**QUANTIFYING AIR LEAKAGE THROUGH PARTY WALLS IN TORONTO SEMI-
DETACHED AND ROW-HOME DWELLINGS.**

By

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Abstract: Quantifying Party Wall Air Leakage in Toronto Semi-Detached and Row Homes, Austin Todd, Master of Building Science, Ryerson University, 2018

This study contributes to the development of quantifying and understanding building air tightness as it relates to Toronto semi-detached and row homes, particularly party walls. While infiltration characteristics of single family detached homes have been widely developed and understood, the isolation of semi-detached and row home single family dwelling units is relatively unexplored. When quantifying air leakage in a building attached to an adjacent dwelling unit, air is drawn through the exterior envelope as well as the party wall (i.e. shared common wall). The purpose of the proposed testing method, guarded blower door testing, is to isolate air leakage through the party wall from the envelope. Currently the party wall is considered a fire-rated assembly but is not part of the air barrier system. Issues associated with party wall air leakage include spread of fire, indoor air quality, transfer of tobacco smoke between dwellings, and heat loss through the party to attic detail. Data collected on buildings constructed between 1890 and 1920 (Century buildings) has been compared to the data collected on buildings constructed between 2012 to 2017 (new buildings). Air leakage has been collected on twenty-six of Century semi-detached homes with solid masonry construction and twenty-one new semi-detached/row homes of lightweight wood frame construction. Each unit was tested independently and simultaneously, or “guarded”, with the adjacent unit, to pressure neutralize allowing for quantification of envelope and party wall air leakage. Party wall leakage was found to be similar to leakage through the exterior walls. The leakage accounted for 22% of the total infiltration in Century old buildings and 38% in Modern dwellings.

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1.0 Introduction

Four major components can be identified in residential homes: weather barrier, thermal barrier, air barrier, vapour barrier; all of which are components of the building envelope. In a single family dwelling all six sides of the building are exposed to the exterior environment. When looking at a multi-unit residential building (MURB), the dwelling is only partially exposed to the exterior environment and a new main component is introduced; a fire barrier; under the Ontario Building Code this wall is referred to as a *party wall*. This is a physical separation between two dwelling units that is intended to mitigate the spread of smoke and fire within a dwelling. In theory, this assembly should be air tight to separate the dwellings, but the air leakage characteristics of row housing are relatively unknown.

The original housing stock of Toronto residential buildings falls into the typology of Century Homes as defined by Blaszak and Richman (2013). While reporting on detached single family residential buildings, Century Homes are categorized as the highest energy intensity per floor area of the four main housing archetypes in Toronto. With residential homes in Canada being responsible for 17% of total energy consumption and 16% of greenhouse gas emissions, there is incentive to retrofit these homes to higher energy efficiency standards (CMHC, 2008). Air leakage through the envelope has a direct energy cost because in a mixed climate with harsh conditions the infiltration air often needs to be conditioned, therefore increasing the load on mechanical systems. For this reason, envelope upgrades that include increased insulation levels and improved airtightness are a common choice. However, reducing the infiltration rate of the exterior envelope can increase the infiltration rate through the party walls (Gadgil, Price, Shehabi, & Chan, 2006)(Finch, Straube, & Genge, 2009).

Leakage through the envelope is associated with the economics of retrofit strategies by reducing energy consumption and greenhouse gases, so for decades airtightness testing and research has been focused on the envelope (Finch et al., 2009). Air leakage also occurs through party walls between dwellings but this leakage is typically considered to be adiabatic, meaning there is no real heat loss through the surface because the air in the adjacent units is of relatively similar temperature, however, a study suggest that in townhomes the party wall may contribute to heat loss through air leakage. The implications associated with party wall air leakage are functions of indoor air quality impacting health and comfort that don't have a direct associated economic value, such as tobacco smoke, cooking odours, and sound transmission (Finch et al., 2009) (Gadgil et al., 2006) (Love & Sherman, 1990). A study conducted by Gadgil et al. (2006) in Minnesota stated that nearly 50% of renters in an apartment claim that second hand tobacco smoke enters their apartment from other units.

Performing air tightness testing on single family residential dwellings has become common throughout North America through governing organizations and energy auditing programs, but there are currently no industry standards specifically designed for testing the air tightness of MURBs (Urquhart, Richman, & Finch, 2015). When depressurizing a dwelling that has an attached adjacent unit to perform air tightness testing the measured air flow is infiltrating through the envelope as well as from the adjacent unit and with standard testing procedures the amount associated with each assembly can't be quantified. As governing bodies are striving towards implementing reduced energy consumption by implanting higher performance standards into building codes the air infiltration rate will need to be better controlled in order to meet energy standards. While the envelope is tightening measures will need to taken ensuring proper indoor air

quality through controlled party wall air leakage. To quantify leakage from the envelope and party walls separately a standard will need to be implemented so the result are reproducible.

This study focuses on quantifying air leakage through the party wall of Century semi-detached homes as well as Modern semi-detached and row homes to understand the dwellings air leakage characteristics, as well as quantify party wall air leakage, through the use of an experimental testing method.

1.1 Research Objectives

The objectives of this research are derived from the research questions stated above. The objective is to contribute to the understanding of the air leakage characteristics of Toronto's old and new semi-detached and/or row housing typology. As this research is preliminary in this area, a much larger sample size would be required to understand the air leakage characteristics of Toronto's existing housing stock, it's intended that insight will be drawn to the two different typologies and the leakage characteristics of the two assemblies. The primary research objectives are:

1. Contribute towards determining a testing procedure to accurately quantify party wall air leakage.
2. Compare and analyze data from buildings of the same typology.
3. Compare and analyze data against the two different typologies.

1.2 Research Questions

This research is being driven by a knowledge gap associated to MURBs air leakage characteristics; more specifically to understanding the leakage characteristics of Toronto dwellings. The research questions this report intends to answer are:

1. What are the air leakage characteristics of semi-detached Century homes in Toronto?

2. What are the air leakage characteristics of semi-detached and row Modern homes in Toronto?

2.0 Background

2.1 Air Barrier System in the Ontario Building Code

In the past century a lot has changed in the way we construct our homes. It was most common to construct homes out of solid brick masonry, which is the Century homes tested, and then as demand increased the industry shifted to light-weight wood frame construction to increase productivity and decrease cost. Field testing of semi-detached Century homes was done on buildings constructed between 1890 and 1920, long before the first Ontario Building Code regulation took effect in 1975. The building code was introduced to standardize how buildings are constructed, increase the safety of the structure and construction process, and hold construction practice accountable in the legal system. Amendments are made to the Code in between editions to stay current with standards and technologies and Supplementary Standards have been added to address energy efficiency standards in buildings. Traditionally the Building Code has been used as a tool to ensure safety and set the minimum acceptable construction standard that must be achieved. With heightening environmental concerns, such as climate change and aging energy infrastructure, the Building Code is also being used as a tool to set higher building standards to minimize energy consumption.

Modern semi-detached and row homes tested in this study were construction between 2014 and 2017 and would have been built under the regulations of the OBC 2012. For this study the section related to air barriers, *Section 9.25.3 Air Barrier System*, will be of focus. The prescribes the requirements of an air barrier in Ontario are (Ontario Building Code, 2012):

9.25.3.1. Required Barrier to Air Leakage

(1) Wall, ceiling and floor assemblies that separate *conditioned spaces* from unconditioned spaces or from the ground shall be constructed so as to include an *air barrier system* that will provide a continuous barrier to air leakage,

(a) from the interior of the *building* into wall, floor, *attic or roof spaces* sufficient to prevent excessive moisture condensation in such spaces during the heating season, and

(b) from the exterior inward sufficient to prevent moisture condensation on the room side during the heating season.

An air barrier system is comprised of materials connected to continuously wrap the envelope. As prescribed by 9.25.3.2 sheet and panel type materials used as the primary air barrier system shall not have leakage characteristics greater than $0.2 \text{ L}/(\text{s}\cdot\text{m}^2)$ measured at an air pressure differential of 75 Pa.

The air barrier system has been designed to mitigate airflow through from the conditioned to unconditioned space, or from the exterior and interior environment. Since the party wall is not part of the building envelope is it not considered part of the air barrier system.

This fails to address leakage that can occur between two conditioned spaces when dwellings are connected. A party wall is a fire rated assembly that's covered in Part 9 under 9.10.11. *Firewalls* (Ontario Building Code, 2012).

“9.10.11.1 Required Firewalls

(1) Except as provided in Articles 9.10.11.1. and 9.10.11.4., a *party wall* on a property line shall be constructed as a *firewall*.

9.10.11.3 Construction of Firewalls

(1) Where *firewalls* are used, the requirements in Part 3 shall apply.”

Party wall means a wall (Ontario Building Code, 2012),

- (a) That is jointly owned and jointly used by two parties under an easement agreement or by a right in law, and
- (b) That is erected at or upon a line separating two parcels of land each of which is, or is capable of being a separate real estate entity.

The key takeaway is that the party walls are not considered part of the air barrier and are instead rely on the airtightness characteristics of a rated fire wall.

2.2 Current Industry Standards

The airtightness of a building is related to the unintentional air infiltration of the building and is important because it impacts energy consumption and transportation of contaminants. The use of blower door fans was first developed by researchers in Sweden in 1977 in attempt to determine the tightness of building envelopes (M.H. Sherman & Chan, 2003). There are multiple methods of measuring building airtightness, however, previous literature reveals that majority of testing is done using blower door fans and is now the industry standard (McWilliams, 2002). Of the exiting body of knowledge associated with residential building airtightness majority of the data available is on single family residential dwellings (M.H. Sherman & Chan, 2003). Although semi-detached and row-home dwellings may be viewed as single family residential buildings, there are multiple occupancies within the same building envelope so these buildings are susceptible to air

leakage through the party walls. Currently there are no industry standards that address and separate air leakage from the exterior and interior party walls (Urquhart et al., 2015).

The Ontario Building Code has no provision for mandatory airtightness testing, however, required airtightness testing has been proposed for future code iterations. Airtightness testing would be introduced in a two-phase system with the first phase being introduced in 2020 and the second phase being introduced in 2022. The first phase would require airtightness of new building to be reported with no prescribed requirements and the second phase would introduce minimum airtightness requirements. The proposed 2022 airtightness targets are in OBC Supplementary Standard SB-12 *Energy Efficiency for Housing* in SB-12 Table 3.1.1.4.A, as seen below:

Table 1: OBC SB-12 Airtightness Targets

Building Type	Airtightness Targets				
	ACH @ 50Pa	NLA @ 10 Pa		NLR @ 50 Pa	
		cm ² /m ²	in ² /100 ft ²	L/s/m ²	cfm/ft ²
Detached	2.5	1.26	1.81	0.93	0.18
Attached	3.0	2.12	3.06	1.32	0.26
Column 1	2	3	4	5	6

Currently in the building code these values aren't prescriptive or mandatory but allow for substitutions for design parameters if the values are met. For example, if a detached dwelling achieves no more than ACH₅₀ - 2.5, NLA – 1.26 cm²/m², or NLR 0.93 L/s/m² the building can be designed with less insulation, as prescribed in SB-12. The building is to be tested under as operated conditions with CAN/CGSB 149.10 *Determination of the Airtightness of Building Envelops by Fan Depressurization Method*, or NRCan *EnerGuide Rating System Technical Procedures Version 15.2*, which also references CAN/CGSB 149.10. Although not stated, it's likely that the attached building type is given a larger allowance because it's assumed that there is less heat loss associated with the party wall.

Depending on project scope and requirements there are various airtightness standards that can be applied to MURB projects. Although MURBs often refer to highrise or condo buildings they will be reviewed because of the similar party wall characteristics in semi-detached and row-home dwellings. Finch et al. (2009) state that the most convenient and common reporting metric is the equivalent leakage area at a reference pressure of 50 Pa (ELA₅₀) and summarizes applicable standards below in Table 2:

Standard	ELA ₅₀
LEED v2.2 for New Construction	2.1 cm ² /m ² @ 50Pa
ASHRAE - tight exterior enclosure	0.7 cm ² /m ² @ 50Pa
ASHRAE - average exterior enclosure	2.1 cm ² /m ² @ 50Pa
ASHRAE - leakage exterior enclosure	4.3 cm ² /m ² @50Pa
International Energy Conservation Code (IEEC), Enclosure Leakage	2.9 cm ² /m ² @50Pa
National Building Code of Canada 2005	0.23 cm ² /m ² @ 50Pa
Air Tightness Teating and Measurement Association	1.5 cm ² /m ² @50Pa

Table 2 Existing Airtightness Standards and ELA Targets

LEED has introduced a mandatory air leakage performance metric to address tobacco smoke, as well as other indoor air pollutants, from transferring between units in highrise MURBs LEED references that the testing procedures described by RESNET or ENERGY STAR Multifamily High Rise Program Testing and Verification Protocols, Version 1.0 must be used. ENERGY STAR references that for apartment compartmentalization the testing must conform to ASTM E779-10 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization or ASTM E1827-11 Standard Test Methods for Determining Airtightness of Buildings Using an Orifice

Blower Door. RESNET also refers to conform with ASTM E779-10. All of the above listed testing standards were developed for single-zone testing and are not applicable to understanding the air leakage characteristics in a MURB. To understand the air leakage characteristics of a MURB, the air flow rates through the exterior envelope and the interior partition walls should be separated.

While energy implications associated with air leakage has typically been a strong focus because it can be directly associated with money, the impacts of air infiltration not associated with money are often overlooked; occupant health and comfort. This is a difficult area because increased occupant health and comfort can't be calculated through increased airtightness. The impacts of air infiltration on occupant health and comfort in single family dwellings are subject to the state of the exterior environment. There is an increased risk associated occupant health and comfort in MURBs because a dwelling is exposed to the pollutants produced in adjacent dwellings as a function of airflow through the party walls.

“Air tightness means measuring the flow through the building envelope as a function of the pressure drop across the building envelope” (M.H. Sherman & Chan, 2003). Typically, air leakage testing results can be described in one of three forms: (Finch, Straube, & Genge, 2009)

1. Fan flow (L/s)
2. Equivalent leakage area (ELA)
3. Air Change rate per Hour (ACH)

Airflow rate is the total rate at which air enters through leakage paths in a building under a given pressure differential. This number is a result of values produced by the blower door test. The formula is (Hutcheon & Handegord, 1995):

$$Q = C (\Delta P)^n$$

Where: Q = Airflow Rate per Unit Area [m^3/s]

C = Flow Coefficient [$\text{m}^3/\text{s} \cdot \text{Pa}^n$]

ΔP = Pressure Differential [Pa]

n = Flow Exponent [dimensionless]

The value n is a flow exponent correlating to the orifice flow with theoretical ranges of 0.5 to 1.0; with 0.5 representing turbulent flow (many small leaks in the envelope) and 1.0 representing laminar flow (one large leak in the envelope). If the value is above or below the theoretical limits the validity of the test has been compromised and the data should not be used. Flow paths can change during a multi-point test with varying pressures causing change in the geometry of the envelope leaks. If the flow paths change during the testing, the n value may be slightly below 0.5. If the data has a flow coefficient n that is below 0.5, 0.65 will be substituted (Finch et al. 2009, Richman 2015) Values C and n are constants that are both produced when a multipoint test is done. However, if a multipoint test is not done flow exponent n can be assumed 0.65 and flow coefficient C calculated based on airflow (Finch et al. 2009, Sherman 2004).

Not included in this equation is R^2 correlation coefficient which is also calculated in the multi-point regressions. This value must be above 0.95 to be considered accurate data (ASHRAE 2007, Richman 2015).

3.0 Literature Review

The literature review is separated into two sections; 1. Methods of measuring airtightness in MURBs, and; 2. Related field studies. There are many methods to measure airtightness in MURBs that have largely been developed by researchers interested in advancing the body of knowledge. The most relevant methods were selected for review.

Testing of similar nature has been conducted through various efforts to quantify air leakage through party walls. While some of the methods and typologies are not applicable to this study, it provides insight to the subject and highlights that there has been a gap of knowledge and focus on airtightness testing in MURBs.

3.1 Methods of measuring airtightness in MURBs

Feustel (1990) states that there are two fundamental approaches to measuring air infiltration in a building; the first is to measure the infiltration directly under the present environmental conditions; and the second to measure the airflow under and induced pressure differential between the interior and exterior environment. Measuring the infiltration directly can be done with tracer gas, where a gas is released into the interior environment and the rate of dilution represents the rate of infiltrating or exfiltration air. These measurements represent the infiltration only under the present environmental conditions, although mathematical formulas can be applied to correct for temperature deltas. Direct infiltration method will not be discussed further. The second approach of inducing a pressure differential to measure airflow is the standard and what has been adopted by the industry. Feustel states that the most accurate results are obtained at high pressure differentials that are unnatural to building operation. This is because exposing the zone to artificially high pressures activates leakage areas and overpowers the effects of environmental

factors, such as wind and stack effect (Urquhart, Richman, & Finch, 2015). Induced pressure differential method is referred to as blower door testing.

The literature available suggests that there are two main methods of performing blower door testing on a MURB to address party wall leakage. The first method uses a single blower door fan and measures the pressure differentials in adjacent units as proposed by Nylund's Method (Nylund, 1981). Nylund's Method is based on the theory that the amount of pressure differential caused to an adjacent unit by inducing a pressure differential on a test unit can be calculated to estimate party wall airflow. In 1990 the zone pressure diagnostics method was developed for single family application to detect air leaks into adjacent enclosed areas outside of the air barrier, such as the attic, knee walls and garage (D. Bohac, 2002). This concept was further developed by Lstiburek (2000) as the inverse method that is calibrated with the building and analytical model, and further developed by Richman (year), as a method to quantify airflow between attached dwellings through pressure measurements.

A second approach to quantifying air leakage characteristics in MURBs is using multiple blower doors to create pressure boundaries between zones. Lagus & King (1986) tested this method by performing both tracer gas measurements and multi-fan measurements on the same dwellings and verified that the method is accurate. Love (1987) also verified the use of multiple blower doors against Nylund's Method on 14 attached dwellings. The concept is based on the theory that if you depressurize two adjacent zones to the same pressure differential the party wall separating the zones will be pressure neutralized and eliminate flow through the assembly; air requires a pressure differential to cause airflow through an assembly. The difference of the blower door test done without pressure neutralizing and with represents the leakage through the party wall. Pressure neutralization testing has been referred to with different names throughout its

development, but in this study it will be referred to as the guarded blower door method (Ueno & Lstiburek, 2015). For the remainder of the literature review, the guarded blower door method will be discussed.

3.2 Previous Case Studies

The concept of guarded blower door testing was developed from the desire to quantify and separate air leakage from the exterior and leakage from adjacent dwellings. Without any standards dictating testing procedures for multi-zone buildings, the testing procedures have largely been developed by researchers and academics. These methods can be applied to most applications where multiple zones are identified and is applicable to the typologies defines in this study. There is limited research available on the use of this method and significantly less available on the specific typology of semi-detached and row homes; a great deal of the research effort has been focused on low and high rise apartment settings where there are dwellings surrounding a suit on multiple sides.

In 2003 Sherman and Chan published a report titled “Building Airtightness: Research and Practice”. The intent of this report was to perform a large literature review on published articles related to airtightness in buildings. Three typologies, single-family, multi-family, and non-residential buildings, was explored. The report highlights that there is a much larger amount of information and data available on the air leakage characteristic in single-family dwellings than in multi-family dwellings. There was 23 recent studies (1980 – 2003) on air leakage of multi-family dwellings reviewed and of the 23, only 4 focused on the air leakage of row homes. Although similar studies have been done since this report was published, it highlights the lack of research for this typology. The report summarizes that the leakage rates of 7 to 52% was reported by (Lagus & King, 1986), (Reardon, Kim, & Shaw, 1987), (Love & Sherman, 1990), and (Cornish et al.,

1989). These are all pioneering studies in the field of guarded blower door testing that highlighted the significance of party wall air leakage in row homes.

Lagus and King (1986) performed air tightness testing on a total of 24 naval housing units in Norfolk, Virginia and Pensacola, Virginia. The housing units were row-homes in six blocks of four units. Both the tracer gas method, complying with ASTM E 741-83, and guarded blower door method, complying with SATM E 779-81, was used to measure the air tightness of the units. In Norfolk, the resulting data showed that the tracer gas dilution method yielded leakage areas that were two to three times larger than the results from the guarded blower door testing. In Pensacola, and the data was opposite with the tracer gas yielding slightly higher leakage areas than the guarded blower door method. The Sherman air leakage model was used to calculate the leakage area using tracer gas and although the wind speed and direction data was available there was no attempt at incorporating that data into the analysis. Results from tracer gas testing provide data for only the specific environmental conditions it was tested under and therefore leave room for uncertainty. The guarded blower door method was performed by inducing the same pressure on either side of the test suit in attempt to “eliminate or at least minimize cross-apartment leakage”. The resulting data showed an average party wall leakage contributing 24% of the total flow, with a flow rate ranging from 7% to 24%.

Love and Sherman (1990) used the guarded blower door method to analyze party wall air leakage in 24 row homes, complying with CAN/CGSB 149.10. The row homes are located in Calgary, Alberta and built between 1965 and 1982 using light-weight wood construction. Similar to Lagus and King, fans were installed in adjacent suits and operators communicated via walkie-talkie to induce the same pressure in those suits during testing. Resulting data indicates that between 17 to 52% of the total leakage is through the party all, with an average of 37%. When

comparing the results to the results from Lagus and King (1986), it's suspected that the percentage of airflow through the party wall is much greater because overall the envelopes tested in Calgary were tighter, causing the party wall to be the path of least resistance under induced pressurization.

Bohac et al. (2007) focused on the reduction in airflow between units in various MURBs pre- and post-retrofit with the intention of reducing second-hand tobacco smoke being transmitted between dwellings. The study measured airflow using the guarded blower door method on a duplex, 8-plex, 12-plex, 138-unit, 11-storey, and 4-storey. Given the typology of this research report, only the duplex, 8-plex, and 12-plex will be analyzed because they are in a row-home configuration. These are all wood-frame construction built between mid-1930's to 1970. Prior to the retrofit the average whole-building leakage flow rate was 1431 CFM₅₀ and the guarded test results showed that an average of 485 CFM₅₀ was through the party wall; 34%. Under depressurization, a smoke pencil and infrared camera was used to detect leaks and measures for sealing was undertaken. Ventilation systems were also upgraded for reduced losses in ducts and at penetrations. After the retrofit process the party wall air leakage was on average reduced to 409 CFM₅₀; 29%.

Dentz and Conlin (2012) performed guarded blower door testing on six row-home units (not in the same development) with the intent of obtaining real data on the amount of air that leaks through the exterior envelope and through interior party walls for the purpose of analyzing cost savings of retrofits. Details of the guarded testing is limited in the report, but the average leakage through party walls is 12% of the total air flow. The authors warn that the guarded data must be analyzed with caution because the party walls are far more connect to the exterior than they are to the interior. In one instance, the guarded testing resulted in zero reduction of airflow

suggesting that the party wall is so connect to the exterior that guarding the adjacent unit does not stop airflow from occurring where the party wall is connected to the exterior envelope.

Ueno and Lstiburek (2015) conducted an in-depth analysis on the air leakage characteristics, with focus on the party walls, in a row-home consisting of five dwellings. It was recognized that party wall air sealing has been an area of difficulty for builder in the past, so experimental methods were used on these row homes to test for party wall air leakage improvement, as well as envelope sealing methods. Improved air sealing techniques included:

- Sealing of interior top and bottom plates (caulking or spray latex sealant)
- Sealing party wall at attic separation with spray foam
- Sealing top plate of garage connection to party wall with spray foam
- Butyl tape seal from bottom of exterior sheathing to foundation, over exposed area of party wall at envelope connection, over wood ledger/blocking at foundation, and from the top of exterior sheathing to top plate.

Units were built with selective upgrades to compare the air leakage results against units built with conventional methods, however, it was found that the buildings didn't perform as expected and one of the improved units performed worse than a conventional unit. Exterior tapered sheathing was expected to be a large contributor in reducing overall air leakage, but conclusions were made that although the sheathing air tightness was improved other leaks existed that didn't allow for improved overall results. Average total air leakage is 4.9 ACH₅₀; average end unit leakage is 3.9 ACH₅₀, average middle unit leakage is 5.6 ACH₅₀. The guarded results show an average of 16.2% reduction when eliminating party wall air flow. End units show an average of 11.5% reduction and the middle units showed an average of 19.3% reduction. To further the speculations of Dentz and

Conlin (2012) that the party wall may be well connected to the exterior, the author had the same speculations and performed a series of pressure measurements to test this theory. The data suggests that during the guarded testing air flow between the units is not fully eliminated because the party wall is well connected to the “tucked in” garage on the main floor, allowing air to be drawn through the party wall.

Holton and Prah (Holton & Prah, 2005) suggest that party wall in row homes could be a source of heat loss caused by venting into the attic. This causes negative impacts on energy efficiency and results in ice damming. A factor that accelerates this issue is the air space that is often detailed in a party wall cavity, and the authors question whether this air space is necessary for fire performance. Lowe et al. (2007) studied this issue further and provided empirical evidence suggesting that air movement through the party wall can be a significant heat loss mechanism. Blocking is typically installed at floor penetrations and similar details but the air flow is driven by stack effect and the pressure differential allows for air to bypass through any small gaps. Another detail that exaggerates the issue is that the detail where the party wall intersects into the ceiling the party wall shaft is blocked by mineral wool firestopping; this is not an air barrier. The infrared images collected by Holton and Prah indicate that there is significant heat loss.

Conclusions from this literature review conclude that party walls in all MURBs are a source of air leakage. Data collected suggests that the amount of leakage is dependant on the type of construction used, materials used, and details at specific intersections. Typologies need to be further analyzed with larger sample sizes to draw conclusions on the party wall leakage characteristics of that typology and further analyzed to study the leakage characteristics associated with the details that have been used on critical details/intersections. Two of the studies reviewed suggest that guarded testing may not fully eliminate air flow through the party wall because of

connectivity to the exterior through the envelope. Further research needs to be done in this area to quantify the airflow that is occurring through these intersections and verify the validity of guarded testing. Additionally, further research should be conducted to quantify airflow within the party wall assembly that is venting through the top of the assembly into the attic space.

3.3 Literature Review Summary

Of the two different types of applicable airtightness testing through induced pressurization, pressure measurements and flow measurements, using blower door fans to read flow measurements is the most applicable for this research project. To further this, the guarded blower door method used to create pressure neutralization boundaries between zones is an accepted method of quantifying party wall air leakage. There is also a large body of knowledge on guarded blower door testing to support this research project and similar case studies that have used this method allowing for comparison between studies.

Previous research reports and case studies have produced results on party wall air leakage characteristics in semi-detached and row homes. Pioneering studies began in the late 1980's and early 1990's highlighting that party wall air leakage is occurring in buildings and can pose occupant discomfort and health concerns. In these early studies, the data shows that approximately 7% to 52% of total leakage is through the party walls. More recent studies show averages of 34%, 19% and 12% total leakage through party walls.

There is a large body of knowledge on single family air leakage characteristics, less knowledge on air leakage characteristics in MURBs, and even less knowledge on semi-detached and row-housing dwelling typologies. With speculation that the OBC will be moving towards

mandatory airtightness testing, it's critical that these typologies are understood so the collected data can properly be analyzed.

4.0 Methodology

Testing was performed using Minneapolis Model 3 blower door fans. Collection of Century homes data used both DG500 and DG700 pressure gauges with readings recorded manually by fan operators. Modern homes data was collected and logged digitally using DG700 gauges that were controlled using the software TECLOG3.

All tests were conducted in general accordance with CAN/CGSB-149.10-M86 *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method* (CGSB, 1986). The preparation for this type of testing includes sealing all intentional openings in the envelope to highlight leakage through the construction assemblies. The Energy Conservatory, manufacturers of equipment used in this study, produced a document titled *Blower Door Application Guide: Beyond Single Family Residential* (Brennan, Clarkin, Nelson, Olson, & Morin, 2014) that provides an in-depth overview of multi-blower door setups and controlling the fans with an automated system, TECLOG3. This guide provided assistance in understanding the technical aspect of performing guarded blower door testing and was used in conjunction with CAN/CGSB-149.10-M86 to perform the testing.

Century homes data was previously collected by Richman and Labbe (2013). This unpublished data on twenty-eight dwellings was analyzed for the purpose of this study. Modern homes data including twenty-one dwellings was performed for the purpose of this study. Century homes were all semi-detached dwellings constructed of double wythe brick masonry, with the

exception of one triplex. Modern homes were a combination of semi-detached, row-home, and stacked row-home all constructed of light-weight wood frame. Party wall details of Century homes is not known because construction drawings were unavailable and destructive diagnostics were not an option but it is assumed that all party wall assemblies were the same. Section 4.1.2 has details that show the specific party wall details of the Modern homes.

After the data collection period, an analysis was conducted based on the reporting metrics defined in this report. The two data sets are analyzed individually and then analyzed against each other

4.1 Test Specimen Selection

The intent of this research is to test a small sample size of the two building typologies in Toronto. The original set of data collected was done on an older housing stock, hereafter referred to as Century homes, and the recent data collected was done on new housing stock, hereafter referred to as Modern homes (Jermyn, 2014). Although the sample size will not be a fair representation of the Toronto housing stock, it will provide insight to the air leakage characteristics of that typology and allow for future research. Unpublished data on old was provided through previous efforts conducted by Labbe and Richman [2013] in collaboration students from Humber College. This data set contains testing on 14 pairs of semi-detached single-family dwellings constructed between 1890 and 1920.

4.1.1 Century Homes

Earlier mentioned, the Century home data was collected through the efforts of Richman & Labbe (2013). The data and information provided on this data set will be reported as previously

recorded and then analyzed in this study. Fourteen pairs of semi-detached Century homes tested were constructed of double-whythe solid brick masonry between the years of 1890 to 1920. Dwellings were obtained through a public call for volunteers in select Toronto neighbourhoods with many semi-detached Century homes.

Construction drawings were not available for the homes due to their age, but the buildings are describes as being all duplexes, except for one triplex. The units all have full basements with rectangular first and second floors and third floor lofts. Many of the units had additions on the back of the house constructed of light-weight wood construction. Common with the exterior walls, party walls are constructed with double-whythe solid brick masonry. A cross-

Figure 1 Double-Whythe party wall assembly

section of the common party wall in this typology is depicted in Figure 1. On the top and bottom of the row courses the space is filled with grout and the space between the rows separating the two sides of the wall is often left as an air cavity, however unintentional grout can fall into the void during the brick laying process. Grout installed between the rows of brick is intended to attach the bricks to each other and create a monolithic surface, acting as an air barrier. It was not noted if the party walls tested had interior finished, such as drywall or plaster.

A summary of the Century home geometry is seen below in Table 3. A variety of homes were tested with a floor area ranging from 90 m² to 254 m², and an average of 184 m². The percentage of the total surface area that is party wall is relatively similar except for the middle unit of the triplex which has approximately double the party wall surface area.

Century Home Characteristics Summary

Dwelling Code	Floor Area (m ²)	Building Volume (m ³)	Surface Area with Party Wall (m ²)	Surface Area of Exterior Wall (m ²)	Surface Area of Party Wall (m ²)	Party Wall / Total Surface Area (m ²)	Unit Type
1A	171	454	440	315	125	28%	End
1B	178	459	427	312	115	27%	End
2A	254	664	565	426	139	25%	End
2B	203	537	483	344	138	29%	End
3A	193	504	454	339	115	25%	End
3B	188	488	424	308	116	27%	End
4A	185	489	432	323	110	25%	End
4B	195	522	446	332	114	26%	End
5A	180	467	443	330	114	26%	End
5B	177	469	435	311	124	29%	End
6A	203	493	381	284	97	25%	End
6B	203	493	381	284	97	25%	End
7A	196	517	442	322	120	27%	End
7B	193	478	437	240	198	45%	Middle
7C	176	441	412	332	80	19%	End
8A	212	540	455	335	121	26%	End
8B	204	540	447	327	120	27%	End
9A	90	236	257	193	64	25%	End
9B	98	242	256	195	61	24%	End
10A	208	530	466	345	121	26%	End
10B	208	527	469	349	121	26%	End
11A	134	340	355	262	93	26%	End
11B	138	365	362	267	95	26%	End
12A	204	556	469	385	85	18%	End
12B	219	550	459	378	82	18%	End
Min	90	236	256	193	61	18%	
Max	254	664	565	426	198	45%	
Mean	184	476	424	313	110	26%	
Std. Dev.	36	95	66	53	28	5%	

Table 3 Century Home Geometry Summary

4.1.2 Modern Homes

Modern data was collected with technical support and equipment provided by BlueGreen Consulting Group. A concern with the process of collecting data on semi-detached Century dwellings was the difficulty in obtaining volunteer homeowners to participate in the testing as well as scheduling the testing between multiple homeowners. To collect data on Modern dwellings the approach was to contact construction developers and offer the guarded blower door testing

with the agreement that a report is provided to them summarizing the results of the air tightness testing in their buildings. Data was collected from four different developments and will be referred to as development 13 & 14, 15, 16, and 17

Table 4 is a summary of the Modern home building characteristics. Similar to Century

Modern Homes Characteristics Summary							
Dwelling Code	Floor Area (m ²)	Building Volume (m ³)	Total Surface Area (m ²)	Surface Area of Exterior Wall (m ²)	Surface Area of Party Wall (m ²)	Party Wall / Total Surface Area (m ²)	Unit Type
13A	185	510	459	289	170	37%	End
13B	185	510	459	289	170	37%	End
14A	185	510	459	289	170	37%	End
14B	185	510	459	163	296	64%	Middle
14C	185	510	459	289	170	37%	End
15A	242	647	508	381	127	25%	End
15B	244	655	486	231	255	52%	Middle
15C	203	543	471	206	265	56%	Middle
16A	169	455	382	235	147	38%	End
16B	150	398	400	174	226	57%	Middle
16C	150	398	400	174	226	57%	Middle
16D	150	398	400	272	128	32%	End
17A	198	381	372	226	146	39%	End (S)
17B	108	266	276	133	143	52%	End (S)
17C	108	266	276	133	143	52%	End (S)
17D	184	354	354	158	196	55%	Middle (S)
17E	99	244	258	85	173	67%	Middle (S)
17F	99	244	258	85	173	67%	Middle (S)
17G	184	354	354	158	196	55%	Middle (S)
17H	99	244	258	85	173	67%	Middle (S)
17I	99	244	258	85	173	67%	Middle (S)
Min	99	244	258	85	127	25%	
Max	244	655	508	381	296	67%	
Mean	162	411	381	197	184	50%	
St. Dev.	46	131	87	84	46	13%	

Table 4 Modern Home Characteristics Summary

homes the floor area range is 99 m² to 244 m² with an average of 162 m². This data set contains row homes and stacked row-homes, so the percentage of party wall area is greater at 50% average.

Development 13 & 14 is a three-storey duplex and triplex constructed on the same plot of land in Toronto. Construction was completed in 2014 and all units were occupied at the time of testing in 2017. All five units were tested unguarded and guarded as diagnostic work being performed by BlueGreen Consulting Group. The homeowners wish for the identity of the building to remain anonymous, therefore the exact location of the building and pictures have been excluded.

Figure 2 is a detail of the typical party wall constructed on Development 13 & 14. As seen in Figure 2, there is a 1” air gap in the centre of the wall cavity with specifications for firestop and blocking at each floor intersection. An area of concern with this detail is where the party wall meets the roof; this is the only building tested that has a flat roof. Based on the literature, stack effect can cause hot air to rise through the air cavity in the party wall and if inadequate air sealing and insulation is not installed at the top of the party wall this will not only be a source for heat loss but additional a high-risk area for condensation accumulation. Only depressurization was conducted on this series of testing.

Development 15 is a three-storey five-plex constructed in Markham, Ontario in 2017. Two of the five units were occupied and the occupants didn’t want to participate in air tightness testing so three units were tested. This project is part of a new subdivision with hundreds of new homes

and the three units tested are show rooms, so they were all fully finished and furnished. The guarded data collected from unit C doesn't represent a properly guarded test because it was only guarded on one side against unit B. Data from the guarded test on unit C will still be analyzed to quantify the party wall air leakage through one of the two walls.

Figure 3: Development 15 street view

Both pressurization and depressurization was conducted on Development 15, however, the results from pressurization are abnormal. The results from pressurization will be discussed in the next section.

Party wall details were not obtained for this development, but a section view, seen in Figure 4, indicated that the details are similar to those seen at Development 13 & 14. Both consist of 2x4 wood stud with fiberglass batt insulation but the location of fire-rated gypsum wall board and size, if any, of the air space is unknown.

Figure 4: Development 15 Party Wall Section View

Development 16 is a two-storey four-plex located in Caledon, Ontario and was finished construction in 2017. This development was built by a not-for-profit construction company that uses volunteer staff for majority of the on-site construction.

Figure 5: Development 16 Street View

Figure 7: Development 16 Exposed Party Wall

Figure 6: Development 16 Party Wall - Envelope Detail

Like typical blocking and firestopping at party wall floor intersections, the party walls are also blocked where they are exposed to the exterior envelope as seen in Figure 6. Beside this four-plex is a six-plex that is being built to the same specifications. Figure 7 is an image showing the party wall to envelope detail at the top of the first floor and shows that in this particular unit the party wall on the second floor does not align with the party wall on the first floor. This could cause abnormal airflow through this assembly and could jeopardize the fire-rating of this assembly.

Development 17 is a three-storey fifteen-plex located in Markham, Ontario and was finished construction in 2017. Of the fifteen units in this complex, only nine were tested because of the lack of equipment available to test the entire block at once. In hindsight the remaining 6 units could have been tested after the initial testing of the nine units was complete but time was a very limiting factor for this testing. Testing could only be scheduled for a Sunday and the units were being turned over to occupants in the following days.

The layout of Development 17 was outside the original scope of work because unlike any of the other buildings tested this building has stacked units. It was decided to proceed with testing because performing guarded testing will still produce party wall air flow data for analysis. **Error! Reference source not found.** depicts the layout of the floorplan. Unit A is the width of the building from the front façade to the back

Figure 8: Development 17 Layout

on the main floor and has a below grade crawlspace with the same footprint. Unit B faces the front

façade of the building on the second and third floor and is half the width of the building. Unit C mirrors Unit B and faces the back façade.

Figure 9: Development 17 Front Facade

The party wall at Development 17 is similar to the other party walls that are seen in the other developments tested. Unique to this assembly is that staggered strips of gypsum board have been installed on the interior of the wall where the 1" air cavity is to hold the batt in place. The party wall section detail in Figure 10 shows that where the party wall aligns with the roof trusses there is no additional mineral wool or firestopping installed at the top of the assembly.

Figure 10: Development 17 Party Wall Detail

4.2 Blower Door Testing

The second series of testing done on new buildings was done to closely replicate the previous testing on Century homes [Richman and Labbe]. Fan depressurization was conducted in general accordance with CAN/CGSB-149.10-M86 *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method* (CGSB, 1986). The testing standard states that “this is a method for the determination of the airtightness of building envelopes. It is not a method for determining the actual air leakage which occurs through a building envelope under the influence of wind and buoyancy pressures of the operation of heating and ventilation systems”. The concept that differentiates this method from similar methods, such as ASTM E779-03 *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, is that intentional openings in the envelope are sealed prior to testing therefor isolating leakage through just the construction assemblies. Intentional openings include kitchen range hood fans, bathroom exhaust fans, ventilation systems, ect.. that intentionally introduce a hole into the construction assembly with the purpose of moving air (or gas fumes). Plumbing service penetrations are not addressed because they are already technically sealed; the municipal connection pipes are filled with water, not allowing any air to enter under (de)pressurization; the p-traps create a water seal not allowing any air to enter the ventilation stack under (de)pressurization. If there are any gaps that surround where the service penetration enters the envelope and breeches the air barrier, that is considered a fault in the air barrier and is captured in this testing. Using CAN/CGSB-149.10-M86 rather than ASTM E779-03 allows for a better representation of the actual construction quality rather than what to expect under normal operation conditions.

The testing method CAN/CGSB-149.10-M86 was selected as the guiding standard for this study and was modified with the method of guarded blower door testing. As described in the literature review, guarded blower door testing, also referred to as pressure neutralization method, is when two adjacent zones are depressurized simultaneously to the exact same pressure to eliminate a pressure differential between the adjacent zones and cancel airflow through the assembly connecting the zones. In theory, using the guarded blower door method in a semi-detached home effectively eliminated airflow through the party wall. Comparing the data of a dwellings unguarded and guarded blower door test allows for the quantification of airflow through the party wall.

Figure 11 Guarded Blower Door Testing Schematic

4.2.1 Procedure

Testing was conducted using Minneapolis Model 3 blower door fans and DG-700 pressure and flow gauges. In the testing done on Century homes the fans were controlled manually by operators with the fan controllers. In the testing done on Modern homes all fans were controlled centrally by connecting the DG-700 gauges and fan controllers to TECLOG3, a software developed by The Energy Conservatory used to log data and control multiple blower door fans in multiple zones. The “old” buildings were pressurized and depressurized against the exterior environment to produce data. The intent was to also pressurize and depressurize the new buildings, but logistical limitations, which will be discussed later in 7.0 Discussion allowed for only depressurization testing to be performed on developments A, C, and D.

All building envelopes were prepared as per the requirements of CAN/CGSB 149.01-M86 Table 2 *Preparation of Intentional Openings*. This included sealing all intentional openings in the building envelope such as sealing bathroom exhaust fans and kitchen range hood fans with a variety of cardboard, plastic, and painters tape. In all testing done in new buildings the mechanical systems included sealed furnace and water boiler systems that was turned off and HRV units that was turned off with mechanical dampers shut during testing.

CAN/CGSB 149.01-M86 Guarded Testing Procedure	
Phase	Procedure
Building Preparation	1. Turn off all mechanical equipment.
	2. Seal all intentional openings with tape and/or plastic.
	3. Visually inspect building for defects that could cause abnormalities in the data.
	4. Record building dimensions.
Setup	5. As per the manufacturers specifications, install a blower door fan in all units included in the testing (test suits and adjacent suits).
	6. Install the exterior refence pressure tap in a location that will not be affected by the turbulent flow of the fans or exposed to wind. If wind is present, it is best practice to install multiple exterior taps on each elevation of the building to create an average.
	7. Connect all manometers to one computer using CAT5 communication cable.
	8. Configure TECLOG3 data file according to test conditions and ensure all manometers have a proper connection.
	9. Prior to testing, record a baseline pressure differential as well as at the end of the test.
Testing	10. Perform multi-point pressure testing in a singular suit.
	11. Perform the same multi-point pressure testing in the test suit while maintaining the same pressure in the adjacent suits at the time of the readings.

Table 5 Guarded Testing Procedure

Although CAN/CGSB 149.01-M86 does not explicitly state in the test procedures whether the induced pressure difference is referring to depressurization or pressurization, the title quotes “Fan Depressurization Method” so it is assumed that the standard is referring to depressurization. Although CAN/CGSB 149.01-M86 does not specify to test with both depressurization and

pressurization, the old buildings were tested with both in steps 5-7 of the testing procedure listed above. Other standards, such as U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes, specify to perform both sets of test and report the average between the two. An argument can be made that taking an average of both is a better representation of the building envelope air leakage characteristics because the envelope is never under just depressurization or pressurization from the interior, especially in a mixed climate. A study by Sherman & Dickerhoff (1998) found that pressurization test report 9% higher leakage than depressurization test and that although there is no statistically significant difference, the flow exponent is different between the two tests. A difference in flow exponent and increased leakage rate gives reason to believe that leakage areas are “opening up” under pressurization. Hypothetically, if an exterior sheet membrane was installed over the sheathing, such as house wrap or Tyvek, that was not sealed properly at the seams a depressurization test could pull the defect tight against the building and reduce airflow whereas with a pressurization test this defect could be opened.

The intent was to depressurize and pressurize all units involved in the new building data collection process, but logistical issues only allowed for depressurization testing to be done on some units. Field testing buildings often involves multiple parties, such as tenants and construction companies, so the timeline isn’t always flexible to accommodate schedule extensions. Guarded blower door field testing also has the added complexity of scheduling between multiple tenants within the same development. With some technical difficulties encountered on site, depressurization testing took longer than expected and didn’t allow for pressurization testing to be completed within the scheduled testing period.

5.0 Analysis

5.1 Reporting Metrics

The geometry variable of every dwelling is different, so it should be noted that equivalent data is not as relevant as normalized data. The standard reporting metric of a residential dwelling has been ACH_{50} , representing the number of times the volume of air is replaced by unintentional air leaks under 50 pascals of pressure between the interior and exterior environment. This metric is valuable to compare change within the same dwelling, but is not as effective when comparing dwellings against each other. ACH_{50} is dependent on the building volume to surface area ratio and the equivalent leakage area. If a building of a specific volume to surface area ratio produces 4 ACH_{50} , another building with the same surface area, same equivalent leakage area, but lesser volume will produce a higher ACH_{50} because the amount of infiltrating air will remain the same while the amount of air it has to replace is reduced, resulting in a higher air change rate. Similar to ACH_{50} , equivalent leakage area is not comparable between buildings because the geometry changes.

For comparison between buildings, the equivalent leakage area and flow rate will be normalized, effectively providing data on the leakage characteristics of the construction assemblies. The most common method of reporting large building airtightness in Canada is Normalized Leakage Rate at a pressure differential of 75 Pa, however, for residential reporting this study will be reporting at a pressure differential of 50 Pa (CMHC, 2007). ACH_{50} and equivalent leakage area will be used for comparison on the same dwelling between non-guarded and guarded testing to indicate the ratio of air infiltration from the exterior and party walls.

5.1.1 Airflow Rate

The airflow rate will be stated in litres/second and used to determine the ACH and Normalized airflow rate.

5.1.2 Normalized Airflow Rate

Normalized airflow rate is the airflow rate divided by the surface area of the enclosure. This is the metric used by the Ontario Building Code for material compliance as an air barrier system as well as PHIUS+2015 for building certification. Moving towards a surface area leakage metric from an ACH allows large and small buildings to be compared for construction quality.

5.1.3 Air Change Rate per Hour (ACH)

As stated earlier in this section, the air change rate is the amount of times the volume of air in the building is replaced by infiltrating air under a certain pressure. Since blower doors began standard practice in the industry, 50 Pa is the most common pressure to report (Sherman 2004). The equation for ACH is (Richman 2015):

$$ACH_{50} = \frac{fc(Q)}{V}$$

Where: Q = Air Flow Rate @ 50 Pa [l/s]

V = Building volume [m³]

fc = Conversion factor from L/s to m³/h = 3.6

5.1.4 Leakage Area (EqLa)

Equivalent leakage area represents the sum of all leakage areas in the building in a sharp-edge orifice. It helps to understand the amount of leaks in the building by visualizing them in one square. From here, the n value will help understand if the leakage area is separated into many

smaller leaks across the building envelope or condensed into a few larger leaks that may be easier to detect and address. The equation for flow through a sharp-edge orifice is (RDH, 2013):

$$Q = A \cdot Cd \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}}$$

Where: Q = Airflow Rate per Unit Area [m³/s]

A = Orifice Area [m²]

Cd = Discharge Coefficient [dimensionless]

ΔP = Pressure Difference [Pa]

ρ = Density [kg/m³]

As per CGSB 149.10, the Discharge Coefficient is a constant 0.61 and the reference pressure reported is 10 Pa. The density of air can be assumed at 1.2 kg/ m³; however, the software used for calculations, Tectite, corrects to reflect the temperatures present during testing. To represent the EqLA, Eq..... can be rearranged to show (RDH, 2013):

$$EqLA \Delta \rho = \frac{Q \Delta \rho}{0.61} \cdot \sqrt{\frac{\rho}{2 \cdot \Delta \rho}}$$

5.1.5 Normalized Leakage Area (NLA)

Normalized leakage area (NLA) is the EqLA divided by the surface area of the building. The NLA provides insight to the construction quality allows for comparison between buildings. As discussed in section , some standards use NLA as the reporting metric for performance criteria. The equation for NLA is

$$NLA = \frac{EqLa}{A}$$

Where: NLA = Normalized Leakage Area [cm²/m³]

EqLa = Equivalent Leakage Area [cm²]

A = Surface Area [m²]

The concept with both equivalent leakage area and normalized leakage area is to separate and normalize the leakage areas to all 6 sides of the building, to the exterior enclosure and the interior party wall, as done by Finch et al. (2009). Normalizing the leakage area will allow the construction quality to be compared to standards, such as ASHRAE.

6.0 Results

6.1 Air Flow Rate

Century Homes				
Dwelling Code	Air Leakage Rate (L/s ₅₀)			
	Total	Exterior	Party	% Party
1A	879	765	114	13%
1B	919	751	168	18%
2A	2138	1378	760	36%
2B	1767	1757	9	1%
3A	1004	709	295	29%
3B	1105	865	240	22%
4A	1232	879	353	29%
4B	1609	1264	344	21%
5A	980	670	310	32%
5B	2055	1701	354	17%
6A	2533	2251	282	11%
6B	1207	924	283	23%
7A	1722	1218	504	29%
7B	1737	1113	624	36%
7C	1340	1048	291	22%
8A	937	855	82	9%
8B	1009	881	128	13%
9A	781	631	150	19%
9B	1219	1056	164	13%
10A	1834	1288	546	30%
10B	2226	1937	289	13%
11A	1437	1053	384	27%
11B	1545	1062	482	31%
12A	2000	1555	445	22%
12B	2086	1618	468	22%

Min	781	631	9	1%
Max	2533	2251	760	36%
Mean	1492	1169	323	22%
Std. Dev.	498	427	178	9%

Table 6 Century Homes Air Leakage Rate

Century Homes			
Dwelling	Norm. Air Leakage Rate (L/s ₅₀ /m ²)		
	Total	Exterior	Party
1A	2.00	2.43	0.92
1B	2.15	2.41	1.47
2A	3.78	3.24	5.46
2B	3.66	5.10	0.07
3A	2.21	2.09	2.56
3B	2.61	2.81	2.07
4A	2.85	2.72	3.22
4B	3.61	3.81	3.02
5A	2.21	2.03	2.73
5B	4.73	5.48	2.85
6A	6.65	7.92	2.92
6B	3.17	3.25	2.93
7A	3.89	3.78	4.19
7B	3.97	4.64	3.16
7C	3.26	3.16	3.66
8A	2.06	2.55	0.68
8B	2.26	2.70	1.07
9A	3.04	3.26	2.36
9B	4.76	5.41	2.67
10A	3.94	3.74	4.52
10B	4.74	5.56	2.40
11A	4.05	4.03	4.13
11B	4.26	3.97	5.08
12A	4.26	4.04	5.24
12B	4.54	4.29	5.73

Min	2.00	2.03	0.07
Max	6.65	7.92	5.73
Mean	3.55	3.78	3.00
Std. Dev.	1.12	1.36	1.51

Table 7 Century Homes Normalized Air Leakage Rate

Data from the Century homes shows that the average leakage rate is 1492 L/s @ 50 Pa.

The exterior leakage rate is the results of the guarded test and the interior is extrapolated through deduction.

Modern Homes				
Air Leakage Rate (L/s @ 50 Pa)				
Dwelling	Total	Exterior	Party	% Party
13A	650	361	289	44%
13B	597	386	211	35%
14A	647	382	265	41%
14B	743	375	368	50%
14C	697	363	334	48%
15A	938	700	238	25%
15B	944	510	434	46%
15C	983	--	--	--
16A	455	405	50	11%
16B	450	336	114	25%
16C	523	382	141	27%
16D	385	327	58	15%
17A	343	189	154	45%
17B	323	218	105	33%
17C	355	217	138	39%
17D	472	227	245	52%
17E	362	167	195	54%
17F	450	176	274	61%
17G	459	--	--	--
17H	365	--	--	--
17I	404	--	--	--

Min	323	167	50	11%
Max	983	700	434	61%
Mean	550	337	213	38%
Std. Dev.	208	135	108	14%

Table 9 Modern Homes Air Leakage Rate

Modern Homes			
Norm. Air Leakage Rate (Lps/m ² @ 50 Pa)			
Dwelling	Total	Exterior	Party
13A	1.42	1.25	1.70
13B	1.30	1.34	1.24
14A	1.41	1.32	1.56
14B	1.62	2.30	1.24
14C	1.52	1.26	1.96
15A	1.85	1.84	1.87
15B	1.94	2.21	1.70
15C	2.09	--	--
16A	1.19	1.72	0.34
16B	1.13	1.93	0.50
16C	1.31	2.20	0.62
16D	0.96	1.20	0.45
17A	0.92	0.84	1.05
17B	1.17	1.64	0.73
17C	1.29	1.63	0.97
17D	1.33	1.44	1.25
17E	1.40	1.96	1.13
17F	1.74	2.07	1.58
17G	1.30	--	--
17H	1.41	--	--
17I	1.57	--	--

Min	0.92	0.84	0.34
Max	2.09	2.30	1.96
Mean	1.42	1.66	1.17
Std. Dev.	0.30	0.42	0.51

Table 8 Modern Homes Normalized Air Leakage Rate

Data from the Modern homes shows an average leakage rate of 550 L/s @ 50 Pa; a 63% reduction from the Century homes. Similar to data from the Century homes, the exterior data is the results of the guarded testing and the interior data is extrapolated. Tables .. and ... have blank cells because only part of the party wall(s) were guarded therefore not representing a fully guarded test. The total values for those units have been included since they provide insight on the leakage characteristics of the building typology.

6.2 Air Change Rate

Century Homes				
Dwelling Code	Air Change Rate (ACH ₅₀)			
	Total	Exterior	Party	% Party
1A	7.0	6.1	0.9	13%
1B	7.2	5.9	1.3	18%
2A	11.6	7.5	4.1	36%
2B	11.8	11.8	0.1	0%
3A	7.2	5.1	2.1	29%
3B	8.2	6.4	1.8	22%
4A	9.1	6.5	2.6	29%
4B	11.4	9.0	2.5	21%
5A	7.6	5.2	2.4	32%
5B	15.8	13.0	2.7	17%
6A	18.5	16.4	2.1	11%
6B	8.8	6.8	2.1	23%
7A	12.0	8.5	3.5	29%
7B	13.1	8.4	4.7	36%
7C	10.9	8.6	2.4	22%
8A	6.2	5.7	0.5	9%
8B	6.7	5.9	0.9	13%
9A	11.9	9.6	2.3	19%
9B	18.2	15.7	2.4	13%
10A	12.5	8.8	3.7	30%
10B	15.2	13.2	2.0	13%
11A	15.2	11.2	4.1	27%
11B	15.2	10.5	4.8	31%
12A	13.0	10.1	2.9	22%
12B	13.6	10.6	3.1	22%
Min	6.2	5.1	0.1	0%
Max	18.5	16.4	4.8	36%
Mean	11.5	9.0	2.5	22%
Std. Dev.	3.6	3.2	1.2	9%

Table 10 Century Homes Air Change Rate

Data from the Century homes shows that the average air change rate per house at 50 Pa is 11.5 ACH₅₀. The exterior rate represents the results from the guarded testing when party wall

leakage is eliminated, and the interior is extrapolated. An average of 22% of the total infiltrating air is entering through the party wall(s).

Modern Homes				
Air Change Rate (ACH ₅₀)				
Dwelling	Total	Exterior	Party	% Party
13A	4.6	2.6	2.0	44%
13B	4.2	2.7	1.5	35%
14A	4.6	2.7	1.9	41%
14B	5.3	2.7	2.7	50%
14C	4.9	2.6	2.4	48%
15A	5.2	3.9	1.3	25%
15B	5.3	2.8	2.5	47%
15C	6.5	--	--	--
16A	3.6	3.2	0.4	11%
16B	4.1	3.0	1.0	25%
16C	4.7	3.5	1.3	27%
16D	3.5	3.0	0.5	15%
17A	3.2	1.8	1.5	45%
17B	4.4	2.9	1.4	33%
17C	4.8	2.9	1.9	39%
17D	4.8	2.3	2.5	52%
17E	5.3	2.5	2.9	54%
17F	6.7	2.6	4.1	61%
17G	4.7	--	--	--
17H	5.4	--	--	--
17I	6.0	--	--	--
Min	3.2	1.8	0.4	11%
Max	6.7	3.9	4.1	61%
Mean	4.8	2.8	1.9	38%
Std. Dev.	0.9	0.5	0.9	14%

Table 11 Modern Homes Air Change Rate

Data from the Modern homes shows an average air change rate per house at 50 Pa is 4.8 ACH₅₀; a 58% reduction from the Century homes. Similar to the Century data, the exterior wall area is the result of guarded testing and the interior is extrapolated. An average of 38% of the total infiltrating air is entering through the party walls(s); a 16% increase from the Century homes.

6.3 Leakage Area

Century Homes				
Dwelling Code	Equivalent Leakage Area (cm ² @ 10 PA)			
	Total	Exterior	Party	% Party
1A	1557	1423.0	134.0	9%
1B	1252	1517.0	-265.0	-21%
2A	2592	1986.0	606.0	23%
2B	2486	3560.0	-1074.0	-43%
3A	1365	1025.0	340.0	25%
3B	1537	1310.0	227.0	15%
4A	1723	1288.0	435.0	25%
4B	2267	1801.0	466.0	21%
5A	1352	981.0	371.0	27%
5B	3327	2640.0	687.0	21%
6A	3840	3558.0	282.0	7%
6B	1505	1379.0	126.0	8%
7A	2548	1461.0	1087.0	43%
7B	2452	1394.0	1058.0	43%
7C	2943	1551.0	1392.0	47%
8A	1286	1434.0	-148.0	-12%
8B	1461	1232.0	229.0	16%
9A	1211	835.0	376.0	31%
9B	1850	1537.0	313.0	17%
10A	2641	1575.0	1066.0	40%
10B	3411	3067.0	344.0	10%
11A	2063	1439.0	624.0	30%
11B	1886	1553.0	333.0	18%
12A	3086	2697.0	389.0	13%
12B	2461	1314.0	1147.0	47%

Min	1211.0	835.0	-1074.0	-43%
Max	3840.0	3560.0	1392.0	47%
Mean	2164.1	1742.3	421.8	18%
Std. Dev.	760.9	755.7	508.8	21%

Table 13 Century Homes Equivalent Leakage Area

Century Homes				
Dwelling	Norm. Leakage Area (cm ² /m ² @ 10 PA)			
	Total	Exterior	Party	% Party. Diff
1A	3.54	4.51	1.07	--
1B	2.93	4.86	-2.31	--
2A	4.59	4.67	4.35	--
2B	5.15	10.33	-7.77	--
3A	3.01	3.02	2.95	34%
3B	3.63	4.26	1.96	34%
4A	3.98	3.99	3.97	3%
4B	5.08	5.43	4.09	3%
5A	3.05	2.98	3.26	41%
5B	7.66	8.50	5.54	41%
6A	10.08	12.52	2.92	55%
6B	3.95	4.85	1.30	55%
7A	5.76	4.54	9.04	--
7B	5.61	5.82	5.35	--
7C	7.15	4.67	17.50	--
8A	2.82	4.28	-1.23	--
8B	3.27	3.77	1.91	--
9A	4.71	4.32	5.90	13%
9B	7.22	7.88	5.11	13%
10A	5.67	4.57	8.82	68%
10B	7.27	8.80	2.85	68%
11A	5.82	5.50	6.72	48%
11B	5.20	5.81	3.51	48%
12A	6.57	7.01	4.59	67%
12B	5.36	3.48	14.04	67%

Min	2.82	2.98	-7.77	3%
Max	10.08	12.52	17.50	68%
Mean	5.16	5.61	4.22	41%
Std. Dev.	1.80	2.34	4.92	24%

Table 12 Century Homes Normalized Leakage Area

On average the Century homes tested have an average equivalent leakage area of 2161 cm² at 10 Pa. On multiple instances the exterior leakage area is greater than the total, extrapolating the interior leakage area to be negative, which is theoretically impossible. Theoretically the interior

leakage area should read the same on both sides of the wall, however, % Int. Diff states the amount of discrepancy between the two.

Modern Homes					Modern Homes			
Equivalent Leakage Area (cm ² @ 10 Pa)					Normalized Leakage Area (cm ² @ 10 Pa)			
Dwelling	Total	Exterior	Party	% Party	Dwelling	Total	Exterior	Party
13A	992.1	507.9	484.2	49%	13A	2.16	1.76	2.85
13B	914.1	634.2	279.9	31%	13B	1.99	2.19	1.65
14A	978.0	558.4	419.6	43%	14A	2.13	1.93	2.47
14B	1123.5	566.9	556.6	50%	14B	2.45	3.48	1.88
14C	1029.0	510.8	518.2	50%	14C	2.24	1.77	3.05
15A	1292.8	999.7	293.1	23%	15A	2.54	2.62	2.31
15B	1310.3	702.5	607.8	46%	15B	2.70	3.04	2.38
15C	1359.9	--	--	--	15C	2.89	--	--
16A	681.9	599.7	82.2	12%	16A	1.79	2.55	0.56
16B	561.4	336.0	225.4	40%	16B	1.40	1.93	1.00
16C	809.4	382.0	427.4	53%	16C	2.02	2.20	1.89
16D	585.5	464.2	121.3	21%	16D	1.46	1.71	0.95
17A	488.7	257.2	231.5	47%	17A	1.31	1.14	1.59
17B	455.7	321.7	134.0	29%	17B	1.65	2.42	0.94
17C	494.2	285.1	209.1	42%	17C	1.79	2.14	1.46
17D	710.1	398.7	311.4	44%	17D	2.01	2.52	1.59
17E	498.4	254.8	243.6	49%	17E	1.93	3.00	1.41
17F	625.6	184.9	440.7	70%	17F	2.42	2.18	2.55
17G	705.8	--	--	--	17G	1.99	--	--
17H	512.0	--	--	--	17H	1.98	--	--
17I	572.1	--	--	--	17I	2.22	--	--

Min	456	185	82	12%	Min	1.31	1.14	0.56
Max	1360	1000	608	70%	Max	2.89	3.48	3.05
Mean	795	469	329	41%	Mean	2.05	2.27	1.79
Std. Dev.	296	203	160	14%	Std. Dev.	0.41	0.57	0.72

Table 15 Modern Homes Equivalent Leakage Area

Table 14 Modern Homes Normalized Leakage Area

Modern homes had an average equivalent leakage area of 795 cm² at 10 Pa. Unlike data from the Century homes there are no negative values representing the interior leakage area. The ratio of interior leakage to exterior closely correlated with the ratio of interior to exterior air leakage.

Comparison of Century and Modern Average Values						
	Typology	Air Leakage Rate (L/s ₅₀)	Norm. Air Leakage Rate (L/s ₅₀)	Air Change Rate (ACH ₅₀)	EqLA (cm ² @ 10Pa)	Norm. EqLA (cm ² @ 10Pa)
Total	Century	1492	3.55	11.5	2164.08	5.16
	Modern	550	1.42	4.8	795	2.05
Exterior	Century	1169	3.78	9.0	1742.28	5.61
	Modern	337	1.66	2.8	469	2.27
Party	Century	323	3.00	2.5	421.8	4.22
	Modern	213	1.17	1.9	329	1.79
% Party	Century	22%	--	22%	18%	--
	Modern	38%	--	38%	41%	--

Table 16 Comparison of Century and Modern Average Values

7.0 Discussion

7.1 Air Flow and Air Change Rate

The air flow rate and air change rate are closely correlated, with the percentage of interior leakage representing nearly the same amount in both Century and Modern homes. It's clear that overall the total leakage and unintentional air flow in Modern buildings has gone down significantly. While the total amount of infiltrating air through the party wall has decreased in Modern homes, the percentage of overall infiltrating air entering through the party wall has increased. This is similar to what Finch et al. (2009) and Gadgil et al. (2006) reported that a tighter

envelope may result in increased infiltration through the envelope. Overall the air flow rate was decreased by 63% in Modern homes.

Table 17 Century and Modern Average ACH50

When analysing the envelope and party wall(s) separately the envelope leakage rate was decreased by 71% and the party wall leakage rate was decreased by 34%. If both the envelope and party wall had decreased their leakage at the same rate it’s likely that the percentage of overall air entering through the party wall would have remained the same but the discrepancy between the improvement rates explains why the percentage of infiltration has increased. The increase means that occupants in Modern homes may be more affected by their neighbours in terms of odours and noise transferring through the party wall.

Unit 2B in the Century home data set shows that there is nearly zero air infiltration through the party all. Based on the literature review and data collected showing air leakage through all party wall assemblies, it’s unlikely that this data is accurate and it’s expected that either the data was either incorrectly collected or the building was abnormal. Similar results are seen in data collected by Dentz & Conlin (2012) with a guarded test resulting in 0% reduction of the total

leakage. A potential explanation, suggested by Dentz & Conlin (2012) and Ueno & Lstiburek (2015), is that the party wall may be well connected to the exterior either at the wall or attic interface and allow air to be pulled into and through the party wall even during guarded testing. However, this theory can't be confirmed for this data. There is also room for error when the fans are being operated manually. If the operators took measurements at a time when there was a pressure differential between the two units air would be able to enter through the party wall assembly and potentially resemble the single unit blower door test.

With different types of buildings tested under the Modern homes data set, the different types of building can be separated to be analyzed separately. The outlier in this data set is Development 18 because it introduces a greater party wall area ratio because the dwelling units are stacked and likely to result in a greater percentage of air flow through the party wall(s). When this data is removed, the average overall ACH_{50} through the party wall is reduced from 38% to 34%; which is still significant compared to the Century homes. In the data for Modern homes the data can also be split between end units and middle units. The end units identified are 13A, 13B, 14A, 14C, 15A, 16A, and 16D. The average total air change end units is 4.4 ACH_{50} with 2.9 ACH_{50} through the envelope and 1.4 ACH_{50} through the party wall. Middle units identified are 14B, 15B, 15C, 16B, and 16C. The average total air change for middle units is 5.2 ACH_{50} with 3.0 ACH_{50} through the envelope and 1.9 ACH_{50} through the party wall(s). Based on this data, middle units are 16% more leaky overall and have 37% of the infiltration air coming through the party walls whereas end units have 31%. This correlated with data collected by Ueno & Lstiburek (2015), who found that middle units had overall greater leakage and greater reduction during guarded testing when compared to end units.

Another point of discussion unrelated to party wall air leakage but more so related to whole building leakage and testing procedure is the difference between depressurization and pressurization when performing airtightness testing. Stated earlier, Howard & Dickerhoff (1998) suggest that pressurization will result in 9% higher ACH values. Century homes data was presented as an average between depressurization and pressurization testing that was conducted. During single unit testing the pressurization data is an average of 3% higher than depressurization and during guarded testing there is a 0% difference between depressurization and pressurization during guarded testing. The original scope of work included conducting both depressurization and pressurization testing on all Modern homes, but testing was more labour intensive than planned and there was only time to perform depressurization testing on majority of the dwellings. Only depressurization data was presented in the results section. Development 16 is the only set of Modern homes that was tested with depressurization and pressurization and the results for single unit tested is below:

Development 15 Single-Unit ACH ₅₀			
Dwelling	Depressurization	Pressurization	% Difference
A	5.2	10.4	50%
B	5.3	10.5	50%
C	6.5	12.7	48%

Table 18 Development 15 Depressurization vs. Pressurization

The discrepancy between depressurization and pressurization on Development 16 is large; approximately 49% higher during pressurization. An investigation revealed that during pressurization there was a large amount of air flowing through the weep holes of the brick façade. Although destructive investigation would be required for verification, it's suspected that the house wrap is not properly taped at the seams and during pressurization the seams are billowed allowing air to exit. Under depressurization, these seams would be pulled tight to the sheathing and greatly

reduce airflow through these leakage areas. This example raises the question as to if both depressurization and pressurization should be standardized for building airtightness testing because if only depressurization was conducted, this relatively major envelope flaw would otherwise be undetected.

The normalized leakage rate is derived by dividing the leakage rate by the building surface area. The century homes average full-building normalized leakage rate (NLR) is 3.55 L/s₅₀/m² of surface area. Data from the guarded testing shows that the NLR for the exterior envelope is 3.78 L/s₅₀/m² and the party wall NLR is 3.00 L/s₅₀/m². These results show that the leakage rate through the envelope is 21% greater than leakage through the party wall. For modern homes the full-building NLR is 1.42 L/s₅₀/m², the exterior envelope NLR is 1.66 L/s₅₀/m² and the party wall NLR is 1.17 L/s₅₀/m². In the modern homes data the party wall is 30% more leaky than the party wall.

Table 19 Century and Modern Average Normalized Leakage Rate

It's likely that the issue of infiltrating air through the party wall will be address through code changes and meeting the criteria for certifications. If buildings are required to meet certain levels of airtightness, such as with PHIUS+2015, air leakage through the party wall will need to

be address and the industry will produce solutions. However, when retrofitting and restoring Century semi-detached homes the leakage through the party wall should be a higher concern. Unpublished data provided by BlueGreen Consulting Group shows the air leakage results of a semi-detached Century home that underwent an extensive envelope retrofit. Pre-retrofit the percentage of the air change rate associated with the party wall was 17%; post-retrofit the percentage of air change rate associated with the party wall was 46%. Although the overall ACH, and corresponding energy demand, of the building was reduced, the occupants are more exposed to the effects of increased party wall infiltration.

7.2 Leakage Area

The equivalent and normalized leakage area was a desired reporting metric for this study, however, the data suggests that extrapolating the interior leakage area from the total and guarded testing may not be an accurate metric.

Equivalent leakage area was derived through deduction, as done by Finch et al. (2009). The total ELA was calculated with a single dwelling test, the envelope ELA was calculated through the guarded test, and by deduction the party wall ELA was the difference between the two. However, this testing was done on a single unit and not on all units surrounding the dwelling. In theory, the calculated ELA on both sides of the same wall should be the same. Data collected from both Century and Modern homes suggest that the deduction method can't be used to accurately state the ELA of the envelope and party wall(s).

All Century dwellings tested were semi-detached, except for dwellings 7A, 7B and 7C. As seen in Table 12 there are multiple occurrences of the envelope leakage area being larger than the

total leakage area, and applying the deduction method causing the party wall leakage area to be a negative value. This is theoretically impossible and invalid data. A potential explanation is that there was a slight pressure difference between the two dwellings during the guarded testing allowing for airflow into a unit during pressurization and causing a reverse airflow through the party wall to cause a negative area value. Where negative values weren't present, the % Int. Diff. column states the difference of the interior normalized leakage areas, which theoretically should be the same. On average, there was a 41% difference of the interior normalized leakage reported on either side of the wall.

The issue of negative leakage area values was not present in the Modern data; its suspected that the use of an automated fan controller and prolonged time-averaged data resulted in more accurate values. The computer automation system, TECLOG3, automatically adjusts the fans to remain relatively steady within a small fraction of the target pressure differential. It's not expected that the same degree of accuracy would be expected from multiple people controlling the fans manually and controlling over walkie talkies to take a reading when they hit the target pressure. Using TECLOG3 also makes it easier to take longer time-averaged pressure readings and visually see when an abnormality, such as strong wind, is occurring and impacting the results.

Reviewing the Century data revealed that in some instances there are discrepancies in the data collected during the guarded testing, meaning that the pressures were not at the same pressure on either side of the assembly. What exaggerates the problem is when the baseline pressure is different in the suits. For example, in a semi-detached if Suit A has a baseline of 0.0 Pa and Suit B has a baseline of -2.0 Pa when they are both depressurized to -50 Pa Suit A will be at -50 Pa but Suit B would be corrected to -48 Pa to account for the baseline pressure. If there is a discrepancy where the reading in Suit A is collected at a higher pressure than Suit B, the discrepancy will be

made larger through baseline correction and potentially not fully pressure neutralize the assembly. This is likely what caused negative values to occur since it's possible that airflow was still occurring through the assembly during guarded testing.

Only two of the twenty-one units test was part of a semi-detached building so the % Int. Diff column was not included, but the data has been analysed for accuracy of ELA readings. The only semi-detached dwelling in the data set is dwelling 13A and 13B. The interior wall of 13A equals 484.2 cm² through the deduction method and 13B equals 272.9 cm²; this is a 44% difference between the two values, which is similar to data from the Century homes. The other dwellings part of this development is the triplex of units 14A, 14B, and 14C. If the ELA data was accurate for these dwellings, the interior ELA from 14B should be the sum of the interior ELA from 14A and 14C. The interior ELA of 14B is 556.6 cm²; the interior ELA of 14A is 419.6 cm² and the interior ELA of 14 C is 518.2 cm² equaling a total of 937.8 cm². Similar to previous data, there is a 41% discrepancy between the theoretical and actual values.

Development 15 was also analyzed for better understanding of the ELA's recorded. On this site sequential testing was performed meaning that Units A, B, and C were all tested individually, Unit B was guarded against just A, Unit B was guarded against just C, and then all units were guarded simultaneously. Sequential testing provides useful data that allows for the air leakage characteristics to be defined for the envelope as well as each of the two party walls separately. Below is a summary of the sequential testing:

DEPRESSURIZATION			
Dwelling	Equivalent air-leakage area ELA ₁₀ (cm ² @ 10 Pa)		
	Full	Exterior	Interior
Unit 2, Single	1310.3	N/A	N/A
Unit 2, Guarded	1310.3	702.5	607.8
		SUM	607.8

Table 21 Dwelling 15B Guarded Data

DEPRESSURIZATION			
Dwelling	Equivalent air-leakage area ELA ₁₀ (cm ² @ 10 Pa)		
	Full	Exterior	Interior
Unit 2, Guard 1	1310.3	990.5	319.8
Unit 2, Guard 3	1310.3	1048.6	261.7
		SUM	581.5

Table 20 Dwelling 15B Sequential Guarded Testing

Table 21 shows the results of the single and fully guarded test and Table 20 shows the results of the sequential guarded testing. In Table 20, aUnit B guarded against A represents the leakage area of the party wall separating the two dwellings; the same is for when Unit B is guarded against C. The sum of the two leakage areas is 4% less than the total interior leakage area calculated by the fully guarded test. Table 14 shows that the interior ELA of dwelling 15A is 293.1 cm²; 8% less than reported in the sequential testing of dwelling 15B.

7.3 Sources of Error

Field testing is complex in nature and there's a variety of potential sources of error during data collection. These errors may go unnoticed unless a building is tested more than once and shows discrepancy in the data. If it appears there are errors in the data it may also be difficult to locate the source of error because there could be multiple sources; every building will have a different set of parameters. Airtightness testing research has developed some potential sources of error, which will be discussed below.

The environmental conditions can impact the data collection; namely wind. Wind exerts pressures on the building that can cause irregular readings. For example, if a strong gust of wind was present on the north façade during depressurization the airflow through that assembly may have increased from a reading taken at the same pressure with no wind present. For this reason, testing during calm days with minimal gusts of wind is ideal. CAN/CGSB 149.10 even recommends that testing is not conducted when wind speeds greater than 20 km/h are present. ASTM E779 states that ideal testing conditions are between 0 to 6 km/h. During testing on Development 16 the wind speeds ranged from 26 to 32 km/hr and the development was in an open field with minimal surrounding structures or vegetation to break the wind. The wind created noise while collecting data, meaning the interior to exterior pressure delta wasn't staying consistent and the fans were having to adjust

to compensate. Likely as a function of wind, the “n” value dropped below the theoretical value of 0.5 during the testing. It would have been ideal to test on a day with less wind but the testing schedule for this development could not be adjusted.

‘n’ is the flow exponent in the power law equation with a theoretical limit of 0.5 and 1.0. A value of 0.5 would represent laminar flow (one large hole) and 1.0 would represent turbulent flow (many small holes) (Hutcheon & Handegord, 1995). A low ‘n’ value was encountered on a number of occasions, both during single unit testing as well as guarded. The values were never below 0.45, but it still indicated that there is a source of error in the data. Data was checked during and immediately after testing for each set of test, so when a low ‘n’ value occurred the test was rerun until adequate data was collected. It’s likely that wind was a factor of error as well as the nature of guarded testing in itself. Wind will introduce error as it will directly effect the environmental and interior pressures. The reason that the nature of guarded testing may cause errors in the data is because during a guarded test the party wall, in theory, is pressure neutralized not allowing any airflow to occur. However, its possible that there may be small amounts of air entering and being drawn through to the other side of the guarded assembly creating an uncommon situation when compared to standard single unit testing. This highlights the importance of maintaining the pressures on either side of the party wall assembly at the exact same pressure.

7.4 Recommendations

After performing numerous field tests on lightweight wood frame party walls, there are several recommendations that can be made. The detailing is very important in these assemblies and is potentially more difficult than exterior envelope assemblies because of the lack of accessible space. Increasing the airtightness of the exterior envelope can be achieved through methods, such

as applying a peel-and-stick membrane to the exterior sheathing, but the same cannot be applied to the party wall, especially because of the fire-rated criteria. This assembly should not only be treated as a fire rated assembly, but also as an air barrier assembly. As an air barrier assembly, the air barrier should be continuous, but it also means that the transition between components must be planned for continuity. The recommendations

Figure 12 Party wall envelope detail air barrier disconnect

include reducing the airflow into the assembly as well as compartmentalizing the interior of the assembly. As details are unique for every project, this section won't review specific details but will more so make general recommendations.

The first recommendation is to stop air from entering the assembly. This can be accomplished at the party wall to envelope interface as well as at the party wall to conditioned living area interface. Figure 6 and Figure 7 from Section 4.1.2 have been used again for reference. Figure 13 is an image of the party wall exposed at the exterior and Figure 12 is the correlating detail. The fire rated gypsum

Figure 13 Exposed party wall

is located on the interior side of the party wall assembly with fire-rated gypsum against the envelope perimeter. Although a house-wrap will be

applied to the exterior sheathing, if, and when, air breaches the house-wrap air barrier the party wall shown in Figure 13 is likely to allow air to enter the assembly. This connection should be detailed to be more airtight at the envelope interface with a material more durable. As per the current Ontario Building Code the party wall is not considered part of the air barrier system because it does not separate conditioned space from unconditioned space. Argument can be made that dwellings should be compartmentalized with an environmental separator, such as an air barrier. A general rule of thumb in construction and architecture practice is that a red line should be able to be drawn continuously around any section view of construction drawings to represent a continuous air barrier system. Looking to Figure 12, the air barrier for the envelope is the exterior house-wrap membrane and the party wall air barrier would be the interior gypsum meaning that there is a disconnect in the air barrier system. If an exterior air barrier system is used, it is recommended that a layer of fire-rated gypsum is moved to the interior of the assembly so the air barrier system could be connected at the envelope interface and properly compartmentalize the dwellings. If an interior air barrier system is implemented, the current location of the party wall gypsum may be sufficient if it is treated as an air barrier system.

Data from the field testing indicates that airflow is occurring between the dwellings through the party wall, so it's important that detailing is implemented to limit airflow from occurring. Areas of concern will be mechanical penetrations as well as floor joist intersections. Products are

available for mechanical penetration fire-sealing, which also act as an air seal, so these products should be employed and inspected for quality control during the construction phase.

Floor joist intersections are more challenging because it's a system that must be planned and phased properly for adequate air sealing.

Figure 14 is a party wall floor joist detail. Red dots have been added on just the left side of the

Figure 14 Party wall floor joist detail

detail to show the transitions that should be sealed to

reduce airflow. The main areas of concern are at the headers and the framing bottom plate. These are wood to wood connections that will expand and contract over time creating voids that will allow airflow to occur. The top plate is not a concern because the drywall connecting the wall to the ceiling is plastered, effectively creating a continuous seal. At the bottom plate the drywall

doesn't often connect with the sheathing to allow for the installation of flooring, so the bottom plate to sheathing connection is exposed.

Figure 15 is a slightly different detail that seen in Figure 14 with gypsum located on the interior of the assembly

Figure 15 Party wall interior sealing

so additional caulking has been added to seal the connection between the gypsum and bottom plate.

In the details reviewed there is no prescription for caulking to be installed at the headers in the party wall. This is a wood to wood connection that will allow for leakage unless a sealant material is applied. This is a critical detail for air leakage and is likely where the bulk of the leakage is occurring in these party wall assemblies. Although Figure 16 is a

Figure 16 Sill plate air sealing best practice

joist to foundation detail, it is applicable to party walls. Caulking is applied to the top and bottom of the rim joist to seal the wood to wood connection. This is a practice that should be standard in party wall construction to reduce airflow through the assembly.

The final recommendation in party wall construction to reduce air leakage is to compartmentalize the party wall between floors. In light weight wood frame construction party walls, it's common for there to be an airspace on the interior of the assembly. Previously stated in the background, there is research that shows heat loss as a function of air leakage occurring at the top of the party wall into the attic, which indicates that stack effect is occurring in the wall assembly. The taller the air shaft is in height the greater the stack effect is creating high pressures that force conditioned heated air out of the building. Stack effect in party walls could also be a mechanism that draws air into the assembly from dwelling units and transfer the air between units. The stack effect can be reduced by creating an airtight seal at each floor. In Figure 14 fire-rated gypsum can be seen between the two floor joists headers. However, this detail is not often adequately air sealed creating a very tall air cavity in the party wall assembly. Applying a fire-rated air sealing material, such as caulking, to the top and bottom of this fire blocking and sealing

it to the adjacent wood members would effectively compartmentalize the party wall between each floor and reduce the stack effect within the assembly.

Diagnostics and identification of party wall air leakage sources was not performed in this body of research; just quantification of air flow. Now that this research has indicated that air flow is occurring through our party wall assemblies, future research would include further quantification of party wall air leakage characteristics as well as qualitatively identifying the main sources of leakage. Field testing methods of qualitatively identifying air leakage include smoke pencils and infrared scanning. During depressurization a smoke pencil will be able to visually identify where air is infiltrating because it will cause turbulent flow of the smoke. Additionally, the building could be filled with theatrical smoke and pressurized so smoke could be seen infiltration on the other side of the party wall. Infrared scanning only works when there is a temperature differential and the greater the differential the better the readings. Dwellings on either side of a party wall are commonly similar temperature, meaning that under normal operating conditions an infrared scan would not be an effective method of locating air leakage sources. During cold weather, the adjacent suit could have its heating system turned off and windows open to neutralize the interior temperature with the exterior temperature. Under these conditions, the test suit could be depressurized and an infrared scan would be able to identify sources of air flow through the party wall assembly.

8.0 Conclusions

Building air leakage through the exterior is associated with the energy required to condition the uncontrolled infiltrating air whereas air leakage through party walls is associated with occupant health and comfort. Air leakage through the party wall transfers contaminants between dwellings, such as stale air, tobacco smoke, cooking odours, and noise. With current industry standard airtightness testing methods the quantity of air coming through the envelope and the party wall can be differentiated. This can cause inaccurate calculations of building energy modelling and potential occupant discomfort if adjacent dwellings are well connected. With the importance of differentiating the air leakage being highlighted through this paper, it's important that the industry moves towards creating a testing standard suitable for testing MURBs.

The literature review suggests that there is very little information available on the air leakage characteristics of MURBs, and even less available for semi-detached and row-home typologies. Different methods of testing existing and have been in development by academics and industry since the early 1980's, but the guarded blower door method seemed to have the most data and literature to support the methodology. From the literature reviewed on semi-detached and row-home dwellings, the party wall(s) air leakage accounts for roughly 7 to 52% of the total leakage; this is similar to the data that was collected for this study.

The purpose of this research study was to expand the current body of knowledge associated with airtightness testing in MURBs, specifically quantifying party wall air leakage in Toronto semi-detached and row-home dwellings. Both semi-detached Century homes, constructed between 1890 to 1920 of solid brick masonry construction, and row-home Modern homes, constructed between 2014 to 2017 of lightweight wood framed construction, was tested with single unit and guarded blower door testing. This testing methodology allowed for the quantification of air leakage through

the envelope and party wall(s) in these dwellings, and also allowed for comparison against the two typologies.

Semi-detached Century dwellings had an average of 11.5 ACH₅₀ with 22% of the air flow occurring through the party wall. Within this data set the ACH₅₀ values varied greatly from a range of 18.2 to 6.2. These homes were built well before a building code was established in Ontario so the concept of a continuous air barrier was not as much of a concern as with Modern homes. Research is suggesting that as the envelope is made to be more airtight the overall percentage of airflow through the party wall is increase; it is important that an airtightness strategy is employed for party walls is retrofit work is being done to the envelope.

Semi-detached and row-home Modern homes had an average of 4.8 ACH₅₀ with 38% of the air flow occurring through the party wall. The ACH₅₀ range was lesser than seen in the Century homes with a max value of 6.7 and a min value of 3.2. None of the units tested met the airtightness target of 2.5 for semi-detached homes set by the OBC SB-12. Modern homes will be more energy efficient with the correlated energy savings with air infiltration reductions, however, with a greater percentage of the overall airflow occurring through the party wall(s) occupants will be most susceptible to the associated contaminations.

The results presented show there is a significant amount of air leakage occurring through party walls in Toronto semi-detached and row-home dwellings; old and new. As the building code and industry standards move forward and increase the airtightness of dwellings, it's critical that airtightness strategy is employed for party walls to ensure that occupants health and comfort is maintained.

8.1 Future Research

This study quantified the air leakage characteristics in two Toronto typologies while separating envelope leakage from party wall leakage. Further research is still required in this field to further the understanding air leakage in MURBs. Topics that should be expanding from this study are:

- Increase the sample size of low-rise residential MURBs testing for airtightness.
- Identify and analyze the components in the party wall assembly that are contributing towards air leakage.
- Quantify air leakage through the party wall at envelope connections; namely the exterior wall and roof.
- Identify accurate methods of producing and interior party wall ELA.

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WITHDRAWN / RET

Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method

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NATIONAL STANDARD OF CANADA

**DETERMINATION OF THE AIRTIGHTNESS OF BUILDING
ENVELOPES BY THE FAN DEPRESSURIZATION METHOD**

Prepared by

Canadian General Standards Board

Approved by

Standards Council of Canada

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Note: CGSB also recognizes the contributions of D. Saum of Infiltec Inc. to the development of this standard.

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CANADIAN GENERAL STANDARDS BOARD

DETERMINATION OF THE AIRTIGHTNESS OF BUILDING ENVELOPES BY
THE FAN DEPRESSURIZATION METHOD

1. SCOPE AND FIELD OF APPLICATION

- 1.1 This is a method for the determination of the airtightness of building envelopes. It is not a method for determining the actual air leakage which occurs through a building envelope under the influence of wind and buoyancy pressures or the operation of heating and ventilation systems.
- 1.2 The method is applicable to small detached buildings (especially houses) but with appropriate modifications, it can also be used for other buildings or parts of buildings.

2. PRINCIPLE

A fan or fans are used to exhaust air from the building at rates required to maintain specified pressure differences across the building envelope. The air flows and the pressure differences are measured. The intention is to subject the complete envelope to a simultaneous and similarly directed air pressure. The flows are corrected to reference temperature and reference pressure. The relationship between flow and pressure difference is used to calculate the equivalent leakage area of the building envelope.

3. TERMINOLOGY

- 3.1 **Airtightness:** the degree to which unintentional openings in the building envelope have been avoided.
Building envelope: that portion of the heated structure which separates conditioned from unconditioned space and the soil.
Intentional opening: an opening in the building envelope deliberately made to fulfill a particular function.
- 3.2 Although the definition of each quantity symbol is usually included in the paragraph in which it appears, Table 1 provides a list of quantity definitions for those quantity symbols which are included in the body of the standard.

4. APPARATUS

4.1 Fan

- 4.1.1 The fan or fans shall have a total air flow capacity capable of producing a pressure difference of at least 50 Pa between the inside and outside of the building envelope. (Sufficient capacity for testing new detached houses may be about 1500 L/s and for older detached houses it may be about 2500 L/s.)
- 4.1.2 The fan shall have a variable speed control or a control damper in series with the fan.
- 4.1.3 The fan shall be calibrated in air flow units or be connected to an air flow metering system.
- 4.1.4 The accuracy of air flow measurement shall be $\pm 5\%$ of the measured flow rate.
- 4.2 **Pressure-measuring apparatus** — This device (e.g., a micromanometer) shall be capable of measuring pressure differences from 0 to at least 50 Pa. It shall have an accuracy of ± 2 Pa and shall only be operated within its calibration range.
- 4.3 **Thermometer(s)** — This device shall be used to measure temperature in degrees Celsius and it shall have an accuracy of $\pm 1^\circ\text{C}$.
- 4.4 **Sealing apparatus** — This apparatus shall be used to seal the fan into a window or a door.
- 4.5 **Pressure averaging and damping equipment**

- 4.5.1 **Pressure averaging container** — This device shall be suitable for connection of not less than four tubes from exterior pressure taps and shall be constructed as described in Appendix A.

- 4.5.2 **Capillary tubes** — A pressure averaging container shall not be required if capillary tubing, of dimensions corresponding to those in Table A-1 of Appendix A, is added to the outside ends of the tubes from the pressure taps on the exterior walls of the building (par. 6.1.12). The tubes from the outside pressure taps shall be manifolded together before connecting to the pressure measuring device.

5. LABORATORY CALIBRATION OF APPARATUS

- 5.1 All equipment shall be calibrated originally. Recalibrate all measuring devices when any major component is replaced.
- 5.2 Calibrate the air flow measuring device in accordance with the manufacturer's instructions or alternatively, calibrate it in accordance with Appendix B-1 and record this fact.
- 5.3 When the fan is calibrated, calibrate it in accordance with Appendix B-2.
- 5.4 Calibrate the pressure measuring device in accordance with the manufacturer's instructions or alternatively, calibrate it in accordance with Appendix B-3.

6. TESTING

6.1 Set-Up Procedures*

- 6.1.1 Measure and record the outdoor air temperature, t_o .
- 6.1.2 If par. 7.1.3 will be used to calculate corrected volumetric air flow rates at ambient test conditions, record the ambient atmospheric pressure, P_a . A report on the atmospheric pressure from the local weather station if not corrected to sea level, should normally be sufficient.
- 6.1.3 Include in the test all rooms which are heated to more than 10°C except rooms with separate ventilation (e.g., boiler room, enclosed furnace rooms and garages).
- 6.1.4 Switch off all fuel combustion equipment, exhaust fans, vented dryers and air conditioners.
- 6.1.5 Shut off all pilot lights on vented gas-fired appliances.
- 6.1.6 Prepare intentional openings as detailed in Table 2.
- 6.1.7 Remove or cover ashes in fireplaces. Check chimneys and furnace flues for excessive soot and do not perform the test if soot is likely to enter the building.
- 6.1.8 Open all interior doors except those to rooms which are not included in the test (par. 6.1.3).
- 6.1.9 Install the test apparatus such that air will be exhausted from the building. To eliminate the possibility of disturbance of the flow entering the nozzle when using a bell-mouthed nozzle apparatus, ensure that no obstructions are placed within one throat diameter away from the centre of the nozzle entrance as shown in Figure 1A. When using a blower door apparatus, ensure that no obstructions are placed within the width of the door and closer than three quarters of one fan diameter in front of the fan as shown in Figure 1B. Figure 2 shows the general arrangement of the apparatus during the test.
- 6.1.10 **Routine Inspection** — After setting up the apparatus, take the following steps to check all the measuring devices.
- 6.1.10.1 Visually inspect for various physical defects.
- 6.1.10.2 Visually inspect for proper installation in accordance with manufacturer's specification.
- 6.1.10.3 Inspect the levelling of devices which require this precaution (e.g., a manometer).
- 6.1.10.4 Ensure that all indicators are at zero settings.
- 6.1.11 Seal the joints between the apparatus and the envelope.

* It is recommended that the test not be conducted if the wind speed is greater than 20 km/h.

- 6.1.12 Attach the exterior pressure taps to the exterior walls of the building envelope such that all the square-cut ends point upwards or downwards. For detached residences, secure the exterior pressure taps at points at least 2 m above grade if possible, and at the horizontal mid-points of the principal exterior walls facing in each direction. See Figure 3 for the recommended locations of the exterior pressure taps on some common shapes of houses.
- 6.1.13 Protect the interior and exterior pressure taps from the influence of the fan.
- 6.1.14 When the building to be tested has walls, ceilings or floors common with rooms that are not included in the test but which are heated to more than 10°C, make provision to reduce the pressure in the adjacent rooms to match the pressure in the rooms under test at each test point.
- 6.1.15 For fireplace chimneys without a damper, perform the test with no sealing unless the leakage is so large that the test cannot be performed. In this case, seal the fireplace at the opening and report this matter as a deviation from the usual test procedure in the test report. (See par. 8.1, item n.)
- 6.2 Test Procedures**
- 6.2.1 Whenever a pressure reading is taken, it should be taken for a long enough time to be within ± 1 Pa of its stable value.
- 6.2.2 Seal the fan or fans and record the pressure difference across the envelope, $\Delta P_{O,i}$.
- 6.2.3 Remove all seals on the fan or fans and switch on the fan or fans.
- 6.2.4 Adjust the air flow to produce a pressure difference of 50 Pa across the envelope. (See par. 6.2.7.)
- 6.2.5 Adjust the pressure in any adjacent rooms (par. 6.1.14) to achieve a zero pressure difference across common partitions.
- 6.2.6 When conditions have stabilized, measure and record the air flow rate in litres per second (Q_m), the pressure difference (ΔP_m) in Pa and the intake air temperature at the fan in degrees Celsius (t_i).
- 6.2.7 Repeat par. 6.2.4 to 6.2.6 at pressure differences of 45, 40, 35, 30, 25, 20 and 15 Pa, in that order. For each test, the measured value of the pressure difference shall be within ± 2.5 Pa of the above specified pressure difference.*
- 6.2.8 Repeat par. 6.2.2 to measure the pressure difference, $\Delta P_{O,f}$.
- 6.2.9 Correct the ΔP readings in accordance with par. 7.5 and the Q_m readings in accordance with par. 7.4.
- 6.2.10 Verification of Data**
- 6.2.10.1 Using the corrected data from par. 7.4 and 7.5 determine the following in accordance with Appendix C:**
- the regression coefficients (C and n) and the correlation coefficient (r) of the fit of the data;
 - the percentage difference between the estimated air flow ($\hat{Q}_i$) and the measured air flow (Q_i) at each measured pressure difference (ΔP_i);
 - the relative standard error of $\hat{Q}$ at $\Delta P = 10$ Pa (which is also the relative standard error of ELA). (See par. 7.7.2.)
- 6.2.10.2 Repeat the entire test if any of the following conditions is not met;
- $0.50 \leq n \leq 1.00$
 - $r > 0.990$
 - $\left| \frac{\hat{Q}_i - Q_i}{Q_i} \right| < 0.06$ for all i ***
 - the relative standard error of $\hat{Q}$ at $\Delta P = 10$ Pa (or ELA) is less than 0.07.
- 6.2.11 When the purpose of the test is to show an increase in the airtightness of a building envelope as a result of sealing unintentional openings, perform the test as described both before and after the sealing work.

* A measurement of air flow rate at a pressure difference of 10 Pa may also be included.

** The C , Q_i and $\hat{Q}_i$ values determined in accordance with Appendix C are those under reference conditions.

*** The Q_i and $\hat{Q}_i$ values in this paragraph are those under reference conditions.

6.2.12 **Completion of the Test** — After the test:

- a. remove all seals applied in accordance with Table 2;
- b. reopen dampers as necessary;
- c. relight the gas pilot light.

7. **CALCULATIONS**

7.1 **General Description**

7.1.1 This method gives an equivalent leakage area (ELA), a C_r value (often used to obtain forced-air change rates) and an air flow rate which are constant for all test ambient conditions.

7.1.2 ΔP , C_r and Q_r are defined as follows:

ΔP is the corrected pressure difference across the building envelope and is in units of Pa.

C_r is a constant used to determine Q_r .

Q_r is a constant used to determine ELA.

7.1.3 The method described in this standard should be used to determine ELA, a constant C_r value and air change rates. If the actual outside air flow under test conditions is required, it can be determined using the following:

$$Q_a = Q_r \sqrt{\frac{101.325}{P_a} \frac{(t_o + 273.15)}{(20 + 273.15)}}$$

where: Q_a is the corrected outside volumetric air flow rate into the building at outdoor test conditions (L/s)

Q_r is as defined above (L/s)

P_a is the ambient atmospheric pressure (kPa) from par. 6.1.2

t_o is the outdoor air temperature (°C) from par. 6.1.1.

7.2 **Determination of the Area of the Building Envelope**

7.2.1 Use interior dimensions when determining the area of the building envelope.

7.2.2 Include all ceilings (flat or sloping), floors and walls (including doors and windows) that are correspondingly below, above and adjacent to unheated spaces and spaces heated to less than 10°C. For example, include:

- a. ceilings below unheated attics and roofs;
- b. basement floors and floors above unheated basements (or unheated portions thereof), cellars, crawl spaces, cold storage rooms, garages and floors exposed to the ambient environment such as floors above carports, floors of bay windows and floors of buildings (or parts thereof) supported above grade;
- c. exterior above grade and below grade walls and walls adjacent to unheated portions of basements, cellars, crawl spaces, cold storage rooms, unheated porches, garages and stairwells to basement entrances.

7.2.3 The area of the building envelope is the total area of all eligible ceilings, floors and walls.

7.3 **Determination of the Interior Volume Enclosed by the Building Envelope** — It is recommended that the interior volume enclosed by the building envelope be determined and recorded. Include the total volume of all rooms specified in accordance with par. 6.1.3.

7.4 **Correction of Air Flow Readings** — Correct each air flow reading for differences in the indoor, outdoor and calibration air temperatures in accordance with Appendix D.

7.5 **Correction of Pressure Difference Readings** — Using the following equation, correct each pressure difference reading, ΔP_m :

$$\Delta P = \Delta P_m - \frac{(\Delta P_{o,i} + \Delta P_{o,f})}{2}$$

- 7.6 **Determination of Correlation Coefficient** — Applying the procedure described in Appendix C to the corrected data, fit a curve of the form:

$$Q_r = C_r (\Delta P)^n$$

where: Q_r , C_r and ΔP are as defined in par. 7.1.2

n is the flow exponent and is dimensionless.

7.7 Calculation of Equivalent Leakage Area

- 7.7.1 The density of air at the reference conditions of $t_r = 20^\circ\text{C}$ and $P_r = 101.325 \text{ kPa}$, ρ_r , is:

$$\rho_r = \frac{P_r}{R (t_r + 273.15)}$$

where: ρ_r is in units of kg/m^3

$$\Delta P_r = 10 \text{ Pa}$$

R = gas constant for air = $0.287055 \text{ J/g}\cdot\text{K}$

P_r = barometric pressure under reference conditions (kPa)

t_r = reference temperature of outside ambient air ($^\circ\text{C}$)

Therefore:

$$\rho_r = \frac{101.325}{0.287055 \times 293.15} = 1.204097$$

- 7.7.2 Calculate the equivalent leakage area, ELA, using the following equation:

$$\text{ELA} = .001157 \sqrt{\rho_r} \cdot C_r \cdot 10^{n-0.5}$$

where ELA is in units of m^2

ρ_r is the air density at reference conditions, as provided in par. 7.7.1

C_r and n are determined in accordance with par. 7.6.

The above equation is based on the assumption that the leakage openings in the building envelope can be combined and represented by a single sharp-edged orifice.

7.8 Calculation of Normalized Leakage Area

When the purpose of the test is to compare the ELA of different buildings, it is recommended that the normalized leakage area, NLA, should be used. To calculate NLA, use the following equation:

$$\text{NLA} = \frac{\text{ELA}}{\left(\frac{\text{Area of the Building Envelope}}{\text{Envelope}} \right)} \times 10\,000$$

where: NLA is in units of cm^2/m^2

ELA is in units of m^2

Area of the Building Envelope is in units of m^2 .

8. TEST REPORT

- 8.1 The test report shall include the following information:
- The name and address of the company which conducted the test
 - The name of the tester
 - The address of the building under test
 - The date of test and the date of the report
 - The test conditions which include the outdoor temperature in degrees Celsius, comments on the wind speed, direction and variability
 - A description of the building envelope
 - The area in square metres of the building envelope

- h. The measured original instrument data (air flow metering device data), the corresponding pressure differences in pascals and the fan intake air temperatures in degrees Celsius
- i. The corrected air flow rates in litres per second at each corrected pressure differential
- j. Values for C_r and n
- k. The determined correlation coefficient, r
- l. The equivalent leakage area (ELA) in square metres
- m. When applicable, items h. to l. inclusive before and after sealing work
- n. Any deviation from the method prescribed.

8.2 It is recommended that the test report include the following:

- a. A sketch of the building under test showing the locations of the pressure taps and the location of the fan, if the building is of an unusual shape
- b. The ambient atmospheric pressure in kilopascals
- c. A plot of the measured air flow rates versus the corresponding pressure differences on log-log paper
- d. The interior volume in cubic metres enclosed by the building envelope
- e. The normalized leakage area (NLA) in square centimetres per square metre.

8.3 Specimen Test Report

It is recommended that the test report follow the format given in Appendix E.

TABLE 1

SYMBOLS

Quantity Symbol	Quantity Definition	SI Unit	Unit Symbol
C, C_r	a regression coefficient; a constant used to determine Q_r (Appendix C)	litres/second·Pascal ⁿ	L/s·Pa ⁿ
ELA	equivalent leakage area	metre ²	m ²
NLA	normalized leakage area	$\frac{\text{centimetre}^2}{\text{metre}^2}$	cm ² /m ²
n	a regression coefficient; flow exponent; a constant used to determine ELA (Appendix C)	—	—
P_a	ambient atmospheric pressure	kilopascals	kPa
$\Delta P_{O,i}$	initial pressure difference across the building envelope with the fan(s) <u>not</u> operating and sealed	Pascals	Pa
$\Delta P_{O,f}$	final pressure difference across the building envelope with the fan(s) <u>not</u> operating and sealed	Pascals	Pa
ΔP_m	measured pressure difference across the building envelope	Pascals	Pa
ΔP	corrected pressure difference across the building envelope	Pascals	Pa
P_r	barometric pressure under reference conditions (101.325 kPa)	kilopascals	kPa
Q_a	corrected volumetric air flow rate into the building at outdoor test conditions	litres/second	L/s
Q_m	measured air flow rate indicated by the flow measuring device before any corrections for the difference in the operating temperature and the calibration temperature	litres/second	L/s
Q, Q_r	corrected air flow rate (Appendix C)	litres/second	L/s
$\hat{Q}$	estimated air flow rate (Appendix C)	litres/second	L/s
r	correlation coefficient (Appendix C)	—	—
R	gas constant for air (0.287055 J/g·K)	joules/gram·Kelvin	J/g·K
t_o	outdoor air temperature	degrees Celsius	°C
t_i	intake air temperature at the fan	degrees Celsius	°C
t_r	reference temperature of outside ambient air (20°C)	degrees Celsius	°C
ρ_r	density of air at reference conditions	kilograms/metre ³	kg/m ³

TABLE 2

PREPARATION OF INTENTIONAL OPENINGS

fireplace flue	no preparation
fireplace	
— with damper	CLOSE
— with doors	CLOSE
— without damper	see par. 6.1.15
doors on enclosed furnace room*	CLOSE
fireplace combustion air intake damper	CLOSE
fuel fired furnace and/or stove flues	SEAL
fuel fired furnace and/or stove flues in enclosed furnace room*	no preparation
furnace combustion air intake	
— with damper	CLOSE
— without damper	SEAL
ventilation air intake	
— with damper	CLOSE
— without damper	SEAL
fuel fired hot water system flues	SEAL
floor drains	FILL
plumbing traps	FILL
exhaust fans	
— with motorized damper	CLOSE
— without motorized damper	no preparation
air to air heat exchangers designed to operate continuously	
— intake and exhaust openings	SEAL
other air to air heat exchangers	
— intake and exhaust openings, with motorized damper	CLOSE
— intake and exhaust openings, without motorized damper	no preparation
dryer vents	
— with exhaust diverter	WINTER POSITION
— with motorized damper	CLOSE
— without motorized damper	no preparation
windows and doors	LATCH
exhaust systems common to more than one unit	SEAL
window air conditioners	SEAL
attic hatch	CLOSE

* An enclosed furnace room is a room expressly built to contain a furnace and/or stove, with a combustion air intake to the outside of the building, and to prevent air flow to and from the remainder of the building.

A. Bell-Mouthed Nozzle Apparatus

— Top and Side View

— shaded area shall be free of obstructions.

c is the centre of the nozzle entrance.
d is the diameter of the throat of the nozzle.

B. Blower Door Apparatus

— Front View

d is the diameter of the fan.
w is the width of the blower door.

— Side View

— Shaded area shall be free of obstructions.

FIGURE 1

Area Which Shall Be Free of Obstructions

FIGURE 2

**The General Arrangement of the Equipment during the Test
Showing one Possible Air Flow Metering System**

NOTE:

1. The heavy dots indicate the recommended locations for the exterior pressure taps.

FIGURE 3
Recommended Locations for Exterior Pressure Taps

CONSTRUCTION AND CALIBRATION OF PRESSURE AVERAGING CONTAINER

A-1 CONSTRUCTION

To reduce the effect of pressure fluctuations from the four static probes placed on the outside walls of the building envelope, a pressure averaging container may be used. (See par. 4.5.2.) It shall be provided with sufficient line losses to result in an averaging of high frequency disturbances, to make reading of pressure easier and more reliable. The selected averaging time shall be in the order of 5 ± 1 s.

The equation relating the time constant of a tube/container system and its critical parameters, assuming adiabatic, laminar, capillary flow, is:

$$t^* = \frac{128}{\pi} \frac{\mu}{\gamma P} \frac{L \cdot V}{d^4}$$

where: t^* = time constant of the tube/container system (s)

μ = absolute viscosity of the air (Pa.s)

γ = specific heat ratio of air = 1.4

P = pressure (Pa)

L = tube length (m)

V = container volume (m^3)

d = tube inside diameter (m)

For a 5 s time constant, at room conditions, this reduces to:

$$L \cdot V = 9.16 \cdot 10^8 d^4$$

Table A-1 and Figure A-1 give the length versus diameter relationship for a 1 L ($0.001m^3$) container.

A 0.50 mm inside diameter by 57.3 mm long tube should be used.

A typical cylindrical configuration is shown in Figure A-2. Configurations other than this cylindrical one may be used as long as the container is sealed and rigid with an internal volume of 1 L.

A-2 CALIBRATION

Because the actual time constant is very sensitive to the value of the inside diameter of the tube, the following calibration procedure shall be undertaken.

1. Attach a length of tube to the container.
2. Seal all leaks except the pressure measurement tap.
3. Pressurize the container to greater than 50 Pa.
4. Uncap the damping capillary tube and record the pressure as the air flows out.
5. Calculate the time constant using the formula below:

$$t^* = \frac{-(t_2 - t_1)}{\ln \left(\frac{\Delta P_2}{\Delta P_1} \right)}$$

where: t_1 = time at which ΔP_1 is measured (s)

t_2 = time at which ΔP_2 is measured (s)

ΔP_1 = first (higher) pressure difference (Pa)

ΔP_2 = second (lower) pressure difference (Pa)

ln = natural logarithm

NOTE: $(t_2 - t_1)$ should be in the order of 5 s.

6. Shorten the tube and repeat steps 1 to 5 until a time constant of 5 ± 1 s is obtained.

7. Make all other tubes the same length and ensure they are from the same stock as that which was calibrated.
8. Ensure that the entrance and exit edges of the inside diameter of the tubes are sharp and clean.

TABLE A-1
Damping Tube Length VS Inside Diameter

(5 s time and 1 L container)

Tube Inside Diameter (mm)	Tube Length ⁽¹⁾ (mm)
0.4	23.4
0.5	57.3 ⁽²⁾
0.6	119
0.7	220
0.8	375
1.0	916

Note: (1) *Lengths should be confirmed by test.*

(2) *The 0.5 mm diameter by 57.3 mm long tube is recommended.*

FIGURE A-1

Damping Tube Length VERSUS Tube Inside Diameter

* Each of the tubes must be of the same length and must be cut from the same stock.

FIGURE A-2

**A Typical Cylindrical Configuration for a
Pressure Averaging Container**

CALIBRATION

Reference: Fan Engineering — Seventh Edition

— Published by Canadian Blower and Forge Co. Ltd in 1970.

B-1 PROCEDURE FOR CALIBRATION OF AIR FLOW MEASURING DEVICE

1. Install the air flow measuring device to be calibrated in the test set-up shown in Figure B-1.1. To eliminate the possibility of disturbance of the flow entering the nozzle when using a bell-mouthed nozzle apparatus, ensure that no obstructions are placed within 1 m of the front of the nozzle or any closer than 0.5 m away from all sides of the nozzle. Seal the joints.
2. Activate the fan and adjust the flow control damper to produce a desirable flow rate. (See step 8.)
3. Measure and record the air temperature (t_c) and atmospheric pressure (P_c) at the inlet of the device.
4. Perform a pitot static traverse across the horizontal diameter of the tube at the pitot traverse plane shown in Figure B-1.1 and at the horizontal pitot tube stations indicated in Figure B-1.2.
5. As in step 4 above, perform a pitot static traverse down the vertical diameter of the tube at the pitot traverse plane shown in Figure B-1.1 and at the vertical pitot tube stations indicated in Figure B-1.2.
6. Calculate the flow rate, Q , using the equation below:

$$Q = \frac{1}{N} \cdot \sum \sqrt{\frac{2}{\rho_c} \cdot P_{v_i}} \cdot \frac{\pi}{4} \cdot D^2 \cdot 10^3$$

where: N = total number of pitot tube readings

P_{v_i} = velocity pressure of the "i th" pitot tube measurement

ρ_c = density of air at inlet of the calibration apparatus (as calculated using the same equation as in par. 7.7.1)

D = diameter of the device

7. Measure and record ΔP as indicated in Figure B-1.1.
8. Repeat steps 2 to 7 for at least three more flow rates including the maximum flow rate of the fan. The flow rates selected shall be uniformly spaced within the range of zero to this maximum flow rate.
9. Determine the calibration curve for the air flow measuring device by plotting Q versus ΔP as shown in Figure B-1.3.

*See Appendix B-4.

FIGURE B-1.1

Test Set-Up for Air Flow Measuring Device Calibration

Reference: ASHRAE Handbook — 1985 Fundamentals

Published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.,
1791 Tullie Circle, NE, Atlanta, Georgia 30329, U.S.A.

FIGURE B-1.2

Pitot Tube Traverse for Round Tubes

FIGURE B-1.3

Typical Calibration Curve

B-2 PROCEDURE FOR CALIBRATION OF FAN

1. Construct an airtight test chamber with painted plywood walls reinforced with "two-by-four" studs and with suggested dimensions of 3 m, 2.5 m, and 2.5 m for length, width and height respectively. Caulk all joints.
2. Determine the leakage air flow rate of the test chamber, q_l , following the procedures described in pars. 6.2 to 7.6 inclusive and using the set-up shown in Figure B-2.1.
3. Plot q_l vs ΔP .
4. Install the fan and the flow measuring device as shown in Figure B-2.2.
5. Cover both the fan and the duct and set the ΔP reading on the pressure indicator to zero.
6. Remove the covers, install an appropriate orifice plate and set the damper position.
7. Adjust the fan r/min to obtain a pressure differential of 15 Pa and record the flow rate, Q , as measured by the calibrated flow measuring device.
8. Calculate the net flow rate, Q_n as follows;
$$Q_n = Q + q_l \text{ (at the measured } \Delta P \text{)}$$
9. Repeat steps 7 and 8 for pressure differentials of 20, 25, 30, 35, 40, 45 and 50 Pa.
10. Repeat steps 6 to 9 inclusive.
11. Develop calibration curves or an equation of Q_n versus r/min for various ΔP values (eg., Figure B-2.3).

FIGURE B-2.1

Measurement of Leakage Air Flow Rate of Test Chamber

FIGURE B-2.2

Calibration of Fan

FIGURE B-2.3

Typical Calibration Curve for a Fan

B-3 PROCEDURE FOR CALIBRATION OF PRESSURE MEASURING DEVICE

1. Connect the devices as shown in Figure B-3.1.
2. Close valve 3 and adjust valves 1 and 2 to obtain a pressure slightly greater than 50 Pa.
3. Open valve 3 gradually to its fully open position and record both ΔP_m and ΔP at uniform intervals.
4. Close valve 3 gradually to its fully closed position and record both ΔP_m and ΔP at uniform intervals.
5. Determine the calibration curve by plotting ΔP_m vs ΔP as shown in Figure B-3.2.

FIGURE B-3.1

Set-Up for Calibration of Pressure Measuring Device

FIGURE B-3.2

Typical Calibration Curve for Pressure Measuring Device

B-4 CONSTRUCTION AND LOCATION OF FLOW STRAIGHTENERS

Reference: Laboratory Methods of Testing Fans for Rating

- Published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) as Standard 51-1985
- Published by the Air Moving and Conditioning Association, Inc. (AMCA) as Standard 210-85
- Straighteners shall be used during calibration but their use in the general arrangement of the equipment during the actual test is optional. The downstream plane of the straightener shall be located between 5 and 5.25 duct diameters upstream of the plane of the Pitot traverse or piezometer station. The form of the straightener shall be as specified in Figure B-4.1. The dimension D is the inside diameter of a circular cross-section duct or the equivalent diameter of a rectangular cross-section duct with inside transverse dimensions of a and b where $D = \sqrt{4ab/\pi}$. The dimension y which is the thickness of the straightener elements, shall not exceed 0.005 D.

Reference: AMCA Standard 210-74
ASHRAE Standard 51-74

NOTE: All Dimensions shall be within $\pm 0.005D$
except y which shall not exceed $0.005D$.

FIGURE B-4.1

Flow Straightener

DETERMINATION OF THE FIT OF TEST DATA

If data has been collected at N corrected pressure differentials $\Delta P_1, \Delta P_2 \dots \Delta P_N$ giving corrected air flow rates $Q_1, Q_2 \dots Q_N$ respectively, the following procedure should be used to fit an equation of the following type:

$$Q = C \Delta P^n *$$

to the data, and to determine the correlation coefficient (r) and various other measures of the goodness of fit. Units of the terms in the equation are given in par. 6.2.6.

1. Calculate the following sums:

$$\sum_{i=1}^N Q_i^2 \ln \Delta P_i = Q_1^2 \ln \Delta P_1 + Q_2^2 \ln \Delta P_2 + \dots + Q_N^2 \ln \Delta P_N$$

$$\sum_{i=1}^N Q_i^2 (\ln \Delta P_i)^2 = Q_1^2 (\ln \Delta P_1)^2 + Q_2^2 (\ln \Delta P_2)^2 + \dots + Q_N^2 (\ln \Delta P_N)^2$$

$$\sum_{i=1}^N Q_i^2 \ln Q_i = Q_1^2 \ln Q_1 + Q_2^2 \ln Q_2 + \dots + Q_N^2 \ln Q_N$$

$$\sum_{i=1}^N Q_i^2 (\ln Q_i)^2 = Q_1^2 (\ln Q_1)^2 + Q_2^2 (\ln Q_2)^2 + \dots + Q_N^2 (\ln Q_N)^2$$

$$\sum_{i=1}^N Q_i^2 (\ln \Delta P_i) (\ln Q_i) = Q_1^2 (\ln \Delta P_1) (\ln Q_1) + Q_2^2 (\ln \Delta P_2) (\ln Q_2) + \dots + Q_N^2 (\ln \Delta P_N) (\ln Q_N)$$

$$\sum_{i=1}^N Q_i^2 = Q_1^2 + Q_2^2 + \dots + Q_N^2$$

2. Next calculate the following quantities:

$$s_{xx} = \left(\sum_{i=1}^N Q_i^2 \right) \left(\sum_{i=1}^N Q_i^2 (\ln \Delta P_i)^2 \right) - \left(\sum_{i=1}^N Q_i^2 \ln \Delta P_i \right)^2$$

$$s_{yy} = \left(\sum_{i=1}^N Q_i^2 \right) \left(\sum_{i=1}^N Q_i^2 (\ln Q_i)^2 \right) - \left(\sum_{i=1}^N Q_i^2 \ln Q_i \right)^2$$

$$s_{xy} = \left(\sum_{i=1}^N Q_i^2 \right) \left(\sum_{i=1}^N Q_i^2 (\ln \Delta P_i) (\ln Q_i) \right) - \left(\sum_{i=1}^N Q_i^2 \ln \Delta P_i \right) \left(\sum_{i=1}^N Q_i^2 \ln Q_i \right)$$

* The measured air flow rates (Q_m) are corrected to reference conditions in accordance with Appendix D. Therefore, the C, Q_i and Q_i values determined in accordance with Appendix C are those under reference conditions.

3. Calculate the best fit estimates of the regression coefficients, n and C:

$$n = \frac{S_{xy}}{S_{xx}}$$

$$C = \exp \left[\frac{\sum_{i=1}^N Q_i^2 \ln Q_i}{\sum_{i=1}^N Q_i^2} - n \frac{\sum_{i=1}^N Q_i^2 \ln \Delta P_i}{\sum_{i=1}^N Q_i^2} \right]$$

4. Calculate the correlation coefficient (r):

$$r = \sqrt{\frac{(S_{xy})^2}{S_{xx}S_{yy}}}$$

5. Calculate the estimated air flow, $\hat{Q}_i$, on the regression line for all measured ΔP_i :

$$\hat{Q}_i = C \Delta P_i^n$$

Then calculate the relative error of each estimate:

$$\frac{|\hat{Q}_i - Q_i|}{Q_i}$$

6. Calculate the standard error of estimate of Q on ΔP :

$$S_{y/x} = \sqrt{\frac{S_{yy} - n S_{xy}}{\left(\sum_{i=1}^N Q_i^2\right)(N-2)}}$$

Calculate the relative standard error of $\hat{Q}$ at $\Delta P = 10$ Pa ($\hat{Q}_{10}$):

$$\sqrt{\frac{S_{y/x}}{\sum_{i=1}^N Q_i^2}} \sqrt{1 + \frac{\left[\left(\sum_{i=1}^N Q_i^2\right) \ln 10 - \sum_{i=1}^N Q_i^2 \ln \Delta P_i\right]^2}{S_{xx}}}$$

7. For further independent use of the regression coefficients, calculate the standard errors

- a. for $\ln C$:

$$S_0 = S_{y/x} \sqrt{\frac{\sum_{i=1}^N Q_i^2 (\ln \Delta P_i)^2}{S_{xx}}}$$

Whence the standard error range for C is between $\exp(\ln C + S_0)$ and $\exp(\ln C - S_0)$

- b. for n:

$$S_1 = \frac{S_{y/x}}{\sqrt{\frac{S_{xx}}{\sum_{i=1}^N Q_i^2}}}$$

Whence the standard error range for n is $n \pm S_1$

AIR FLOW CORRECTIONS

D-1 GENERAL THEORY

The measured air flow rates (Q_m) need to be corrected for the differences in air density (ρ) between:

- the reference and calibration conditions, and
- the indoor air moving out through the measuring device and the outdoor air moving in through the leaks in the building envelope (the air flow of interest).

-
- In mass flow measuring devices (orifice plates, nozzles, venturis, pitot tubes, etc.);

$$Q \propto 1/\sqrt{\rho} \quad (\text{see Appendix B-1, par. 6}).$$

Because the calibration curve from Appendix B was used to obtain Q_m from the measuring device output;

$$Q_m = \frac{\text{constant}}{\sqrt{\rho_c}}$$

where ρ_c is the calibration air density.

The true air flow rate through the measuring device is

$$Q_i = \frac{\text{constant}}{\sqrt{\rho_i}}$$

where ρ_i is the indoor air density

$$\text{Thus } Q_i = Q_m \sqrt{\frac{\rho_c}{\rho_i}}$$

- Continuity of mass for compressible flow means

$$\rho Q = \text{constant}$$

Thus, the in-leakage air flow rate,

$$Q = Q_i \frac{\rho_i}{\rho_o}$$

where ρ_o is the outdoor air density

From par 7.7.1;

$$\rho \propto \frac{p}{t + 273.15}$$

Now the indoor and outdoor atmospheric pressures are essentially the same. Thus the full correction to Q_m to give Q_a is;

$$Q_a = Q_m \frac{(t_o + 273.15)}{(t_i + 273.15)} \sqrt{\frac{P_c}{P_a} \frac{(t_i + 273.15)}{(t_c + 273.15)}}$$

where Q_a is the corrected outside volumetric air flow rate into the building at outdoor test conditions, L/s

Q_m is the measured air flow rate indicated by the flow measuring device before any correction for the difference in the operating temperature and the calibration temperature, L/s, from par. 6.2.6

t_o is the outdoor air temperature, °C, from par. 6.1.1

t_i is the indoor air temperature, °C, from par. 6.2.6

t_c is the calibration air temperature, °C, from Appendix B

P_c is the calibration atmospheric pressure, kPa, from Appendix B

P_a is the ambient atmospheric pressure, kPa.

D-2 AIR FLOW CORRECTIONS FOR CALCULATING ELA

Q_a , as determined using the formula derived in D-1 above is corrected to reference conditions of $t_i = t_o = 20^\circ\text{C}$ and $P_a = 101.325 \text{ kPa}$ and yields Q_r as follows:

From D-1;

$$Q_a = Q_m \frac{(t_o + 273.15)}{(t_i + 273.15)} \sqrt{\frac{P_c}{P_a} \cdot \frac{(t_i + 273.15)}{(t_c + 273.15)}}$$

Deriving Q_r for estimating ELA:

$$Q_r = Q_a \sqrt{\frac{P_a (20 + 273.15)}{101.325 (t_o + 273.15)}}$$

Thus;

$$Q_r = Q_m \frac{(t_o + 273.15)}{(t_i + 273.15)} \sqrt{\frac{P_c}{P_a} \cdot \frac{(t_i + 273.15)}{(t_c + 273.15)}} \sqrt{\frac{P_a}{101.325} \cdot \frac{(20 + 273.15)}{(t_o + 273.15)}}$$

Simplifying;

$$Q_r = Q_m \sqrt{\frac{(t_o + 273.15)}{(t_i + 273.15)} \cdot \frac{P_c}{101.325} \cdot \frac{(20 + 273.15)}{(t_c + 273.15)}}$$

Note that this can be reduced to;

$$Q_r = Q_m \sqrt{\frac{(t_o + 273.15)}{(t_i + 273.15)}} \times \text{constant for any given fan}$$

where Q_a , Q_m , t_o , t_i , t_c and P_a and P_c are as defined in D-1.

SPECIMEN TEST REPORT

NAME OF CO. _____

ADDRESS OF CO. _____

NAME OF TESTER _____

ADDRESS OF

BUILDING _____

DATE OF TEST _____ DATE OF REPORT _____

WEATHER DATA

OUTDOOR TEMPERATURE _____ °C

WIND SPEED _____ km/h

WIND DIRECTION _____

WIND VARIABILITY _____

ENVELOPE☐ BUILDING ENVELOPEAREA _____ m²☐ OTHER _____INTERIOR VOLUME _____ m³**BUILDING SKETCHES**

MEASURED DATA

ΔP_m (Pa)	Fan Speed (r/min) or ΔP_{nozzle} (Pa)	Q_m (L/s)	t_i (°C)
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____

CORRECTED DATA

ΔP (Pa)	Q_r (L/s)
_____	_____
_____	_____
_____	_____
_____	_____
_____	_____
_____	_____
_____	_____
_____	_____

RELATIVE ERROR

$\left \frac{\hat{Q}_{ri} - Q_{ri}}{Q_{ri}} \right $

$\Delta P_{o,i}$ _____

$\Delta P_{o,f}$ _____

CALCULATED DATA

C_r _____ L/(s.Paⁿ)

n _____

r _____

ELA _____ m²

NLA _____ cm²/m²

RELATIVE STANDARD ERROR _____

PLOT OF MEASURED DATA

References

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