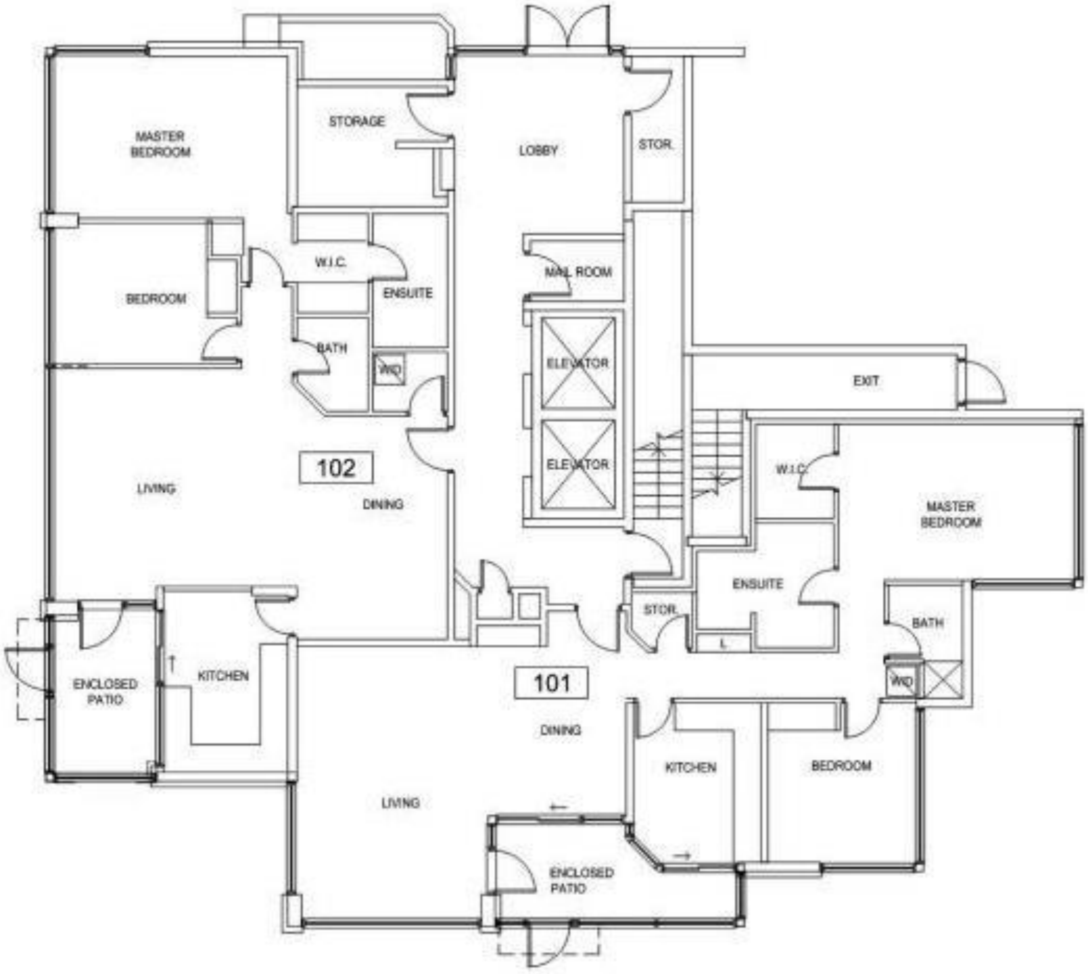

Figure 1 – Ground floor layout (RDH 2011)

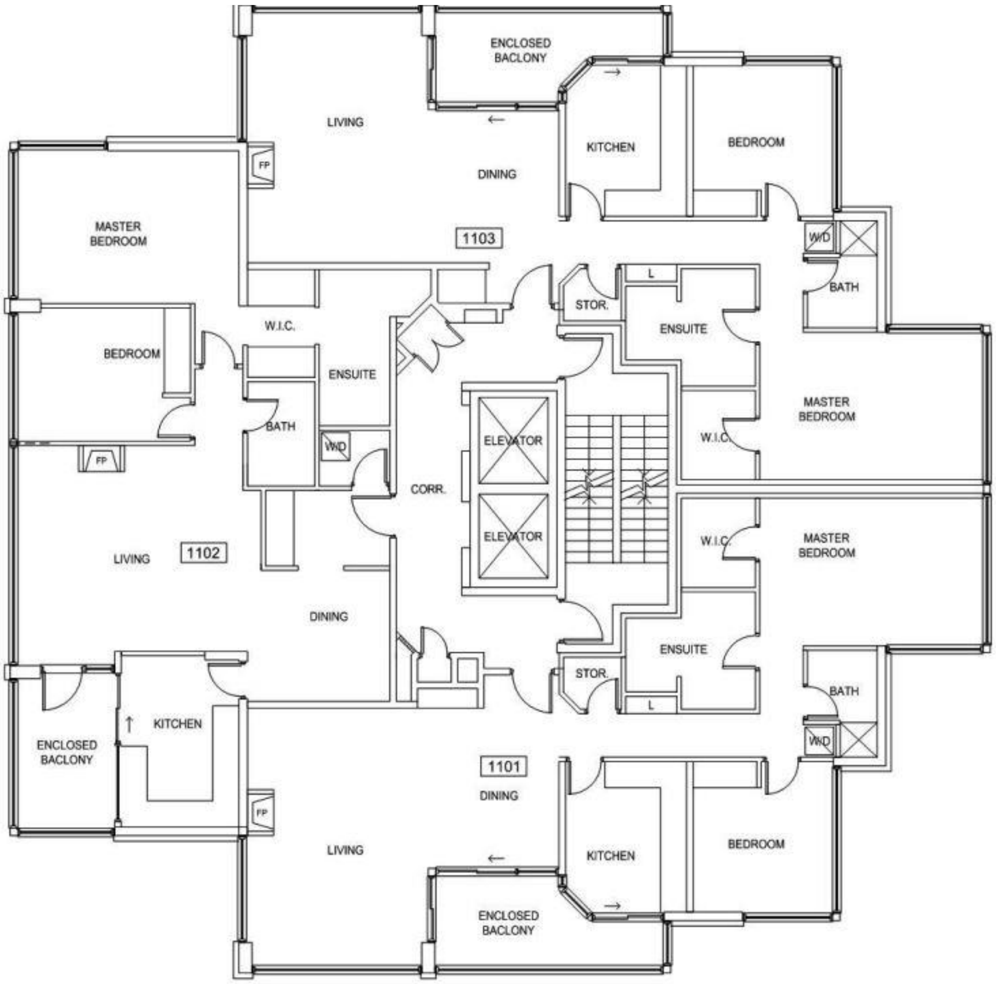

Figure 2 – Floor 2 – 12 layout (RDH 2011)

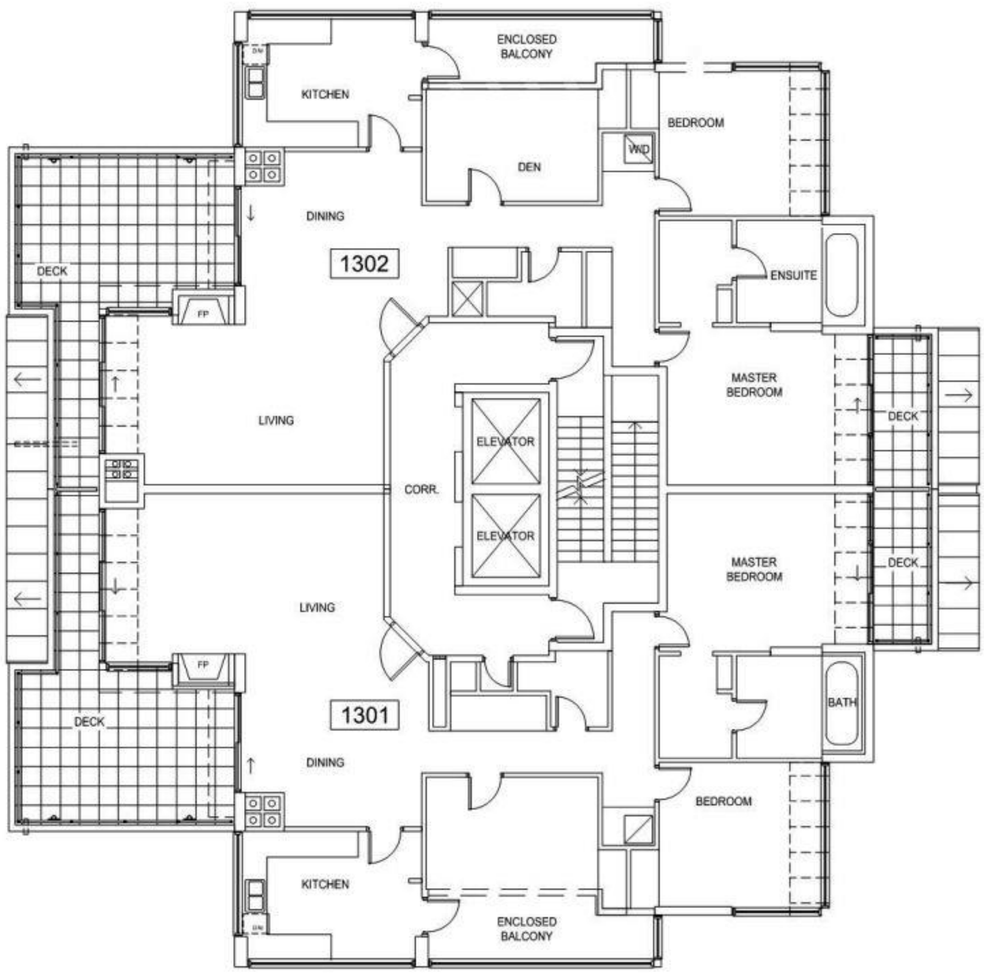

Figure 3 – Floor 13 layout (RDH 2011)

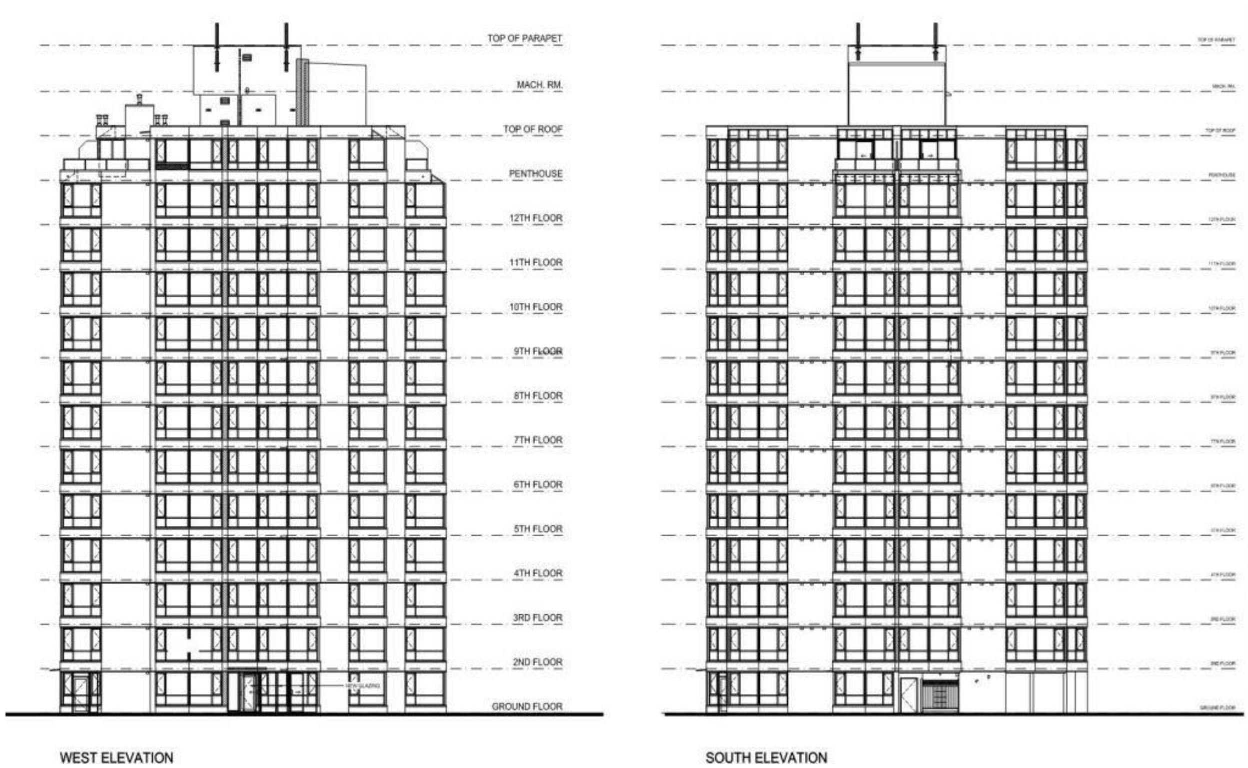

Figure 4 – Elevation view of case study building (RDH 2011)

4.2 Performance Issues

There were a number of issues prior to the retrofit that suggested failure to some degree of the building enclosure. These issues are enumerated in a report by RDH (2010). Highlights are included below:

- 50% of residents reported condensation on windows and leaking windows
- 39% of residents reported failure of the glazed units
- Cracked or deteriorating sealant around window frames (see Figure 1)
- Other issues include; mould, drafts, difficult window operation and fan inadequacy

Figure 5 – Sealant deterioration around window frame (RDH, 2010)

The building received a large-scale enclosure retrofit that was finished in the winter of 2013 (refer to Section 4.4). Pre- and post-retrofit testing of enclosure air leakage was conducted using a guarded-zone fan depressurisation method as outlined by Finch et al. (2009) in order to assess the effectiveness of the retrofit in controlling air leakage through the enclosure.

4.3 Pre-retrofit Building Condition

The case study building wall typology is cast-in-place, exposed concrete. The interior walls are constructed using 2 ½" steel studs and XPS placed in the stud cavities. Figure 2 shows a cutaway of typical wall construction.

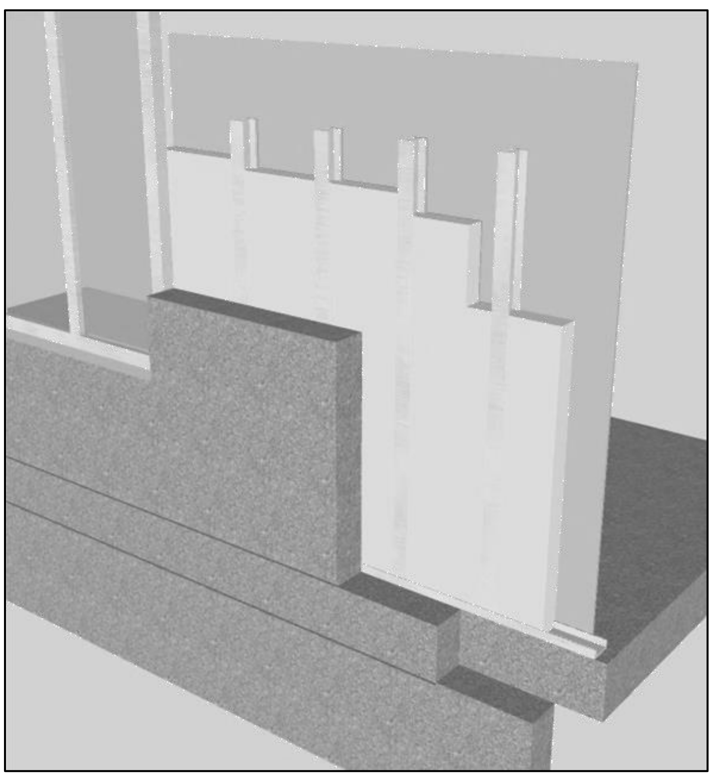

Figure 6 – Typical wall construction - The case study building

The floor slabs are all post-tensioned; a common construction practice to increase slab strength and span (Kang and Wallace, 2006). The original design for open balconies was modified to protect the tensioning cables in the slab. The balconies are enclosed with glass after initial construction. The roof construction is an inverted membrane roof assembly (IRMA). The slope of the roof was achieved via the concrete topping and ballasted with gravel. The windows in the case study building are double-glazed units with a non-thermally broken aluminum frame. The windows open via sliding mechanisms.

Ventilation to individual suites is achieved through a pressurized corridor air supply. An air handling unit (AHU) on the roof draws exterior air into the building and forces it down through a vertical ventilation shaft. Vents passively supply air to each floor from the main air shaft. Door undercuts allow air to reach individual suites from the corridor. Point source contamination is managed by exhaust fans in the kitchen and bathroom of each suite. Windows were made operable to allow for supplemental ventilation (RDH "Case Study 4", 2012).

4.4 Retrofit measures

The retrofit focused on improving energy efficiency, occupant comfort and air tightness (RDH "Case Study 4", 2012). For the purposes of this report, only retrofit measures that pertain directly to enclosure air tightness will be detailed. The air tightness portion of the retrofit focused predominantly on the glazing system. The enclosed balconies and windows were noted to be especially drafty. Cracked sealant, condensation, frost and other issues suggested failure of the IGUs.

To combat the observed problems related to air tightness of the enclosure, the retrofit took the measures included below (RDH “Drawings for tender and permits“, 2011). It must be noted that the measures were consistent across all suites.

The retrofit measures taken include:

- Installed liquid applied flashing at all cold joints and cracks
- Ensured cold joints (where new concrete cures on already cured concrete) were revealed
- Removed all windows and cleaned framed openings
- Installed liquid membrane at window sill, head and jambs
- Installed all new windows (see figure 3) with operable vents, as opposed to sliders
- Replaced and sealed enclosure penetrations, including;
    - in-slab exhaust vents
    - under-slab exhaust vents
    - roof plumbing vent

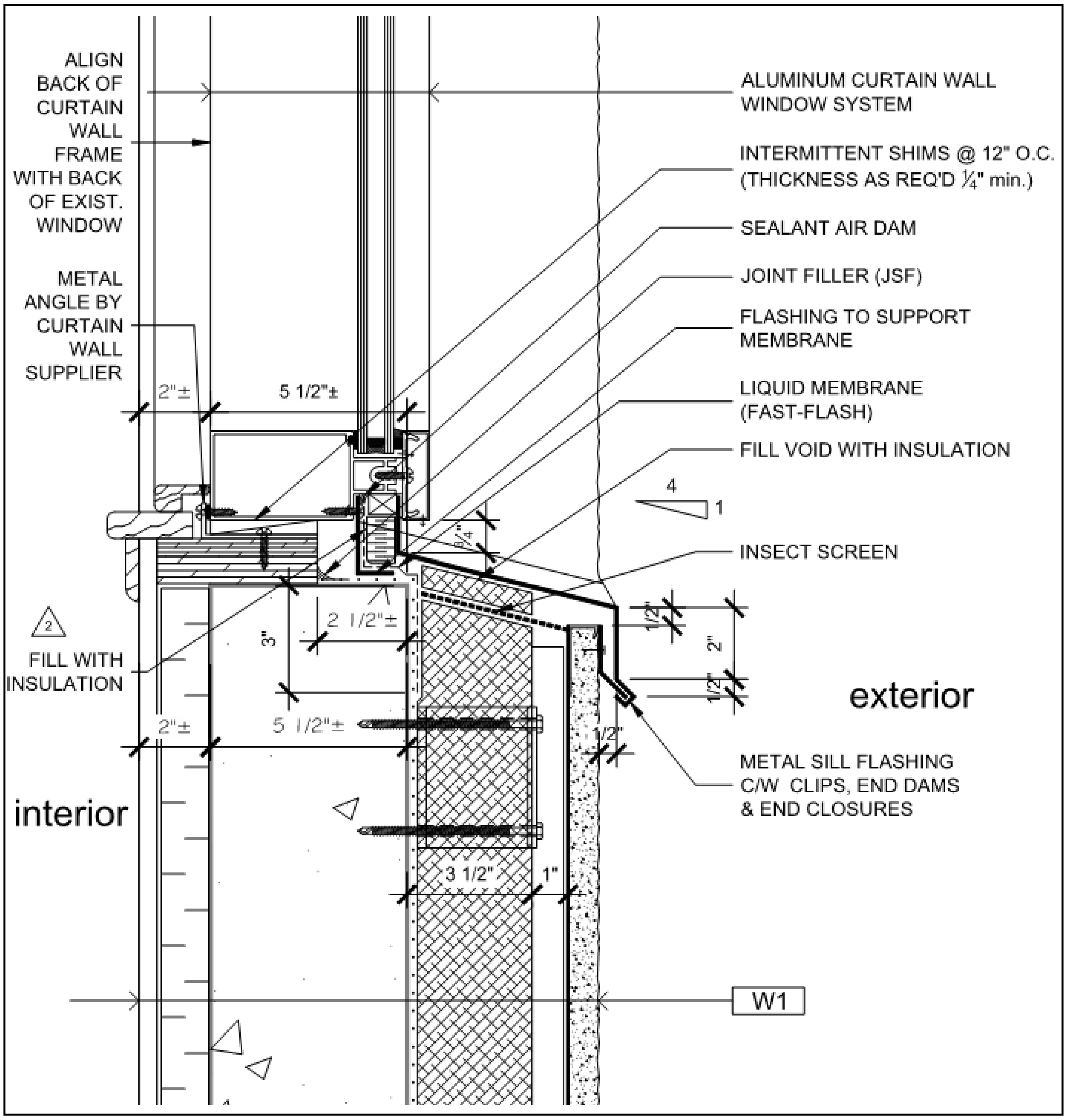

Figure 7 – Detail for window installation (RDH, 2011)

5 Methodology

5.1 Test procedure

Testing was performed using four high-powered, Retrotec Model 3200 – 8500 cfm, blower door fans (Retrotec, 2012). The fans were controlled automatically from a central location using fan control gauges (Retrotec Model DM-2A). The test suite and adjacent suites were pressurized and depressurized with respect to the exterior at varying levels (20, 30, 50, 60Pa).

The pressure intervals were determined by examining literature on fan depressurization methods. Finch et al. (2009) and ASHRAE (2005), note that higher pressure levels, (i.e. 50Pa and greater), are effective in removing environmental noise – the effects of stack, wind and temperature difference. Suites and adjacent areas were pressurized and depressurized to further negate the effects of the HVAC system, stack and wind in the enclosure assembly.

Enclosure openings that would be passively controlled or open during normal building operation were untouched in the testing phase. For example, range hood exhaust fans were turned off, but the passive exhaust vent was not sealed. This procedure was consistent across pre-retrofit and post-retrofit testing and across all suites. Any differences in air leakage rates can be attributed only to retrofit detailing measures.

The test setup below generally describes a pressurization cycle for one test suite. The same procedure was conducted using negative pressures to obtain depressurization data. Each suite was tested for both cycles. The procedure is laid out step by step in

Appendix A and a summary included below. A schematic of the pressure tubes is provided in Appendix B.

The tester must first install fans and pressure sensor tubes. Install a pressure sensor tube across the building envelope as a baseline tube. Next, install door fans between the test suite and corridor and between the corridor and outdoor equalized space (such as the stairwell that is opened to the outdoors). Ensure all doors to adjacent suites on the test floor are open. Install door fans between corridor and outdoor equalized space on the above and below floor. Ensure all doors on the floors above and below the test suite are open. Ensure all controllable openings are closed and all other fans (such as bathroom fans and range exhaust hood fans) are off. Seal the corridor air supply grate on each floor. Ensure that pressure reference tubes are in the correct locations (see Appendix B)

The second step is to pressurize the test suite and adjacent suites. Set fans to pressurize all spaces to 20Pa. Set software to record multiple data points over a ten-second time period. Calculate the R-squared value for the data points over the time period. If the R-squared value is less than 0.95 (Straube and Burnett, 2005), it is necessary to repeat the test. Repeat this process for all pressure intervals (30, 50 and 60Pa).

Winds were calm on all but one day of testing. It was more difficult on the day of high wind velocities (gusting to 15 km/h) to keep the test and adjacent spaces at the required pressure intervals. Tests were repeated, in a few cases up to 5 times, due to unacceptably low R-squared values. The data obtained conformed to previously mentioned test thresholds and, except for the delay and repetition, the data is considered to be as robust as data from any other day. It can be noted, however, that high wind velocities make testing with this method difficult, which is why it is important to test for R-squared and flow exponent values constantly throughout the testing phase.

Figure 4 shows an elevation and plan view of fan placement for the testing phase. It also shows the pressurized areas; including and adjacent to the test suite. The example is at 50Pa, however all pressure intervals would be tested. The large arrows indicate flow through door fans. The small arrows indicate measured air flow through the enclosure.

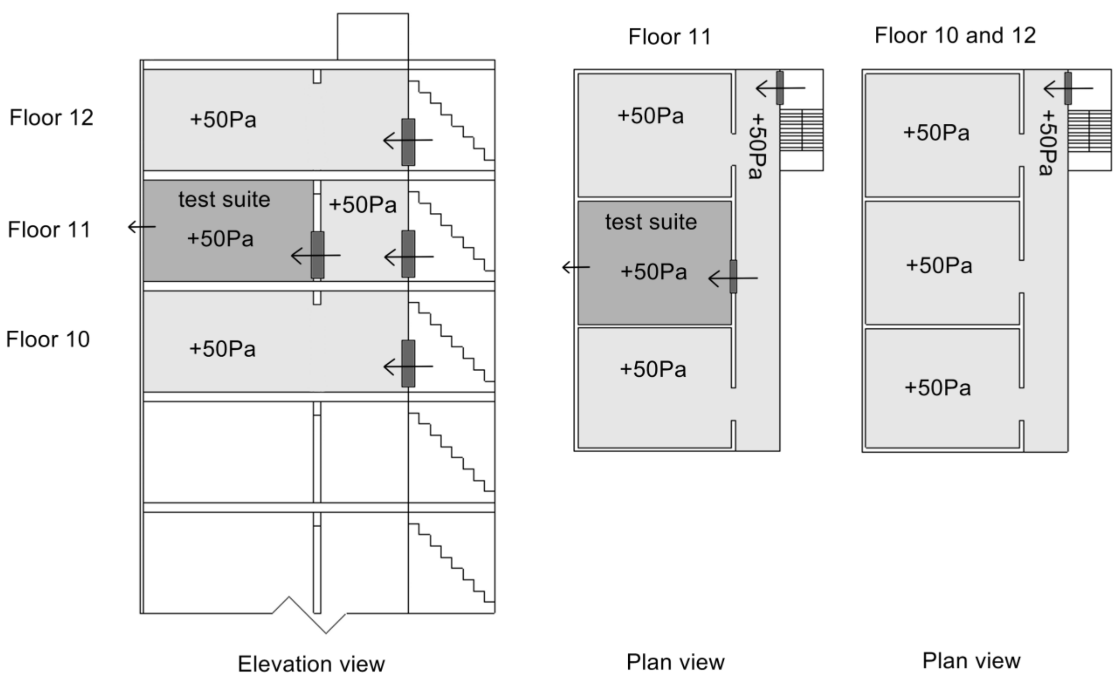

Figure 8 – Guarded-zone method example

5.2 Sampling

In the case of the case study building, all suites were tested on the geometrically unique first and thirteenth floors, as well as all suites on the geometrically similar third and eleventh floors. The total suites tested represent 27% of the suites in the whole building and 18% of the suites in the geometrically similar floors two to twelve. It is difficult to justify sample size in guarded-zone multi-unit air leakage testing. For such a small population number (suites in a building), it is statistically difficult to justify anything less than the total number. It would have been best to test each suite on every floor; however, expense, building schedule, suite geometry and location and environmental conditions all constrain potential sample size. A balance must be struck between what can the ideal test schedule would be and what can feasibly be done. It is an optimization process and will be different for every building. It is recommended that sample size be maximized, within the constraining circumstances, to ensure the most accurate data possible. Any assumptions used to determine sample size should be listed.

Certain assumptions were made to determine sample size for the case study building. First, that the suites on the same floor type are uniform (refer to Section 4.1). Second, testing suites on each floor type would provide representation as to how the leakage rates would compare for other untested suites on the same floor types. Third, that retrofit detailing quality was consistent throughout the building. As a result, the following suites were selected (for floor plans refer to Figures 1-3):

- *Suites 101, 102 (1st Floor)* - as they uniquely incorporate the floor into their enclosure area.
- *Suites 301, 302, 303 (3rd Floor)* - as a representative sample of floors two to eight
- *Suites 1101, 1102, 1103 (11th Floor)* - as a representative sample of floors nine to twelve
- *Suites 1301, 1302 (13th Floor)* - as they uniquely incorporate the roof into their enclosure area and feature penetrations not found in other suites.

5.3 Data Analysis

There are three phases of data analysis:

1) Calculate flow and pressure coefficients
2) Calculate air leakage rates for individual suites and whole building
3) Compare to air leakage rates of other MURBs

5.3.1 Flow and pressure coefficients

The data analysis procedure assumes that uncontrolled air leakage is through passages formed by cracks and joints in the building envelope. It is reasonable to assume, given the nature and scale of the enclosure retrofit, that there are no large openings and that leakage through porous materials is minimal. It is possible to apply known pressures and measured flow rates for the aggregate of openings by using the power law equation (Hutcheon & Handegord, 1995; ASHRAE, 2005).

$$Q = C(\Delta P)^n \qquad \textbf{[1]}$$

Where, ***Q*** = airflow through opening (m^3/s); ***C*** = flow coefficient ($m^3/s/Pa^n$; ***P*** = pressure difference (Pa) between interior (reference pressure) and exterior (baseline pressure); ***n*** = flow exponent (dimensionless).

C and *n* can be calculated by recording multiple measurements over a range of pressure differences (10, 30, 50 and 60Pa). First, the LOG of the average flow rates and the LOG of the average pressure differences are calculated for each pressure interval. The LOG measurements are then fitted to a complete linear least squares routine. This gives the value flow exponent (*n)*, which is the slope of the line through data points on the LOG flow, LOG pressure graph (known as the LOG-LOG graph).

The value for *n* determines the relationship between flow and pressure. The R-squared is calculated at the same time, by assessing the fit of the linear least squares to the data points. R-squared values less than 0.95 are noted as the data may be corrupted (Hutcheon and Handegord, 1995). The value of C is algebraically determined by substituting *n* and *Q* into the equation.

Values for *n* must be in the range of 0.5 – 1 to conform to the power law equation. However, there are circumstances that cause *n* to fall below the theoretically acceptable limit. For the purposes of this study, a value of 0.65 is substituted for *n* when the value drops below 0.5 in the testing phase (Finch et al., 2009; ASHRAE, 2005). A more in-depth discussion of this phenomenon is contained in Section 6.1 of this report.

5.3.2 Air leakage rate determination

Flow for any pressure difference can now be calculated when *C* and *n* are known quantities. Using the power law equation (refer to Equation 1), it is possible to solve *Q*, or flow rate, for any pressure difference. A building will typically experience differences at pressures of 10Pa and 4Pa due to stack effect, wind or HVAC operation (Hutcheon & Handegord, 1995). Some studies and standards preference these pressure differentials for results presentation. The results in this report will be presented at 50Pa for reasons discussed in Section 5.4.5.

The enclosure air leakage rates for individual suites tested before retrofit and after retrofit will be compared. An ACH value for the enclosure of the building as a whole will be extrapolated from the results by theoretical expansion of the measured enclosure area to the total building enclosure area.

5.3.3 Air leakage rates compared to other MURBs

The results of the testing will be compared to the air leakage rates of other MURBs as represented in the extant literature. While the literature is scant, there are opportunities for some comparison and conclusions. Comparable values will be derived from extant literature and compared to the air leakage values for the case study building, both pre-retrofit and post-retrofit.

5.4 Data presentation and metric selection

5.4.1 Equivalent Leakage Area (EqLA)

Equivalent leakage area is a metric that provides an idea of overall enclosure leakage by relating it to the cross-sectional area of a single equivalent hole. ELA is given by the following equation (CGSB, 2013):

$$EqLA = \left(\frac{Q}{C}\right)\left(\frac{p}{2\Delta P}\right)^{0.5} \quad \textbf{[2]}$$

Q = flow rate (m^3/s)
p = air density (kg/m^3)
ΔP = pressure difference (Pa)
C = discharge coefficient = 0.61

The primary benefit in using ELA values is that it allows the average person to easily conceive of the leakiness of the test area. The problem with ELA is that it does not take enclosure area into account and can give misleading figures. For this reason it is difficult to directly compare ELA values among different buildings.

5.4.2 Normalized leakage area (NLA)

NLA is derived from the following equation:

$$NLA = \frac{EqLA}{A} \quad \textbf{[3]}$$

EqLA = Equivalent Leakage Area (cm^2)
A = area across which pressure difference occurs, ie. enclosure area (m^2)

NLA is similar to EqLA in that the metric provides an intuitive idea of the cross-sectional area of enclosure leakage pathways. The advantage of NLA over EqLA is that it takes the area of the enclosure into account thereby allowing comparison between test spaces and buildings of different sizes. It is recommended that NLA be the industry standard metric for reporting air leakage values through the enclosure.

5.4.3 Normalized Flow Rate (Q_{norm})

Q_{norm} is derived from the following equation:

$$Qnorm = \frac{C*Q^n}{A} \quad \textbf{[4]}$$

C = discharge coefficient, dimensionless, function of *n*
Q = flow (L/s)
n = flow coefficient, dimensionless
A = area across which pressure difference occurs ($m^{2)}$, i.e. enclosure of test space

Similar to NLA, the normalized flow rate (Q_{norm}) takes the enclosure area into consideration. While the values for NLA and Q_{norm} are derived from different equations, both rely on the power law equation to define values for *n* and *C*. As such the relative distribution of values is almost identical between both metrics. The differences noted in the discussion for NLA apply equally to the differences in Q_{norm}. Both metrics are acceptable measures for the purposes of comparing tests areas within a building and among different buildings; however, the intuitive nature of NLA makes it preferable.

5.4.4 Air Changes per Hour (ACH)

ACH is derived from the following equation:

$$ACH = \frac{f_c(Q)}{V} \quad \textbf{[5]}$$

ACH = Air Changes per Hour
Q = flow rate @ 50Pa (L/s)
V = total building volume (m^3)
f_c = conversion factor for L/s to m^3/h = 3.6

The ACH value has limited applicability for two reasons. First, while it is an accurate indication of improvement in air tightness from pre-retrofit to post-retrofit; the ACH value does not give information on where the improvements are occurring in a multi-zone building. The building overall might have an acceptable ACH value, but contained within that value are a multitude of suites that are experiencing high leakage rates through the enclosure. These suites may be subject to problems associated with air leakage; however, one would have no idea if only looking at the ACH value.

ACH for a large building can also give somewhat misleading figures if one expects similar values to smaller buildings. If one takes a cube as an example, the ratio of surface area to volume is:

$$SA{:}V = \frac{6x^2}{x^3} \quad \textbf{[6]}$$

Where, *SA* = surface area, *V* = volume and *x* = length of one side.

The ratio is inversely proportional to the increase in *x*. The graph below shows the relationship between surface area and volume as length increases. The relevance to buildings is that the larger the building, given equal proportions, the lower the ratio of surface area to volume. As ACH relies on flow rate through the enclosure, the lower the ratio of surface area to volume is and the lower the ACH number is. As a result, an enclosure can be quite leaky, but the ACH value will be quite low if the cube (building) is large enough.

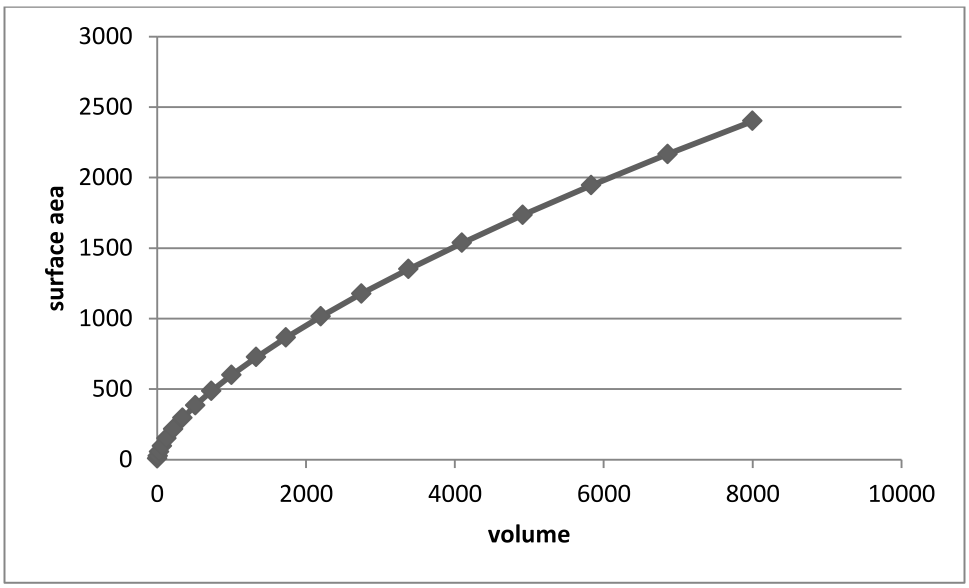

Figure 9 – Surface area to volume ratio of a cube

5.4.5 Recommendation for metric selection

ELA and ACH are not effective metrics for large-scale, multi-zone buildings.   While both metrics have certain advantages, these advantages are not applicable to MURBs and the metric as a whole can give misleading results. NLA and Q_{norm} are more effective at both indicating the effect of the enclosure tightness on the conditions of individual zones and at comparing the air tightness of buildings of different shapes and sizes.

It is imperative that air leakage values can be compared between different buildings. The advantage of NLA over Q_{norm} is that it allows the ability to reliably compare values across different building types, while providing an easy way to conceive of the leakage across a pressure boundary in terms of area as opposed to flow rate.

6 Results

6.1 Flow exponent values and data integrity

The value for the flow exponent (*n*) of the power law equation (refer to Equation 1) determines the relationship between air flow and pressure difference and must be in the range of 0.5 – 1 (Hutcheon and Handegord, 1995). If the value for *n* is 0.5, the flow is turbulent. If the value is 1, the flow is laminar. Air flow through a building enclosure is typically a mixture of laminar flow and turbulent flow (Finch, 2009). Extant literature suggests, when not calculating *n,* to use a value of 0.62-0.66 (most commonly 0.65) to model the mixture of laminar and turbulent flow (Hutcheon and Handegord, 1995; Price et al., 2006, Straube and Burnett, 2006).

The flow exponent values (*n*) were calculated from the data for the purposes of this report and are listed below:

Table 2 – Flow exponent values for individual suites [2]

	Suite 101	Suite 102	Suite 301	Suite 302	Suite 303
Pre-press	0.59	0.56	0.60	0.68	0.54
Post-press	0.56	0.67	0.75	0.85	0.85
Change[3]	***-0.03***	***+0.11***	***+0.15***	***+0.17***	***+0.31***
Pre-depress	0.92	0.80	0.50	0.62	0.61
Post-depress	0.79	0.69	0.60	0.57	0.37
Change	***-0.13***	***-0.11***	***+0.10***	***-0.05***	***-0.24***
	Suite 1101	**Suite 1102**	**Suite 1103**	**Suite 1301**	**Suite 1302**
Pre-press	0.52	0.49	0.53	0.74	0.52
Post-press	0.71	0.56	0.64	0.77	0.72
Change	***+0.19***	***+0.07***	***+0.11***	***+0.03***	***+0.20***
Pre-depress	0.47	0.46	0.78	0.57	0.63
Post-depress	0.61	0.43	0.59	0.57	0.47
Change	***+0.14***	***-0.03***	***-0.19***	***0.00***	***-0.16***

6.1.1 Flow exponent trends

There are two interesting and seemingly contradictory trends in the flow exponent values. First, the post-retrofit pressurization flow exponent values increased over the pre-retrofit pressurization values. The increase suggests that the flow is becoming more laminar and that the leakage pathways are getting smaller (Hutcheon and Handegord, 1995). The average difference for the pressurization flow exponent

[2] pre-press = pre-retrofit pressurization, post-press = post-retrofit depressurization, pre-depress = pre-retrofit depressurization, post-depress = post-retrofit depressurization

[3] positive change indicates a move towards laminar flow (smaller cracks), negative change indicates a move towards turbulent flow (larger cracks)

between pre-retrofit and post-retrofit is +0.13. This is the result one would expect from an improvement in enclosure leakage.

However, the depressurization phase showed a less pronounced, contrary trend. The average difference between pre-retrofit and post-retrofit flow exponent values for the depressurization phase is -0.07 and suggests a move to more turbulent flow and larger leakage pathways. The results data show that the flow rates decrease between pressurization and depressurization (refer to section 6.3), but the flow exponent suggests that leakage pathways are getting larger. This trend makes sense when one considers that the passive exhaust vents were untouched during pre-retrofit and post-retrofit testing. The area of the vent leakage would remain constant while, the smaller leakage pathways (i.e., cracked window sealant) were remediated. So, relative to the pre-retrofit testing, the leakage pathways of the post-retrofit enclosure are larger.

6.1.2 Abnormal flow exponent values

On six occasions, the flow exponent value drops below the theoretical limit of 0.5, while the R-squared value remains at an acceptable level. According to the power law, flow increases as pressure increases, and the function of their relationship, n, determines the degree of increase. If n is below the theoretically possible value, the power law relationship is no longer valid (Walker et al. 1998). In reality, what the test is likely showing is that the higher pressures are engaging one or more components and/or leakage paths in the enclosure assembly. Two examples are included below to better explain the phenomenon.

For the purposes of illustrating the observed phenomenon, various values for Q have been selected to represent flow through a theoretical enclosure at different pressure levels.

Table 3 – Example 1: Theoretical flow exponent values n<0.5

Series 1: Normal

Q	**P**	**logQ**	**logP**	***n***	**r-sq**
940.00	10.00	2.97	1	***0.52***	0.99
1570.00	30.00	3.20	1.48		
2150.00	50.00	3.33	1.70		
2450.00	60.00	3.38	1.78		

Series 2: n<0.5

Q	**P**	**logQ**	**logP**	***n***	**r-sq**
800.00	10.00	2.90	1	***0.43***	0.99
1300.00	30.00	3.11	1.48		
1600.00	50.00	3.20	1.70		
1700.00	60.00	3.23	1.78		

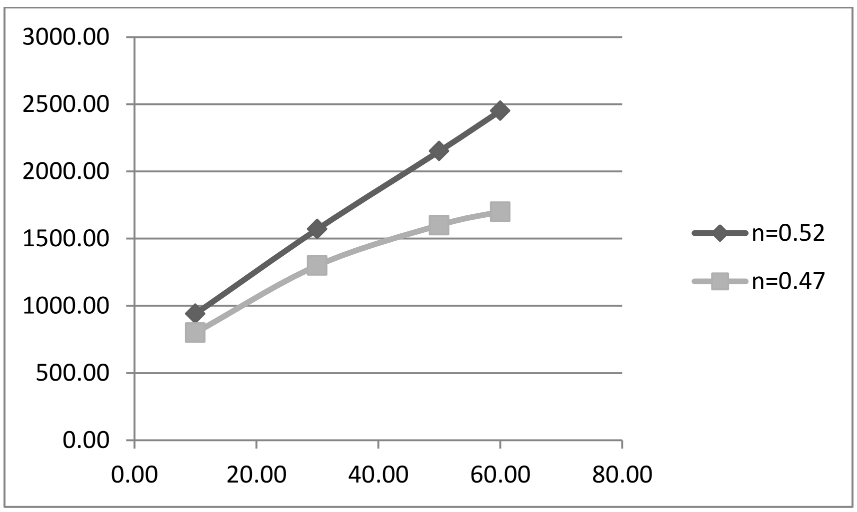

Figure 10 – Flow exponent value <0.5

Table 4 – Example 2: Theoretical flow exponent values n>1.0

Series 1: Normal

Q	P	logQ	logP	n	r-sq
940.00	10.00	2.97	1	***0.52***	0.99
1570.00	30.00	3.20	1.48		
2150.00	50.00	3.33	1.70		
2450.00	60.00	3.38	1.78		

Series 2: n>1.0

Q	P	logQ	logP	n	r-sq
200.00	10.00	2.30	1.00	***1.56***	0.99
1100.00	30.00	3.04	1.48		
2200.00	50.00	3.34	1.70		
3500.00	60.00	3.54	1.78		

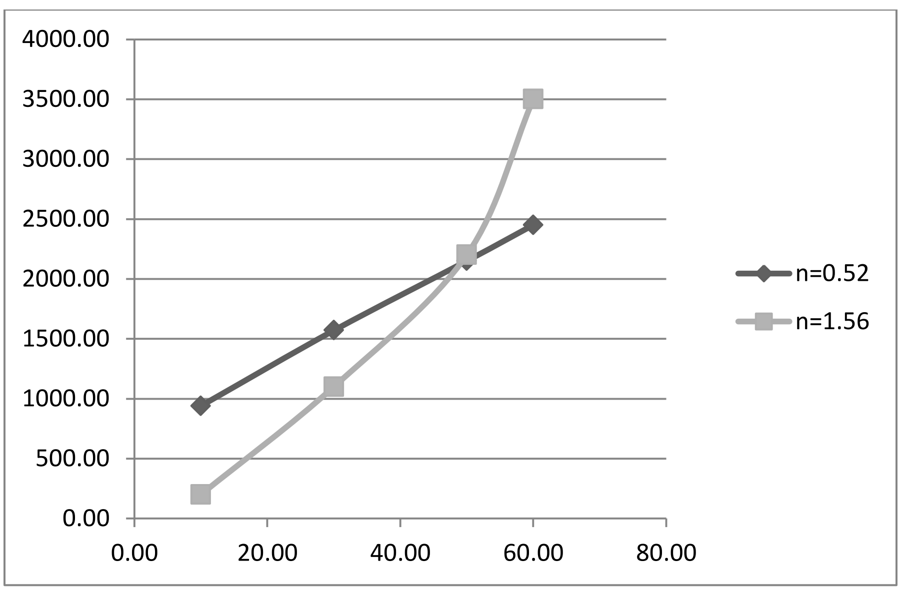

Figure 11 – Flow exponent value >1.0

The graphs representing the two scenarios show a linear relationship between the data points for Series 1. If the geometry of the test space (i.e., the cross-sectional crack area of pathways through the enclosure) does not change at various induced pressure differences, then the ratio will remain constant. In Example 1, the abnormal flow exponent value in Series 2 is created by a tightening enclosure; a decrease in the overall cross-sectional area of leakage pathways through the enclosure at higher pressure differences. Conversely, if the flow exponent value rises above 1 as in Series 2 of Example 2, it shows that the cross-sectional area of leakage pathways through the enclosure is increasing with pressure difference. This observation is backed up by the dramatically increasing flow rates required to keep the test space at a constant pressure at higher pressure differences.

6.1.3 Implications of abnormal flow exponent values for data extrapolation

Data that is derived from a theoretically impossible *n* value is not accurate data as it does not conform to the power law between the flow rate and all pressure differences. It does not give an indication of the geometry or area of the leakage pathways at all pressures, as those leakage pathways are changing relative to pressure. If the linear relationship is invalid, it is impossible to extrapolate air leakage data to pressures other than those that were tested directly.

There are two severe implications of this error. First, building energy simulations, which use normal operating pressures in their models, may have inaccurate estimates of the air leakage rate through the enclosure. Second, some air leakage standards call for buildings to meet specific targets at 4Pa or 10Pa (CMHC, 2013). As noted previously, it is inherently difficult to test air leakage at these pressures, and fan pressurization is used instead. If the flow exponent value is incorrect, so will be the air leakage data at unmeasured pressures. The fallout is a standard based on inaccurate data. Example 3 illustrates the misleading results using inaccurate flow exponent values.

The data used for Example 3 was fabricated for the purposes of this discussion. In Series 1 the flow exponent value has been calculated based on all three data points. In Series 2 the flow exponent value has been calculated based on only the last two data points. The R-squared test is within thresholds for both series. The different flow exponent values, in turn, affect the flow coefficient values (*C*) as noted below. By substituting the pressure difference of 4Pa into the equation (see Equation 1), it is possible to derive flow rates at this pressure difference.

Table 5 – Example 3: Flow exponent effect on extrapolated data

Series 1

Q (L/s)	**P (Pa)**	**logQ**	**logP**	***C* (avg.)**	***n***	***Flow @4Pa (L/s)***
210.00	10.00	2.32	1.00	69.52	0.47	***133.50***
320.00	30.00	2.51	1.48			
460.00	50.00	2.66	1.70			

Series 2

Q (L/s)	**P (Pa)**	**logQ**	**logP**	***C* (avg.)**	***n***	***Flow @4Pa (L/s)***
~~210.00~~	~~10.00~~	~~2.32~~	~~1.00~~	28.56	0.71	***76.47***
320.00	30.00	2.51	1.48			
460.00	50.00	2.66	1.70			

It is evident from Example 3 that the effect of different flow exponent values on flow rates at 4Pa is large. This discrepancy would affect any models that rely on air leakage values as a part of their programming. This is a precedent in the literature of substituting a value for the flow exponent when no value is available from the test data, or the value is theoretically impossible (Hutcheon and Handegord, 1995; ASHRAE, 2005; Straube and Burnett, 2006). The value substituted is usually in the range of 0.62 to 0.66, in an attempt to capture a mix of turbulent and laminar flow through the enclosure (Price et al., 2006).

Example 4 shows how the substitution of different flow exponent values affects extrapolated leakage rates. In Example 4, the corresponding flow coefficient (*C*) has also been changed to reflect the change in the flow exponent value. The data for flow rates (Q) and pressure differences (P) were taken directly from measurements for one of the suites of the case study building during a depressurization test. The original flow exponent value for this particular data set was 0.52.

Table 6 – Example 4: The effect of flow exponent and flow coefficient substitution

Pa	***C=95.30* *n=0.40***	***C=66.45* *n=0.50***	***C=59.28* *n=0.65***	***C=24.51* *n=0.80***
4.00	163.65	132.60	97.45	72.30
10.00	236.09	209.66	176.78	150.48
20.00	311.53	296.50	277.39	262.00
30.00	366.38	363.13	361.04	362.39
40.00	411.06	419.31	435.27	456.17
50.00	449.44	468.80	503.21	545.32
60.00	483.44	513.55	566.53	630.95
70.00	514.19	554.70	626.23	713.76
75.00	528.58	574.16	654.95	754.27

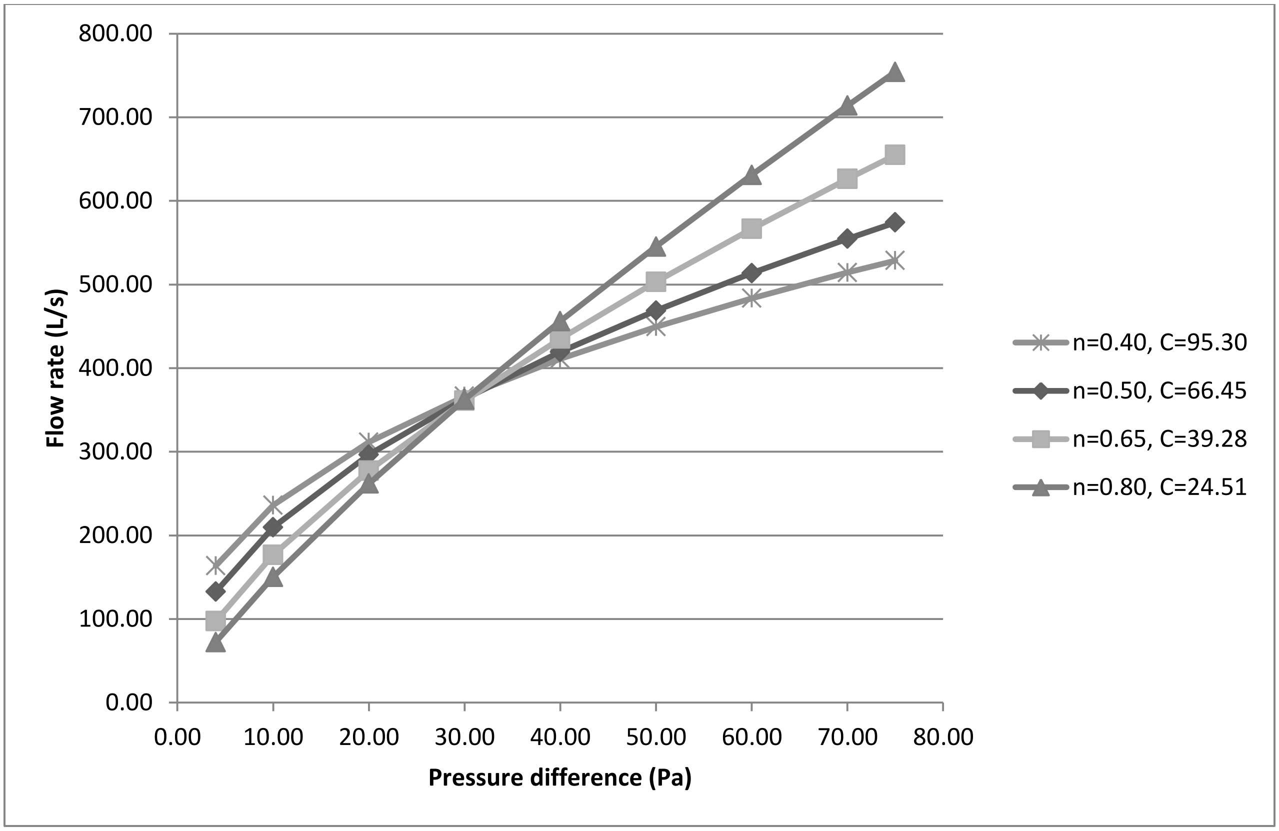

Figure 12 – Substituting flow exponent and flow coefficient values

It is evident from the graph that different flow exponent values are most influential at the lower pressure levels (4Pa and 10Pa) and the higher pressure levels (70Pa and 75Pa). However, as can be noted in the table above, the percentage influence is greatest at the lower pressure levels. For example, at 4Pa the flow rate at n=0.65 is 40% different from the flow rate at n=0.40, whereas at 75Pa the flow rate at n=0.65 is 19% different from the flow rate at n=0.40.

6.1.4 Implications for research and industry of erroneous flow exponent values

It is difficult to justify maintaining an abnormal flow exponent value. In addition to being theoretically impossible, flow exponent values under 0.50 may mislead researchers to conclude that the enclosure is far leakier at operating pressures than it actually is. As noted in the example above, the enclosure appears almost twice as leaky at lower pressure differentials.

Another issue, though one that may not arise frequently, is the substitution of a flow exponent value, without a corresponding change to the flow coefficient value. It is strongly recommended not to change only the flow exponent for two reasons. First, the terms no longer balance making the power law equation invalid. Second, and related, the effect on the data is drastic. Example 5 shows the effect of substituting flow exponent values without corresponding changes to the flow coefficient values.

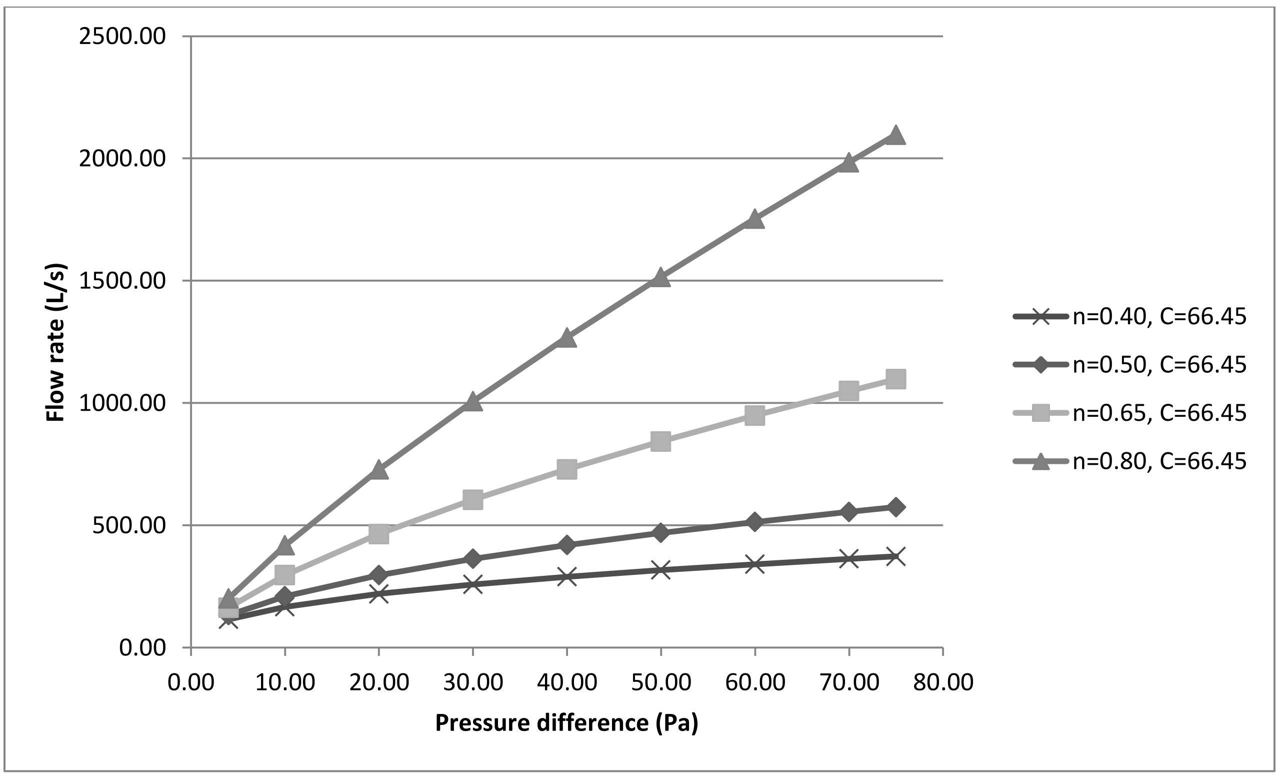

Figure 13 – Flow exponent substitution only

6.2 Flow exponent corrections

The effect of different values for the flow exponent has been shown to have large implications to extrapolated flow rates from the data set. Given this effect, it is not recommended to retain abnormal flow exponent values without considering how this may influence extrapolated flow rates at low and high pressure differentials, especially under normal building operation pressure differentials.

6.2.1 Pre-test corrections

Abnormal flow exponent values are caused by a change in the geometry of the leakage pathways through the building enclosure at various pressure differentials. One possible mitigation is to create a high pressure difference prior to the commencement of each testing phase in an attempt to pre-engage elements of the enclosure assembly that are noticeably engaging at higher pressure differences. Another option is to reverse the process of both pressurization and depressurization phases. In that case, the test phase would commence at the highest pressure differential and work its way down to the lowest. It is noted that elements may only engage at the higher pressure differentials and the mitigations suggested above may have little effect on the data.

6.2.2 In-test corrections

Flow exponent values should be checked at the termination of each test phase along with the r-squared values. In the event of an abnormally low or high flow exponent value with an adequate r-squared value, the enclosure should be checked for any missed leakage pathways, or for any enclosure elements that may be engaging only at higher pressure differences, such as a sticky vent flap. The elements should be fixed and the test phase run again.

6.2.3 Post-test corrections

For the purposes of this report, abnormal flow exponent values were corrected using the following method:

1) Data points at the highest pressure difference were eliminated and effect on the flow exponent noted. If the flow exponent returned to a theoretically acceptable level, the data points were considered incongruous and omitted from the data set.
2) In the event that data point elimination could not reconcile the flow exponent value, then a value for the flow exponent of 0.65 (ASHRAE 2005) was substituted and the value for the corresponding flow coefficient changed accordingly. The data was extrapolated to 50Pa using the substituted flow exponent value rather than the original abnormal flow exponent value.
3) Data is presented at the 50Pa level to avoid the magnified disparity evident in higher and lower pressure differentials (ie. 75Pa and 4Pa) and also to conform to industry reporting practices.

6.2.4 Further research into flow exponent effect on extrapolated flow rates

The relationship between flow exponent values and extrapolated flow rates deserves more attention than the scope of this paper allowed. An interesting field of inquiry would be to study the effect of changing leakage pathway geometry on flow exponent values in a controlled laboratory setting. Additionally, more published literature on how to ensure correct flow exponent values may help researchers and industry professionals get more accurate results.

6.3 Air leakage rates through the enclosure

The air leakage results for each test unit are summarized in the following Tables and Figures. Each metric has its own limitations (refer to Section 5.4); however, all point to the same general trends. The trends are described below using normalized leakage area (NLA_{50}) values. The other metrics have been listed in this section for comparison purposes to other measured data across the literature. Points of particular interest to each metric are included below the metric.

6.3.1 Data for Normalized Leakage Area

The table below presents the normalized leakage area for pressurization and depressurization tests of each suite.

Table 7 – Normalized Leakage Area (NLA_{50}) – cm^2/m^2 @50Pa

	Suite 101	Suite 102	Suite 301	Suite 302	Suite 303
Pre-press	2.70	2.60	4.60	5.10	5.50
Post-press	1.90	1.30	2.40	3.00	1.50
Change	**0.80**	**1.30**	**2.20**	**2.10**	**4.00**
Pre-depress	2.80	2.60	4.30	4.00	5.00
Post-depress	1.60	0.90	1.80	2.30	3.60
Change	**1.20**	**1.70**	**2.50**	**1.70**	**1.40**
Average Pre	2.75	2.60	4.45	4.55	5.25
Average Post	1.75	1.10	2.10	2.65	2.55
Change	**1.00**	**1.50**	**2.35**	**1.90**	**2.70**
Avg. Reduction	**36.36%**	**57.69%**	**52.81%**	**41.76%**	**51.43%**

	Suite 1101	Suite 1102	Suite 1103	Suite 1301	Suite 1302
Pre-press	4.80	18.20	7.00	6.00	10.10
Post-press	3.00	3.20	3.50	2.70	2.60
Change	**1.80**	**15.00**	**3.50**	**3.30**	**7.50**
Pre-depress	9.40	19.90	5.00	7.40	8.40
Post-depress	2.50	7.60	2.10	3.80	5.10
Change	**6.90**	**12.30**	**2.90**	**3.60**	**3.30**
Average Pre	7.10	19.05	6.00	6.70	9.25
Average Post	2.75	5.40	2.80	3.25	3.85
Change	**4.35**	**13.65**	**3.20**	**3.45**	**5.40**
Avg. Reduction	**61.27%**	**71.65%**	**53.33%**	**51.49%**	**58.38%**

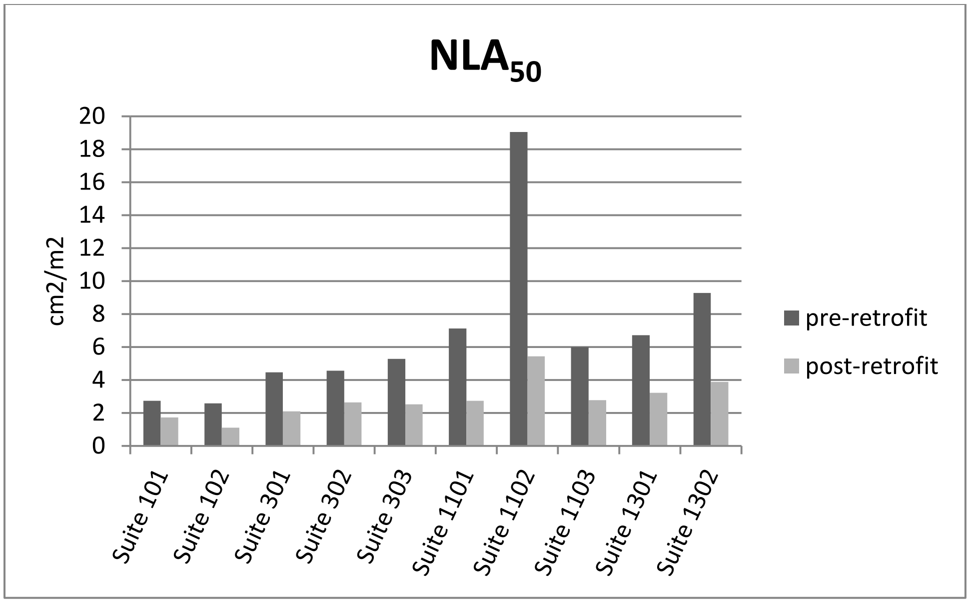

Figure 14 – Normalized leakage area by suite (cm^2/m^2) @50Pa

The following trends were observed based on the results of NLA_{50} data.

6.3.1.1 First Floor suites

The first floor is tighter than any other tested floor when enclosure area is taken into consideration in post-retrofit testing. Suite 101 is 38% tighter than the average suite at 1.75 cm^2/m^2, and suite 102 is 61% tighter at 1.10 cm^2/m^2. An interesting sub-point is that suites 101 and 102 had the lowest improvement when compared pre-retrofit to post-retrofit values, suggesting that the tighter a suite is the less it will improve relative to other leakier suites.

A feature that may help explain the relative tightness of the first floor suites is that they are adjacent (above) the parking garage. Due to the nature of a parking garage and considerations for air quality, fire protection, there should be very little airflow connection between the garage and adjacent spaces. Suites on the first floor are most likely benefiting from this proximity, so that the floor area in contact with the garage has fewer penetrations than enclosure area elsewhere in the building.

6.3.1.2 Third and Eleventh Floor Suites

Suite 1102 was the leakiest suite both pre-retrofit and post-retrofit, though it did improve by 13.65 cm^2/m^2 (72%), which is 14% more than the overall building average. Due to the fact that the suite is leakier than any other suites in both testing phases, it suggests that there exists a feature in the suite that was untouched by details in the retrofit. The fireplace and point source exhaust fans are most likely responsible for the leakiness of this suite. Another explanation is that the suite was particularly leaky pre-retrofit due to air barrier discontinuity due to hardware adjustment and the retrofit detailing, coincidentally was less precise for this suite. There was nothing discovered in the pre-retrofit investigation that suggests anything unique about the geometry or other aspects of the suite other than the fireplace and other ducts that could account for the leakage. Further investigation would be required to identify the exact nature of the discrepancy.

Suite 1102 may be an outlier in the data set though there is no way to prove this without further testing and investigation. However, if it is an outlier it could significantly skew the results and make the case study building look leakier than it really is. For means of comparison, area-weighted calculations of the average suite leakage including Suite 1102 and excluding it are provided below (refer to Table 8). The issue of Suite 1102 points further to the practice, if possible, of investigating test spaces whose values are significantly different from other tested spaces. Given the constraints of time and personnel on this project, further investigation was not possible, though is recommended for future projects to provide for in budgets and scheduling.

Suites on the 11th floor were consistently leakier than suites with almost identical geometry on the 3rd floor both pre-retrofit and post-retrofit, most likely due to the presence of the fireplace. The distribution between adjacent suites on each floor is very similar in the post-retrofit analysis. Suites 302 and 1102 were leakier than the adjacent suites on each floor. This suggests something unique in the geometry of the middle suites (ie. 202, 302, 402…1202) relative to the adjacent suites on each floor that might be contributing to air leakage.

6.3.1.3 Thirteenth Floor Suites

As will be mentioned in the discussion of ELA results, the suites on the thirteenth floor have fireplaces that are most likely contributing to the higher leakage values. The 13th floors suites in contrast to the 11th floor suites also have more operable windows, sliding doors and skylights. It is most likely due to the operability and increased enclosure penetrations that these suites are substantially leakier than other suites. However, it should be noted that suites 1301 and 1302 were significantly improved by the retro-fit, 3.50 cm^2/m^2 (52%) and 5.40 cm^2/m^2 (58%) respectively. In order to verify the above claim it would be necessary to seal the various components in the 13th floor suites that might be accounting for the leakage. If leakage rates drop significantly then the additional penetrations and operable windows/doors are attributable. This phenomenon makes the case for component/suite based testing.

6.3.1.4 Building overall

The building suites had a pre-retrofit NLA_{50} average of 6.77 cm^2/m^2 and an average post-retrofit NLA_{50} of 2.82 cm^2/m^2. The suites improved an average of 3.95 cm^2/m^2 (58%). By using the measured data and extrapolating it to the rest of the suites in the building, an overall average for the building is possible. The weighted overall average for the suites pre-retrofit was 6.67 cm^2/m^2 and 2.80 cm^2/m^2 post-retrofit, delivering an average weighted improvement of 57%. The data ranged 36% from Suite 101 at 1.0 cm^2/m^2 (36%) to Suite 1102 at 13.65 cm^2/m^2 (72%).The median value is 2.70 cm^2/m^2, an improvement of 60%. The three tightest pre-retrofit suites improved by an average of 1.47 cm^2/m^2 and the three leakiest pre-retrofit suites improved by an average of 7.80 cm^2/m^2.

If Suite 1102 is excluded from the data set, the averages vary considerably. The building suites had a pre-retrofit NLA_{50} average of 6.17 cm^2/m^2 and an average post-retrofit NLA_{50} of 2.80 cm^2/m^2. The suites improved an average of 3.37 cm^2/m^2 (55%). The weighted overall average for the suites pre-retrofit was 5.39 cm^2/m^2 and 2.55 cm^2/m^2 post-retrofit, delivering an average weighted improvement of 53%.

The area weighted averages are affected to a higher degree than the suite averages taken directly from the data. It is impossible to exclude Suite 1102 as an outlier without further information; however, its markedly higher values suggest some abnormality. To resolve the issue, overall building trends (refer to sections 6.4 and 6.5) will only be discussed based on collected data and not area weighted calculations due to the smaller impact of Suite 1102 on the direct averages.

A comparison for the analysis including suite 1102 and excluding 1102 is included in the table below.

Table 8 – Comparison of averages with respect to Suite 1102

	Building suite direct averages		improvement	
	pre-retrofit	**post-retrofit**	**avg.**	**%**
Suite 1102 incl.	6.77	2.82	3.95	0.58
Suite 1102 excl.	6.17	2.80	3.37	0.55
	Area weighted suite averages		**improvement**	
	pre-retrofit	**post-retrofit**	**avg.**	**%**
Suite 1102 incl.	6.67	2.80	3.87	0.58
Suite 1102 excl.	5.39	2.55	2.84	0.53

6.3.2 Data for Normalized Flow Rate (Q_{norm})

Table 9 – Normalized Flow Rate (Q_{norm50}) – L/s-m^2 @50Pa

	Suite 101	**Suite 102**	**Suite 301**	**Suite 302**	**Suite 303**
Pre-press	1.50	1.40	2.60	2.80	3.10
Post-press	1.10	0.70	1.30	1.70	0.80
Change	**0.40**	**0.70**	**1.30**	**1.10**	**2.30**
Pre-depress	1.50	1.40	2.30	2.20	2.70
Post-depress	0.80	0.50	1.00	1.20	1.90
Change	**0.70**	**0.90**	**1.30**	**1.00**	**0.80**
Average Pre	1.50	1.40	2.45	2.50	2.90
Average Post	0.95	0.60	1.15	1.45	1.35
Change	**0.55**	**0.80**	**1.30**	**1.05**	**1.55**
Avg. Reduction	**36.67%**	**57.14%**	**53.06%**	**42.00%**	**53.45%**

	Suite 1101	**Suite 1102**	**Suite 1103**	**Suite 1301**	**Suite 1302**
Pre-press	2.70	10.40	3.90	3.40	5.60
Post-press	1.70	1.80	1.90	1.50	1.50
Change	**1.00**	**8.60**	**2.00**	**1.90**	**4.10**
Pre-depress	5.00	10.30	2.70	4.00	4.50
Post-depress	1.30	3.90	1.10	2.00	2.80
Change	**3.70**	**6.40**	**1.60**	**2.00**	**1.70**
Average Pre	3.85	10.35	3.30	3.70	5.05
Average Post	1.50	2.85	1.50	1.75	2.15
Change	**2.35**	**7.50**	**1.80**	**1.95**	**2.90**
Avg. Reduction	**61.04%**	**72.46%**	**54.55%**	**52.70%**	**57.43%**

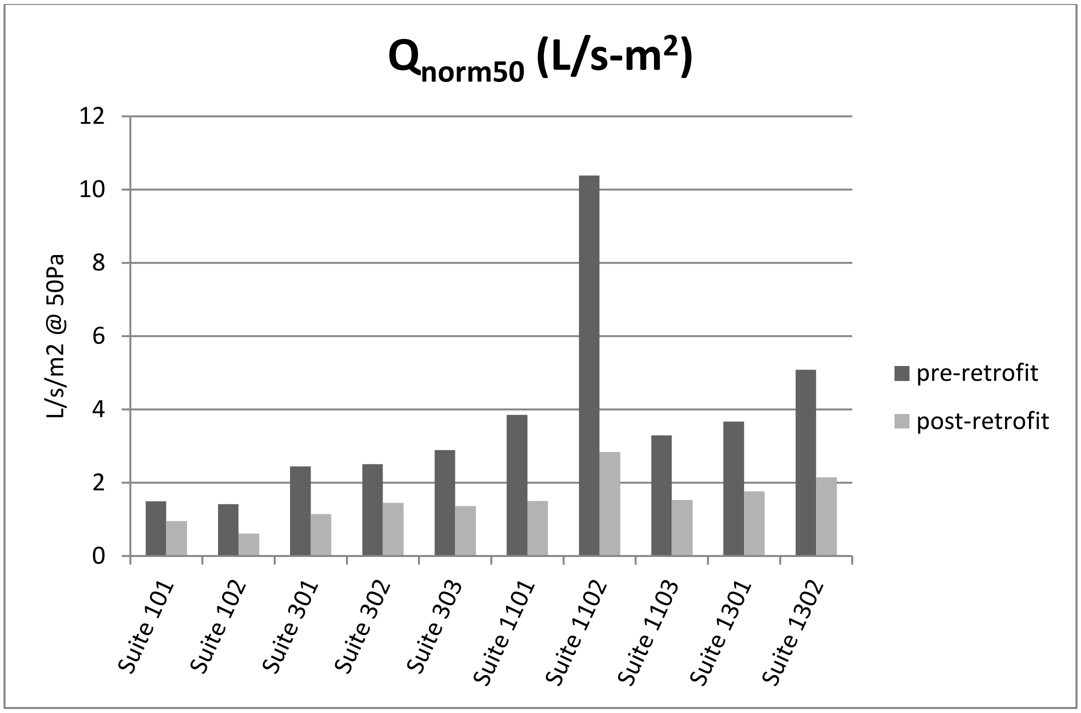

Figure 15 – Normalized flow rate (L/s-m^2) by individual suite @ 50Pa

6.3.3 Data for Equivalent Leakage Area (ELA_{50})

Table 10 – Equivalent Leakage Area (ELA_{50}) – cm^2 @50Pa

	Suite 101	**Suite 102**	**Suite 301**	**Suite 302**	**Suite 303**
Pre-press	536.60	470.40	391.00	358.40	464.40
Post-press	379.40	241.50	200.30	212.90	124.90
Change	***157.20***	***228.90***	***190.70***	***145.50***	***339.50***
Pre-depress	556.80	470.80	364.30	285.60	426.20
Post-depress	314.10	162.80	153.00	160.30	300.10
Change	***242.70***	***308.00***	***211.30***	***125.30***	***126.10***
Average Pre	546.70	470.60	377.60	322.00	445.30
Average Post	346.70	202.10	176.70	186.60	212.50
Change	***200.00***	***268.50***	***200.90***	***135.40***	***232.80***
Avg. Reduction	***36.58%***	***57.05%***	***53.20%***	***42.05%***	***52.28%***

	Suite 1101	**Suite 1102**	**Suite 1103**	**Suite 1301**	**Suite 1302**
Pre-press	407.40	1280.70	594.90	1205.10	1840.90
Post-press	253.00	229.10	292.80	539.50	479.90
Change	***154.40***	***1051.60***	***302.10***	***665.60***	***1361.00***
Pre-depress	795.00	1405.00	418.30	1477.40	1534.50
Post-depress	209.50	537.70	175.70	750.30	934.60
Change	***585.50***	***867.30***	***242.60***	***727.10***	***599.90***
Average Pre	601.20	1342.90	506.60	1341.30	1687.70
Average Post	231.30	383.40	234.30	644.90	707.30
Change	***369.90***	***959.50***	***272.30***	***696.40***	***980.40***
Avg. Reduction	***61.53%***	***71.45%***	***53.75%***	***51.92%***	***58.09%***

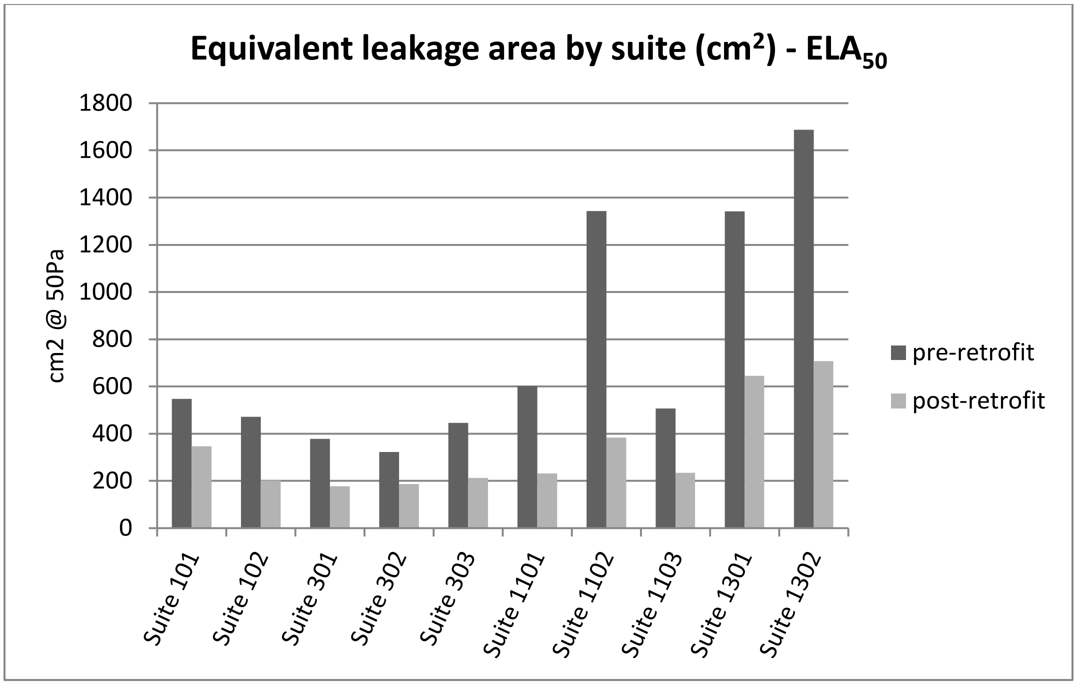

Figure 16 – Equivalent leakage area by suite (cm^2) @ 50Pa

Figure 5 shows the ELA_{50} values for pressurization and depressurization tests of each suite. It can be seen from the graph of ELA that suites on the 13th floor and suite 1102 exhibit considerably higher ELAs. Part of the explanation for this disparity on the 13th floor is the increased enclosure area as these suites include the roof in their envelope.

6.3.4 Data for Air Changes per Hour

Whole building ACH can be achieved by taking flow values from test suites and extrapolating these values to other suites with similar geometry. Floors 2 – 12 are geometrically identical. Suites from two floors within this range were tested (3 and 11). An area weighted ACH calculation was conducted based on enclosure area differences between bottom floors and upper floors. The total building volumetric flow rate was then divided by the total building volume and multiplied by 3600 to achieve an hourly value (see Figure 6).

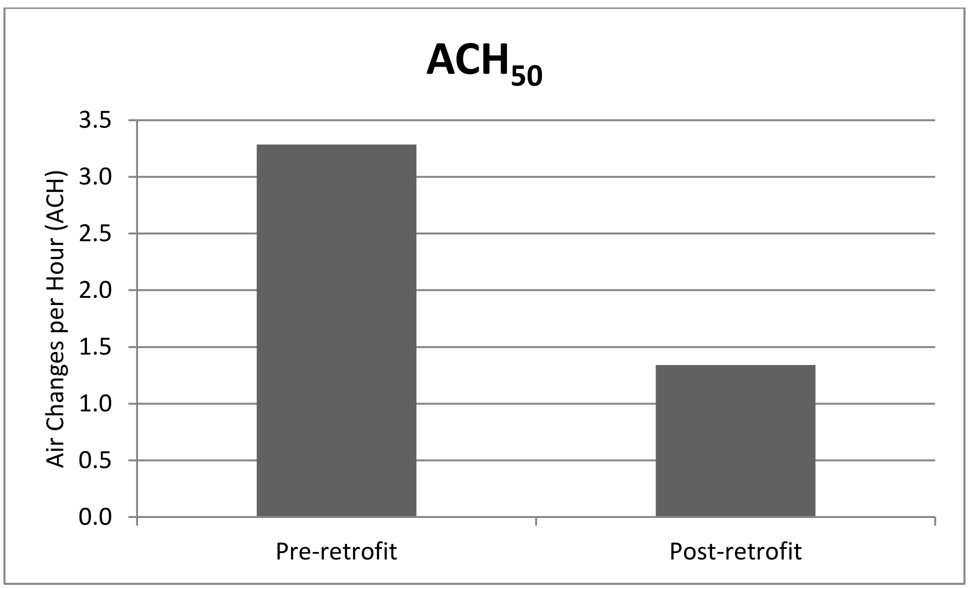

Figure 17 – Comparison of pre and post-retrofit ACH values

The total building enclosure leakage @ 50Pa pre-retrofit was 10526 L/s and 4426 L/s post-retrofit. The total building volume is 14287m^3. ACH_{50} pre-retrofit was 2.65 and 1.12 post-retrofit; an improvement of 58%, which is in line with the percentage improvement from other metrics.

The pre-retrofit ACH_{50} value for the case study building was 2.65. A common target among housing air tightness experts is 3 ACH_{50} (Lstiburek, 2011; IECC, 2012). Building A, if subject to the 2012 International Energy Conservation Code target would have passed easily, and yet there were obvious problems with the tightness of the enclosure (refer to Section 2). Due to the ratio between surface area and volume of typical large buildings and typical small buildings it is much easier to achieve lower ACH_{50} values for large buildings. ACH_{50} can be a good indication of relative enclosure tightness differences among buildings of a similar type, but cannot be compared reliably between buildings of significantly different geometry. ACH_{50} targets for buildings of different geometry, especially buildings with multiple, individually controlled zones, should also be different. The Passive House Institute of the United States (PHIUS) has recognized this deficiency and is moving towards a cladding based leakage target system rather than one based on ACH (PHIUS, 2013).

6.4 Comparison to other MURBs

It is possible to make some comparisons of the case study building to other MURBs in terms of air leakage. The report by Proskiw and Phillips (2001) found the average leakage rate to be 3.2 $L/s\text{-}m^2$ @75Pa (2.49$L/s\text{-}m^2$ @50Pa), with an average improvement of 15% for enclosure retrofits. The CMHC (2013) report found an average leakage rate of 3.66 $L/s\text{-}m^2$ @75Pa (2.85$L/s\text{-}m^2$ @50Pa). The report also noted an average improvement of 31% for MURBs with enclosure retrofits. Gulay et al. (1993) noted a range of 2.10 to 3.15 $L/s\text{-}m^2$ @ 50Pa. Price (2011) noted a mean of 4 $L/s\text{-}m^2$ @ 50Pa. The case study building had an average pre-retrofit Q_{norm50} of 3.11 $L/s\text{-}m^2$ @ 50Pa and post-retrofit Q_{norm50} of 1.32 $L/s\text{-}m^2$ @ 50Pa. A flow exponent value of 0.65

(Straube and Burnett, 2005; ASHRAE E1827 – 96; CHMC, 2013) is assumed in order to derive flow values at the same pressure difference using the power law equation (refer to Equation 1). The graph below compares the values mentioned above to the case study building.

Table 11 – MURB Air Leakage Comparison

Gulay et al. (1993)	2.63	l/s-m2 @50Pa
Proskiw and Phillips (2001)	2.49	l/s-m2 @50Pa
Price (2011)	4	l/s-m2 @50Pa
CMHC (2013)	2.85	l/s-m2 @50Pa
Case study building pre-retrofit	3.11	l/s-m2 @50Pa
Case study building post-retrofit	1.53	l/s-m2 @50Pa

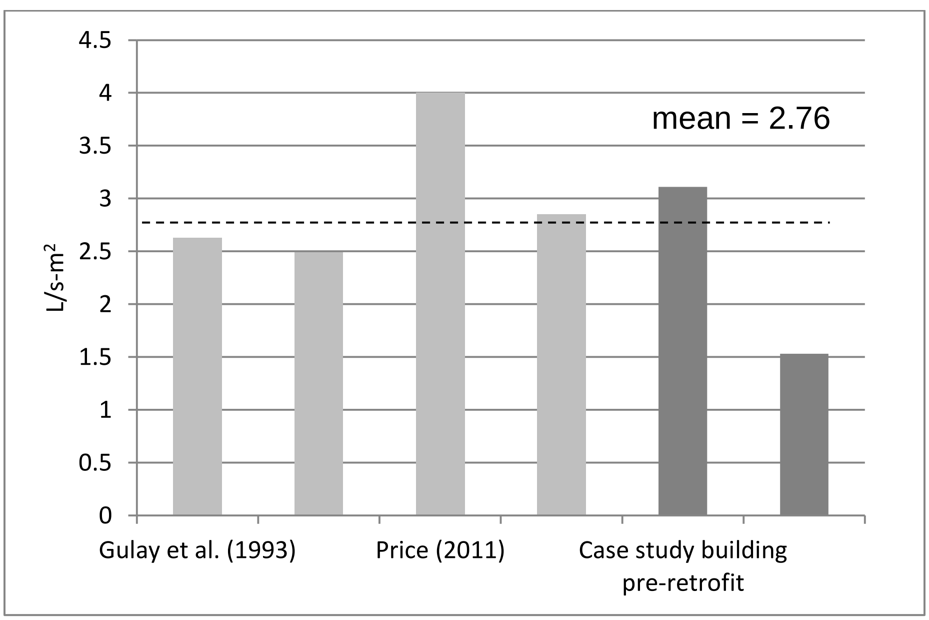

Figure 18 – MURB air leakage comparison

The air leakage results for the case study building pre-retrofit put it slightly above the average in terms of leakiness than the buildings in other studies. However, the enclosure retrofit brought the building to well under average air leakage values. Additionally, the building improved 58%, which is considerably better than the average improvement noted by Proskiw and Phillips (2001) at 15% and the CMHC (2013) report at 31%. The magnitude of the improvement shows the degree of possibility for the retrofit and building construction type details mentioned in this paper.

It is impossible to explain the discrepancy in improvement between the case study building and other MURBs without an in-depth understanding of the retrofit detailing of the other buildings. An interesting avenue for further research would be to run multivariate analyses of retrofit details to measure air leakage improvements among MURBs for which the appropriate data was available.

6.5 Discussion of trends and implications

6.5.1 Potential for large overall improvement and impact

The measures taken (refer to Section 2) in the retrofit improved building enclosure air tightness by an average of 58%. The retrofit measures of the case study building are in line with recommendations made by a recently published report from CMHC (2013) entitled “Air Leakage Control in MURBs.” The results of this paper and evidenced improvement of the case study building are a tacit endorsement of the measures outlined in the CMHC report.

6.5.2 Enclosure penetrations and leakage rates

As one might expect, the results identified a correlation between enclosure penetrations and leakiness. Suites on the 11^{th} floor had more enclosure penetrations than the floors below due to fireplaces. Suites on the 13^{th} floor had more enclosure penetrations due to skylights, more operable windows and fireplaces. Suites on the 13^{th} floor were the leakiest in the building, while suites on the 11^{th} floor were slightly leakier than the floors below. Suite 1102 showed abnormally high leakage rates even considering increased enclosure penetrations. This phenomenon suggests the potential for component/suite based air leakage testing in the future and is an interesting avenue for future research.

6.5.3 Initial leakage value vs. improvement

Every suite improved significantly, with the lowest improvement (36%) coming from one of the best performing suites in the pre-retrofit analysis. Conversely, the largest improvement came from the poorest performing suite, pre-retrofit. The trend suggests that improvement exists in any scenario; however, leakier suites are lower hanging fruit for the same retrofit detailing measures.

Suites with more planned openings were leakier on average than other suites; however improved below the average building improvement. This trend suggests that while leakier suites may improve significantly, a mitigating factor is the amount of operable windows and doors and penetrations through the enclosure.

7 Future Research

Several areas of future research were noted in the course of this work. The following is a list of possible topics and actions to improve knowledge on air leakage rates in MURBs.

1. Effect of leakage pathway geometry on flow exponent values - study the effect of changing leakage pathway geometry on flow exponent values in a controlled laboratory setting.
2. Data integrity related to changing leakage pathway geometry - determine the threshold of leakage pathway geometry changes before data integrity compromise.
3. Flow exponent value corrections – research on how to ensure correct flow exponent values and how to know when flow exponent values may have been compromised.
4. Relationship of air leakage rates to retrofit detailing - run multivariate analyses of retrofit details to measure air leakage improvements among MURBs for which the appropriate data is available.
5. Relationship of components and penetrations to overall test space leakage – research into component/suite based air leakage testing in the future.

8 Conclusions

Building enclosure air tightness can have significant implications for building operation; energy efficiency, enclosure durability and occupant health and comfort. There is a need to retrofit much of the building stock in Vancouver, a high proportion of which are MURBs. It is important to conduct research on air leakage through MURB enclosures both pre and post-retrofit. It is also important to establish methodologies and standards to facilitate building comparison, accurate data gathering and direction for future retrofits.

Currently, there is a lack of literature for MURB air leakage rates through the enclosure. In order to establish a benchmark and improve retrofit direction and planning, more information on leakage rates is needed. Further to this, an understanding of how retrofit detailing affects leakage rates is important. Individual component testing within a test space may provide more detailed information on where leakage occurs and how best to ameliorate it.

Many testing methodologies exist. While each has an advantage in its own way, due to the particular constraints of operating in MURBs, some may be more appropriate than others. The guarded-zone method has proven to be a robust and efficient test methodology and may be considered for standardization of MURB testing.

A better understanding of some of the data derived from testing is important; specifically, the effect of leakage path geometry on flow exponent values. There is little literature on this phenomenon, one which may have significant implications for extrapolated flow rate values. Flow exponent corrections may need to be made pre-test, in-test and post-test.

The presentation of air leakage rate information needs to be standardized. It is too difficult, if not impossible, to compare the various metrics. To this end, normalized leakage area (NLA) (cm^2/m^2) at 50Pa is a suitable metric.

The results of the air leakage testing data show a significant improvement in the case study building enclosure tightness. The retrofit details are in line with a recent report from CMHC (2013) recommending air leakage control measures for MURB retrofits. The results suggest the degree of improvement that might be expected if the same retrofit measures are undertaken for similar MURBs in Vancouver.

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10 Appendices

Appendix A) Testing - Guarded-zone Method

1. **Materials:**

    a. Retrotec Model 3200 – 8500cfm door fans (X4)
    b. Retrotec DM-2A gauges (X4)
    c. Retrotec Fantestic software
    d. Laptop
    e. Tape
    f. Polyethylene sheet

2. **Setup**

    a. **Ensure all uncontrolled openings in the test suite and adjacent spaces are sealed, including:**

        i. the outlet for baseline pressure tubes
        ii. corridor air supply vents
        iii. elevator shafts
        iv. door cutaways and frames
        v. door fan connections to door frame
        vi. other potential leakage paths

b. **Ensure all mechanical ventilation in the test suite is off or closed, including:**
    i. bathroom exhaust fans
    ii. range hood exhaust fans

c. **Connect baseline pressure tubes to gauges**
    i. place pressure tubes on opposite sides of the building and connect them together to create the baseline (Refer to Appendix B for connection schematic)
    ii. connect the baseline to the gauges

d. **Install test suite fan (fan 1)**
    i. ensure reference pressure tube is in the suite
    ii. open all interior partitions in the suite (doors, windows, etc.)
    iii. connect fan outdoor reference tube to baseline tube
    iv. ensure all adjacent spaces are equalised to outdoor pressure
    v. ensure exterior leakage pathways are closed (doors, windows, etc.)

e. **Install corridor fans in floor above and below (fans 2 and 3)**
    i. open doors to all suites on floor above and below test suite.
    ii. ensure all exterior openings are closed
    iii. ensure all mechanical ventilation is closed or off
    iv. ensure all internal doors and windows in the suites are open

f. **Install corridor fan on test suite floor (fan 4)**
    i. ensure all doors to suites adjacent the test suite are open to the corridor

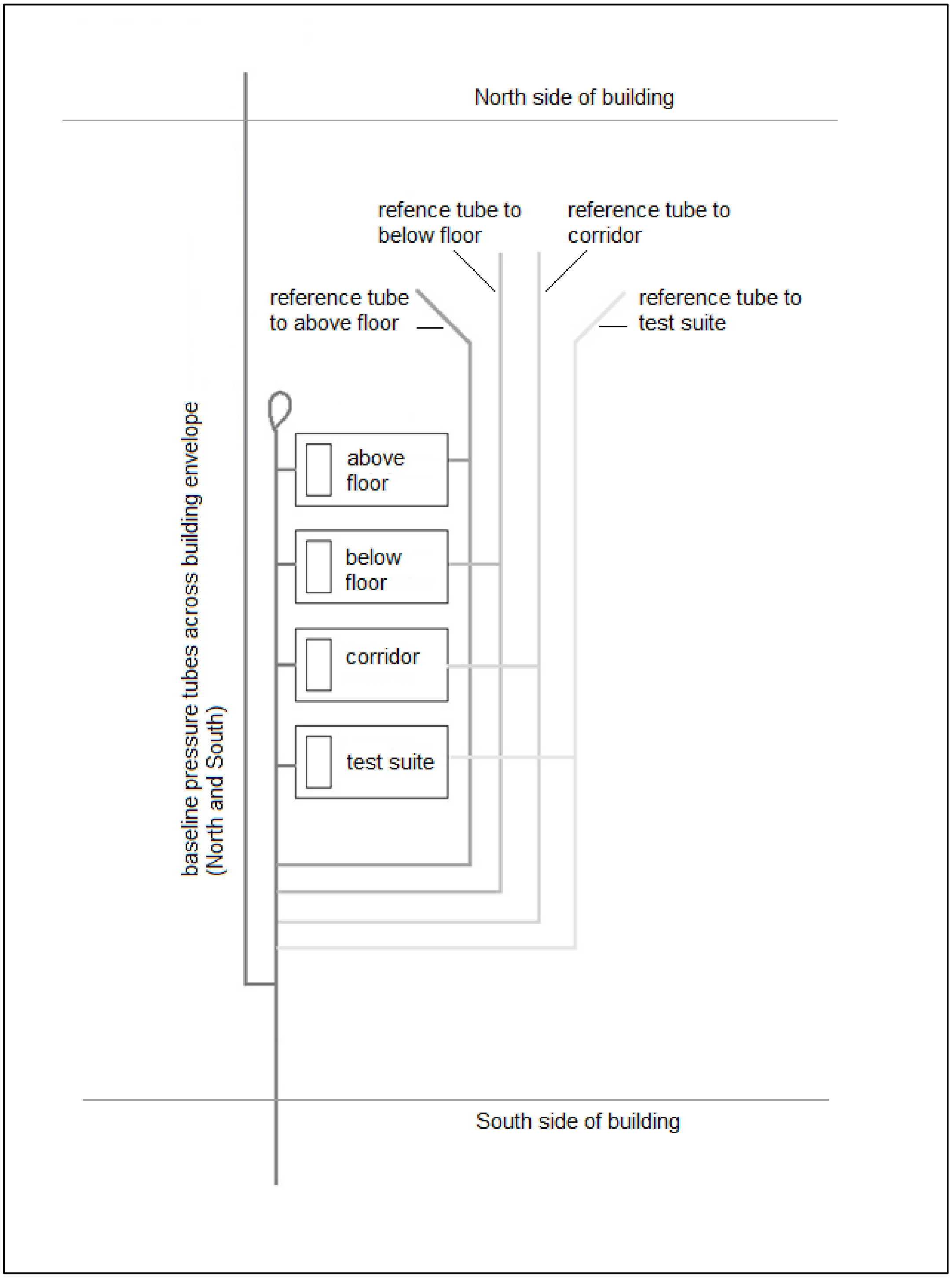
3. **Testing**

a. **Pressurise test suite and all adjacent spaces and record multiple data points over a minimum of 10 seconds for each pressure level**

i. at 10Pa
ii. at 30Pa
iii. at 50Pa
iv. at 60Pa

b. **Switch fan direction and repeat tests**

Appendix B) Pressure tube connections schematic



Appendix C) Air Leakage Results Summary by Suite

Suite 101

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 101 - Pressurize pre-retrofit	-10.00	248.37	117.21	-10.01	2.40	1.00	0.59	1.80	64.09	63.48	1.00
	-30.00	458.51	216.37	-29.99	2.66	1.48			62.00		
	-50.00	635.03	299.67	-50.01	2.80	1.70			63.58		
	-60.00	714.49	337.17	-59.93	2.85	1.78			64.26		
Suite 101 - Depressurize pre-retrofit	10.00	138.27	65.25	10.01	2.14	1.00	0.92	1.24	16.74	17.58	0.99
	30.00	446.66	210.78	29.99	2.65	1.48			19.78		
	50.00	624.08	294.50	49.72	2.80	1.70			17.39		
	60.00	699.56	330.12	60.04	2.84	1.78			16.40		
Suite 101 - Pressurize post-retrofit	-20.00	265.58	125.33	-19.51	2.42	1.29	0.56	1.70	50.63	50.57	1.00
	-30.00	333.94	157.58	-29.65	2.52	1.47			50.41		
	-50.00	447.97	211.40	-49.56	2.65	1.70			50.77		
	-60.00	493.03	232.66	-59.50	2.69	1.77			50.46		
Suite 101 - Depressurize post-retrofit	20.00	169.24	79.86	20.00	2.23	1.30	0.79	1.22	16.10	16.57	0.99
	30.00	249.11	117.55	29.81	2.40	1.47			17.32		
	50.00	359.45	169.63	50.25	2.56	1.70			16.59		
	60.00	404.91	191.08	59.90	2.61	1.78			16.28		

Suite 102

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
0.00											
Suite 102 - Pressurize pre-retrofit	-10.00	228.88	108.01	-10.69	2.36	1.03	0.56	1.79	63.00	62.11	0.99
	-30.00	422.74	199.49	-29.99	2.63	1.48			62.88		
	-50.00	573.10	270.45	-50.04	2.76	1.70			64.03		
	-60.00	580.32	273.85	-59.95	2.76	1.78			58.54		
Suite 102 - Depressurize pre-retrofit	10.00	143.64	67.78	10.00	2.16	1.00	0.80	1.37	22.73	23.40	0.99
	30.00	385.11	181.73	30.11	2.59	1.48			25.22		
	50.00	529.40	249.82	49.99	2.72	1.70			23.11		
	60.00	595.97	281.24	59.78	2.78	1.78			22.54		
Suite 102 - Pressurize post-retrofit	-20.00	151.87	71.67	-19.82	2.18	1.30	0.67	1.32	20.73	21.02	1.00
	-30.00	206.46	97.43	-29.82	2.31	1.47			21.47		
	-50.00	285.44	134.70	-49.85	2.46	1.70			21.07		
	-60.00	318.28	150.20	-59.79	2.50	1.78			20.81		
Suite 102 - Depressurize post-retrofit	20.00	101.96	48.11	20.91	2.01	1.32	0.69	1.10	12.70	12.71	0.99
	30.00	132.58	62.57	30.16	2.12	1.48			12.85		
	50.00	177.42	83.73	49.65	2.25	1.70			12.22		
	60.00	217.02	102.41	60.48	2.34	1.78			13.06		

Suite 301

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 301 - Pressurize pre-retrofit	-10	175	82.55	-9.86	2.24	0.99	0.60	1.65	44.44	45.05	1.00
	-30	349	164.48	-29.71	2.54	1.47			46.06		
	-50	462	217.81	-50.01	2.66	1.70			45.01		
	-60	511	241.13	-59.86	2.71	1.78			44.70		
Suite 301 - Depressurize pre-retrofit	10	187	88.21	10.09	2.27	1.00	0.50	1.76	58.17	57.56	1.00
	30	311	146.56	29.92	2.49	1.48			55.85		
	50	420	198.00	50.20	2.62	1.70			58.10		
	60	460	217.13	60.22	2.66	1.78			58.11		
Suite 301 - Pressurize post-retrofit	-20	117	55.22	-20.12	2.07	1.30	0.75	1.10	12.35	12.63	0.99
	-30	167	78.78	-30.09	2.22	1.48			13.03		
	-50	240	113.28	-49.94	2.38	1.70			12.82		
	-60	260	122.63	-58.60	2.41	1.77			12.31		
Suite 301 - Depressurize post-retrofit	20	103	48.77	20.09	2.01	1.30	0.60	1.23	17.20	16.82	0.99
	30	125	58.91	30.37	2.10	1.48			16.23		
	50	173	81.42	49.53	2.24	1.69			16.74		
	60	197	93.09	59.82	2.30	1.78			17.10		

Suite 302

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 302 - Pressurize pre-retrofit	-10	140	65.97	-10.22	2.15	1.01	0.68	1.47	29.10	29.45	0.99
	-30	315	148.65	-29.92	2.50	1.48			31.02		
	-50	420	198.30	-50.00	2.62	1.70			29.21		
	-60	463	218.66	-60.13	2.67	1.78			28.45		
Suite 302 - Depressurize pre-retrofit	10	121	57.09	10.22	2.08	1.01	0.62	1.46	28.85	29.12	1.00
	30	244	114.92	30.10	2.39	1.48			29.82		
	50	325	153.14	49.92	2.51	1.70			29.08		
	60	359	169.27	59.92	2.55	1.78			28.72		
Suite 302 - Pressurize post-retrofit	-20	113	53.16	-20.14	2.05	1.30	0.85	0.95	8.72	8.97	0.99
	-30	170	80.35	-30.24	2.23	1.48			9.32		
	-50	252	119.15	-49.00	2.40	1.69			9.16		
	-60	285	134.39	-60.03	2.45	1.78			8.69		
Suite 302 - Depressurize post-retrofit	20	107	50.58	20.35	2.03	1.31	0.57	1.29	19.10	19.44	0.99
	30	142	66.80	30.64	2.15	1.49			19.95		
	50	184	86.78	49.88	2.26	1.70			19.60		
	60	199	94.09	60.08	2.30	1.78			19.11		

Suite 303

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 303 - Pressurize pre-retrofit	-10	230	108.35	-10.06	2.36	1.00	0.54	1.81	65.58	65.28	1.00
	-30	413	194.72	-30.00	2.62	1.48			64.82		
	-50	548	258.37	-49.92	2.74	1.70			65.13		
	-60	609	287.38	-60.25	2.78	1.78			65.60		
Suite 303 - Depressurize pre-retrofit	10	180	84.82	9.88	2.25	0.99	0.61	1.65	44.45	44.65	1.00
	30	358	169.14	29.91	2.55	1.48			45.11		
	50	490	231.21	50.31	2.69	1.70			44.91		
	60	536	253.06	60.00	2.73	1.78			44.14		
Suite 303 - Pressurize post-retrofit	-20	66	31.10	-19.03	1.82	1.28	0.85	0.72	5.33	5.24	1.00
	-30	95	45.00	-30.97	1.98	1.49			5.09		
	-50	146	68.76	-50.01	2.16	1.70			5.17		
	-60	177	83.60	-60.35	2.25	1.78			5.35		
Suite 303 - Depressurize post-retrofit	20	86	40.51	21.26	1.93	1.33	0.37	1.43	27.55	26.83	0.97
	30	91	42.91	29.76	1.96	1.47			25.75		
	50	115	54.26	49.85	2.06	1.70			26.88		
	60	125	58.80	60.43	2.10	1.78			27.12		

Suite 1101

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 1101 - Pressurize pre-retrofit	-10	224	105.88	-11.71	2.35	1.07	0.52	1.81	68.51	64.15	1.00
	-30	357	168.40	-29.81	2.55	1.47			61.87		
	-50	477	225.09	-49.99	2.68	1.70			63.57		
	-60	516	243.70	-59.78	2.71	1.78			62.65		
Suite 1101 - Depressurize pre-retrofit	10	228	107.51	12.14	2.36	1.08	0.47	1.85	70.97	70.62	1.00
	30	342	161.24	30.06	2.53	1.48			69.69		
	50	452	213.09	52.15	2.65	1.72			71.20		
	data for 60 Pa unavailable										
Suite 1101 - Pressurize post-retrofit	-20	159	74.82	-20.33	2.20	1.31	0.71	1.27	18.74	18.68	1.00
	-30	208	97.92	-30.12	2.32	1.48			18.57		
	-50	300	141.69	-50.10	2.48	1.70			18.73		
	-60	338	159.50	-59.44	2.53	1.77			18.68		
Suite 1101 - Depressurize post-retrofit	20	141	66.56	20.62	2.15	1.31	0.61	1.35	22.43	22.15	1.00
	30	175	82.57	30.91	2.24	1.49			21.76		
	50	235	110.84	49.46	2.37	1.69			21.96		
	60	269	127.11	59.68	2.43	1.78			22.47		

Suite 1102

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 1102 - Pressurize pre-retrofit	-10	419	197.86	-12.39	2.62	1.09	0.49	2.09	134.18	122.55	1.00
	-30	622	293.47	-30.02	2.79	1.48			115.55		
	-50	825	389.23	-49.96	2.92	1.70			119.03		
	-60	921	434.60	-60.32	2.96	1.78			121.44		
Suite 1102 - Depressurize pre-retrofit	10	403	190.18	12.89	2.61	1.11	0.46	2.08			0.97
	30	545	257.13	29.89	2.74	1.48			114.11	119.98	
	50	775	365.85	51.99	2.89	1.72			125.85		
	data for 60 Pa unavailable										
Suite 1102 - Pressurize post-retrofit	-20	169	79.73	-20.95	2.23	1.32	0.56	1.48	30.69	30.18	1.00
	-30	197	92.87	-29.73	2.29	1.47			29.37		
	-50	272	128.52	-49.89	2.44	1.70			30.41		
	-60	301	141.88	-60.01	2.48	1.78			30.27		
Suite 1102 - Depressurize post-retrofit	20	171	80.71	19.89	2.23	1.30	0.43	1.66	47.33	45.38	0.97
	30	179	84.36	29.83	2.25	1.47			41.58		
	50	257	121.44	49.45	2.41	1.69			48.16		
	60	257	121.08	59.23	2.41	1.77			44.44		

Suite 1103

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 1103 - Pressurize pre-retrofit	-10	304	143.29	-9.93	2.48	1.00	0.53	1.95	90.59	90.06	1.00
	-30	527	248.47	-29.89	2.72	1.48			88.21		
	-50	703	331.55	-49.92	2.85	1.70			90.00		
	-60	785	370.68	-60.02	2.90	1.78			91.43		
Suite 1103 - Depressurize pre-retrofit	10	134	63.09	10.22	2.13	1.01	0.78	1.35			0.99
	30	338	159.27	29.29	2.53	1.47			23.97	22.55	
	50	453	213.80	50.09	2.66	1.70			21.14		
	data for 60 Pa unavailable										
Suite 1103 - Pressurize post-retrofit	-20	184	86.70	-19.55	2.26	1.29	0.64	1.44	27.03	27.79	0.98
	-30	263	124.07	-29.89	2.42	1.48			29.42		
	-50	326	153.63	-49.72	2.51	1.70			26.24		
	-60	396	186.89	-59.36	2.60	1.77			28.47		
Suite 1103 - Depressurize post-retrofit	20	119	56.05	20.03	2.07	1.30	0.59	1.29	20.09	19.69	0.99
	30	143	67.64	30.09	2.16	1.48			19.05		
	50	199	94.01	49.73	2.30	1.70			19.66		
	60	226	106.61	60.01	2.35	1.78			19.94		

Suite 1301

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 1301 - Pressurize pre-retrofit	-10.00	441.08	208.14	-10.50	2.64	1.02	0.74	1.89	80.03	78.37	1.00
	-30.00	979.21	462.09	-30.13	2.99	1.48			78.70		
	-50.00	1406.58	663.77	-50.00	3.15	1.70			77.41		
	-60.00	1608.84	759.21	-60.24	3.21	1.78			77.35		
Suite 1301 - Depressurize pre-retrofit	Data for 10 Pa unavailable		0.00				0.57	2.26			1.00
	30.00	1265.67	597.27	30.22	3.10	1.48			182.18	181.88	
	50.00	1679.87	792.73	50.42	3.23	1.70			180.71		
	60.00	1876.13	885.35	60.04	3.27	1.78			182.76		
Suite 1301 - Pressurize post-retrofit	-20.00	308.57	145.61	-20.27	2.49	1.31	0.77	1.50	30.35	31.27	0.99
	-30.00	457.29	215.79	-30.71	2.66	1.49			32.66		
	-50.00	642.75	303.31	-49.65	2.81	1.70			31.70		
	-60.00	708.60	334.39	-59.56	2.85	1.77			30.37		
Suite 1301 - Depressurize post-retrofit	20.00	486.96	229.80	20.14	2.69	1.30	0.57	1.96	86.99	90.61	0.98
	30.00	673.42	317.79	29.74	2.83	1.47			96.18		
	50.00	851.12	401.64	49.37	2.93	1.69			90.91		
	60.00	933.13	440.34	60.92	2.97	1.78			88.34		

Suite 1302

Test Name	Target Pressure, ΔP_T [Pa]	Flow, Q [cfm]	Flow, Q [L/s]	Pressure, ΔP [Pa]	Log Flow, log(Q) [cfm]	Log Pressure, log(P) [Pa]	Flow Exponent, n	Log Flow Coefficient, log (C)	Flow Coefficient, C [cfm/Pa^n]	Flow Coefficient average, C	R-squared
Suite 1302 - Pressurize pre-retrofit	-10.00	937.73	442.52	-9.97	2.97	1.00	0.52	2.45	282.71	283.68	1.00
	-30.00	1680.67	793.11	-30.15	3.23	1.48			285.95		
	-50.00	2155.33	1017.10	-49.95	3.33	1.70			281.06		
	-60.00	2403.21	1134.07	-60.18	3.38	1.78			285.00		
Suite 1302 - Depressurize pre-retrofit	Data for 10 Pa unavailable		0.00				0.63	2.17			1.00
	30.00	1262.88	595.96	29.95	3.10	1.48			147.29	147.41	
	50.00	1752.88	827.18	50.00	3.24	1.70			147.86		
	60.00	1955.65	922.87	59.95	3.29	1.78			147.08		
Suite 1302 - Pressurize post-retrofit	-20.00	274.52	129.54	-19.86	2.44	1.30	0.72	1.52	31.60	33.47	0.97
	-30.00	424.04	200.11	-29.68	2.63	1.47			36.50		
	-50.00	571.00	269.46	-50.69	2.76	1.70			33.37		
	-60.00	632.82	298.63	-60.79	2.80	1.78			32.43		
Suite 1302 - Depressurize post-retrofit	20.00	349.39	164.88	19.49	2.54	1.29	0.47	1.93	86.47	85.98	0.99
	30.00	425.82	200.94	30.19	2.63	1.48			85.79		
	50.00	524.13	247.34	49.47	2.72	1.69			83.71		
	60.00	602.26	284.21	59.84	2.78	1.78			87.96		