A Study on Single Blower Door Methods for Multifamily Buildings in Montreal

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ABSTRACT

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Blower doors are widely used to test the airtightness of detached houses, where whole building depressurization can be achieved with one blower door. However, testing of multifamily buildings is less common, partly because several blower doors are required to depressurize the entire building. This approach is deemed too costly and impractical outside of research purposes. The emergence of the renovation market has increased the interest in blower door testing of older multifamily buildings, leading to a need for alternative testing methods.

This thesis focused on the theoretical development and field evaluation of three single blower door methods suitable for two and three-unit multifamily buildings, typical to Montreal's residential building stock. The results demonstrated that it is possible to estimate both the external and the interzonal air leakage characteristics of multifamily buildings using only one blower door. This represents significantly more valuable data than is currently obtained with the whole building depressurization technique, allowing an estimate of how retrofit measures will impact natural ventilation, the need for mechanical ventilation and potential energy savings. These single door methods would be of value in weatherization programs where an estimate of the airtightness is required, and practicality and cost are a priority.

ACKNOWLEDGMENTS

I finished my undergraduate studies in 1991 and soon after started working at SIRICON, a building science organization founded by Dr. Paul Fazio. It was there, a few years later, that my colleague Dino Gerbasi convinced me to take a graduate course to keep him company. After much prodding, I agreed and took a course given by Dr. Zmeureanu on the building environment. This course rekindled my interest in academic work and I pursued my graduate studies on a part time basis while working fulltime. It is with great satisfaction that I submit this research thesis and would like to thank the many people that helped and supported me.

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Nomenclature

Term	Definition	Unit (Unit Symbol)
ACH50	Number of times the total air volume of a house changes in an hour, at a reference pressure difference of 50 Pa.	
Base Pressure	The ambient pressure difference across an air barrier, typically caused by wind or stack effect.	Pascal (Pa)
C	Air flow constant used in power law equation to determine air flow (Q).	Litre/second*Pascal^n (l/s*Pa^n)
ELA	Equivalent Leakage Area. The area of a round, sharp-edged orifice that at a pressure difference of 10 Pa would leak the same as the actual house leaks at 10 Pa pressure difference. $ELA(cm^2) = 0.1157 \cdot \sqrt{\rho_{air}} \cdot C \cdot 10^{n-0.5}$	Centimetre^2 (cm^2)
l/s50	Airflow rate at 50 Pa pressure difference.	Litre/second at 50 Pa (l/s @ 50 Pa)
NLA	Normalized Leakage Area. ELA divided by the area of the building envelope.	Centimetre^2 / metre^2 (cm^2/m^2)
n	Flow exponent used in the power law equation to determine air flow (Q).	Dimensionless
P	Pressure difference	Pascal (Pa)
Q	Air flow rate	Litre/second (l/s)
Unit	A dwelling unit/apartment in a multifamily building.	
Zone	A space in a building where air flows freely, separated from other spaces by a pressure boundary. Usually corresponds to a single or a group of units.	

1. Introduction

1.1 Background

At the Kyoto Conference in 1998, Canada and 160 other countries agreed to a Protocol that called for further reductions in greenhouse gas emissions over the next 15 years. Canada's reduction target is 6 percent below 1990 levels for the period spanning 2008 to 2012. The signing of the Kyoto Protocol is part of a natural progression of climate change activities in which Canada is involved and reaffirms our commitment to moving forward on energy, the environment and sustainable development.

Canadians use a great deal of energy to heat their homes, which is not surprising given our harsh climate. Energy use in housing has been the focus of numerous research programs and studies in Canada, leading to the development of an expertise that is recognized internationally. Successful housing programs such as the R2000 program sponsored by Natural Resources Canada (NRCan), the Ideas Challenge funded in part by Canada Mortgage and Housing Corporation (CMHC), and Hydro-Quebec's Noveau Confort program, have showcased our knowledge at home and on the international stage.

So far, the majority of Canada's energy efficiency initiatives have focused on new construction. However, the recent emergence of the renovation market has helped stimulate the interest in opportunities for energy efficiency in older housing stocks. Much of this renewed interest has been directed at multifamily buildings, which offer more energy savings potential than single-family dwellings. The largest concentration of these buildings in Canada is found in Montreal, where the urban environment is significantly different from that of other large Canadian cities. A key reason for Montreal's uniqueness is that a large number of its inhabitants live in the city proper, rather than in suburban areas. Rental accommodation in Montreal consists to a large extent of "multiplexes". Typically, multiplexes are low-rise and low-density multifamily urban dwellings. While multiplexes are found in other cities, an important distinguishing feature of Montreal dwellings is that individual units usually have separate entrances and civic addresses, as detached houses do. Also, Montreal multiplex dwellings have little or no shared interior spaces, such as vestibules, corridors and stairwells.

The energy savings potential of Montreal's multifamily housing stock was the focus of the recent Hydro-Quebec program "ISOLACTION", which was launched in 1995 and completed in 1998. The main objective of this program was to insulate approximately 1000 older multifamily buildings in the Montreal region. The program also raised awareness of several issues concerning the insulation and sealing of older buildings in Montreal. This program, plus the likelihood that other government agencies will continue the work started in ISOLACTION, contributed to the selection of this thesis topic.

Originally developed as research tools, blower doors have proven their worth as practical and effective tools for the building industry. The blower door consists of a heavy-duty fan, pressure and airflow meters, and a supporting frame (figure 1.1). They have been used extensively to test detached homes in programs and research studies sponsored by agencies such as NRCan, CMHC and Hydro-Quebec. NRCan's R2000 program and

Hydro-Quebec's Nouveau Confort program, which set performance criteria for new homes, require a blower door test to ensure that houses are sufficiently airtight.

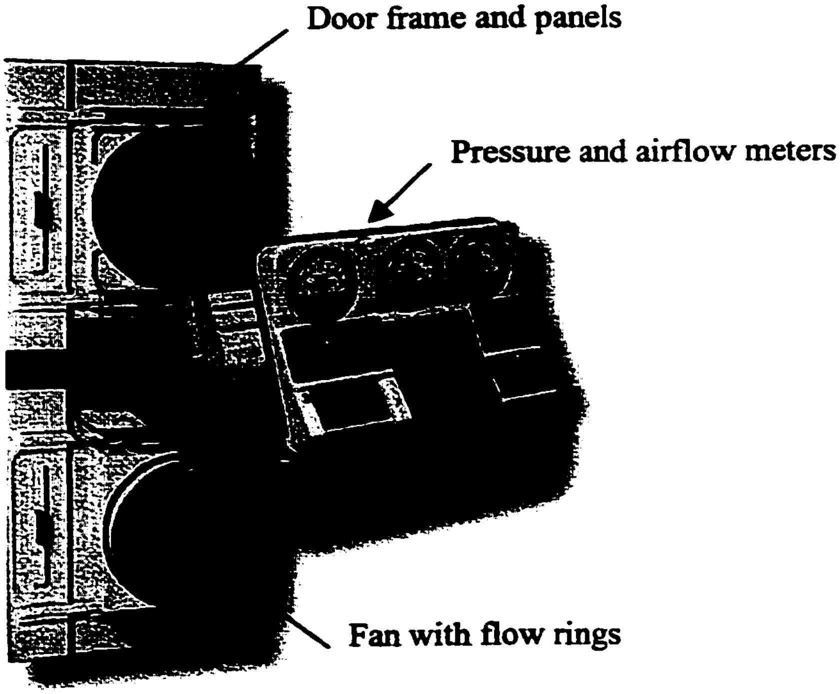

Figure 1. 1 Retrotec Blower Door

Data from blower door testing can be used to quantify the airtightness of the building envelope before and after weatherization work, to estimate natural ventilation, to evaluate the need for mechanical ventilation and to estimate energy savings. However, applying current standards to multifamily buildings, in which individual units have separate entrances, requires multiple blower doors. The use of multiple blower doors is a major hindrance within the scope of a weatherization program, where building inspections must be quick and low cost. This situation has led to an interest in developing alternative approaches for testing these buildings based on measurements obtained using only one blower door.

Another limitation of current standards is that they only specify the calculation procedure of the equivalent leakage area (ELA) of the building shell, not of interior partitions. External leakage alone does not allow an analysis of interzonal air movement or an accurate estimate of natural ventilation in multifamily buildings. The leakage through interior partitions is also needed to obtain complete information. For example, the natural ventilation for a two-story two-unit building will depend on the leakage through the floor separating the units. If the floor is tight, the units behave independently. However, if the floor is very loose, the building behavior approaches that of a single zone. In this case, air moves freely between units and the stack effect is greater. The natural ventilation profile on a unit-per-unit basis will be quite different from the previous case.

1.2 Objectives

The objective of this thesis is to develop and evaluate single blower door methods suitable for low-rise multifamily buildings, typical to Montreal's building stock. Single blower door techniques rely on measurements using only one blower door combined with pressure measurements in adjacent zones to calculate the airtightness of the building envelope and of the interior partitions between units.

This thesis is a step towards the development of effective, practical and innovative approaches for the measurement of envelope airtightness of low-rise multifamily buildings. Federal and provincial agencies planning to launch weatherization programs, which target this building stock, would benefit from this work. The results of this study could lead to the development of technical guidelines for the blower door testing of two and three-unit multifamily buildings. These guidelines could act as a supplement to current blower door manuals and standards.

1.3 Research Approach

This thesis combines experimental and analytical work. The experimental component consists of field testing the blower door methods on buildings in the Montreal area. The analytical component consists of the development of measurement methods, the analysis of the field test results and the evaluation of the suitability of the proposed methods for measuring the airtightness of both the external envelope and the interior partitions.

The protocols for the test methods were developed by the author based on his work experience in the ISOLACTION weatherization program and on a rigorous review of previous studies, which address blower door testing of multifamily buildings. The protocols define the building configurations and the corresponding system of flow equations required for the data sets. An Excel spreadsheet program developed for this thesis is used to solve the data sets for the required airflow information.

Four available buildings, typical of Montreal's multifamily building stock, were identified and selected for testing. Field tests were performed to evaluate the proposed methods, in comparison to baseline test results using multiple blower doors. The collected data was then analyzed and conclusions were made on the applicability of the proposed methods.

1.4 Thesis Overview

Following the introduction, Chapter Two consists of a literature review, which focuses on previous studies dealing with blower door testing of multifamily buildings. The third chapter defines the single blower door methods and provides the protocols and procedures used for the field-testing. Chapter Three also defines the protocol for the baseline test, which is used as the basis of comparison for the single door methods. The fourth chapter presents the test results and an analysis of these, in comparison to the baseline results. Conclusions on the applicability of the proposed methods and recommendations for future work are presented in Chapter Five. Finally, a complete compilation of the field data, including pressures, flow measurements, building takeoffs and calculations, is presented in the appendix.

2. Literature Review

Extensive literature exists on the subject of airtightness testing of residential buildings using blower doors. The majority of studies on this topic have focused on whole building, single zone situations. Several standards provide instructions on how to perform blower door testing using whole building depressurization [1]. In Canada, Standard CAN/CSGB-149.10, "A Method for Testing the Airtightness of Buildings by the Fan Depressurization Method" [2], provides a methodology for determining the airtightness of the building envelope. Other standards include ASTM Standard E779-87, "Test Method for Determining Air Leakage by Fan Pressurization" [3] and ASHRAE Standard 119, "Air Leakage Performance for Detached Single-Family Residential Buildings" [4]. However, only a few studies have investigated the use of fan pressurization techniques for the measurement of interzonal and envelope air leakage in multi-unit buildings. These studies are the focus of this literature review.

2.1 Methods for Air Tightness Testing of Multi-unit R2000 Housing

Sheltair Scientific inc. undertook this research study in 1987, for the R2000 Program and the British Columbia Home Builders Association [5]. This study assisted the R2000 Program administration in evaluating methods of testing the airtightness of multi-unit buildings in British Columbia. At the time of the report, a number of multi-unit R2000 developments were under construction in British Columbia.

Five methods for testing the airtightness of multi-unit buildings were defined in the report and tested on a six-unit development in Whistler B.C. The six units were row-type townhouses and were located above a commercial space. They therefore shared lateral walls and floors with other heated spaces. The five methods defined for this study are presented below:

Method 1: Detached-Unit Method

This approach is similar to the standard test procedure for detached houses. The shared walls and floors are simply treated as part of the exterior shell. The test is performed with the adjacent units open to the outside (open windows or doors).

Method 2: Pressure Equalization Method

This approach requires that all adjacent units be simultaneously depressurized to the same value as the test unit. This is the approach currently required by standard CAN/CSGB-149.10 (6.1.14) [2]. Since airflow to adjacent units is theoretically eliminated, this approach allows the measurement of the airflow through the exterior envelope of the test unit. The principle argument for factoring out airflow from adjacent units is that these are occupied and heated spaces. The assumption is that airflow from these adjacent units does not impact energy costs and does not provide ventilation air.

Method 3: **Pressure Method**

This method was first proposed in Sweden by P. Nylund [6] and later modified by J. Love of the University of Calgary [7]. The Pressure Drop Method factors out the airflow from shared partitions by measuring the pressure difference in adjacent units and estimating the airflow through the partitions. This method is based on the following assumptions:

- the leakage characteristics of adjacent units are the same as those of the test unit,
- airflow through the exterior surfaces of an adjacent unit is equal to the airflow through the partition shared by that unit and the test unit (no by-passes),
- air flow is proportional to the pressure difference according to the power law airflow equation: $Q = CP^n$.

Method 4: Whole Building Method

This method treats the multi-unit building as a single detached unit. The leakage area of the building is assumed to be representative of all the units. The leakage rates of an individual unit can be estimated proportionally to its share of the total exterior surfaces.

If all the units can be opened up to a common space, such as a corridor, it may be possible to depressurize the building to the required pressure difference with only one or two fans. This of course will depend on the size and airtightness of the building. For a large leaky building, many fans may be required. If the individual units do not share any common space, then an individual blower door will be required for each of the units.

Method 5: Single Point Method

This method involves equalizing pressure across shared surfaces at only one pressure point. This approach is therefore the same as method 2, except that the relationship between flow and pressure (the "n" value) would be assumed to be a typical value (e.g. 0.65).

The report concludes that the Detached Unit Method (method 1) is best suited for testing multifamily R2000 buildings. The approach is recommended because it is relatively simple and inexpensive, is consistent with the current standard test and promotes quality construction. Within the scope and objectives of the R2000 program, the report concludes that it is advantageous to treat the shared walls the same way as exposed walls. The principle argument supporting this conclusion is that contrary to popular belief, air movement between units can have an energy penalty, depending upon complex pressure distributions around the envelope. Another strong argument is that the shared walls must be made tight for health and safety reasons, a priority for R-2000 housing.

The Pressure Equalization Method (method 2) required the depressurization of the two adjacent units and the commercial spaces below. During the test, the technicians suspected that the inter-floor truss space was not being depressurized to the required level. Pressure measurements confirmed these suspicions; an opening in the ceiling of the commercial space was made to ensure the depressurization of the inter-floor truss space. The report concludes that bypasses through floors, walls, ceilings make it difficult to carry out this method. To the extent that bypasses are connected to the outside, equalizing pressure in adjoining units will not completely eliminate airflow through the shared envelope area. The report also points out that this method was complicated and required a team of 8 technicians working with portable radios.

Problems were encountered with the remaining methods. The Pressure Drop Method (method 3) did not produce satisfactory results because the pressure differences in the adjacent units were too small (less than 1 Pascal). The report concludes that this method is inappropriate for R-2000 buildings. The authors point out that airflow from adjacent units will always be small since shared walls have no intentional openings. The Whole Building Method (method 4) was not performed because of technical limitations (not enough blower doors were available). No practical method existed for testing the entire building as one single zone. The Single Point Method (method 6) did not produce reliable results. The readings at 10 and 15 Pascal did not correlate well with flow readings at higher pressure differences.

The results and conclusions of this report provide valuable insight into airtightness testing methods for multi-unit buildings. However, the following differences between R-2000 buildings and Montreal multiplexes must be considered when relating the conclusions of the Sheltair report to the building stock addressed by this thesis:

- *Age of the housing stock.* The Sheltair report examined new R-2000 housing whereas Montreal multiplexes, addressed in this thesis, are pre-1970. The construction techniques and airtightness levels are obviously different for these types of buildings.

- *Building configuration.* The Sheltair R-2000 building was a six-unit, row-type development. Montreal multiplexes are usually 2 or 3-floor buildings with one or two units per floor. Contrary to the R-2000 building, ISOLACTION has shown that the individual units in the multiplexes are often well connected (air moves freely between units). Also, the stack effect will have a greater influence on natural ventilation for multiplexes since the dwellings are superimposed.

- *Mechanical ventilation.* R-2000 buildings must have a balanced air exchange system to ensure an adequate level of ventilation. Montreal multiplexes usually have little or no mechanical ventilation. They rely on infiltration and operable windows for ventilation.

Some of the factors influencing the suitability of airtightness tests for the R-2000 would also apply to a weatherization program which target Montreal multiplexes. The Sheltair report states that the cost of an airtightness test for an R-2000 house was in the order of $175 to $200 (1986) and that a multi-unit test would have to respect this price range. The test should be easy to understand and simple to apply, a complicated test would lead to errors and inconsistent application by different people. Price and practicality would also be priorities for selecting a test method for a weatherization program.

2.2 Investigation of a Fan-Pressurization Technique for Measuring Interzonal Air Leakage

This study, published in 1990 by Mark P. Modera and Magnus K. Herrlin [8], analyses a fan-pressurization technique for measuring the interzonal leakage in a multi-unit building. The technique uses two blower doors, one in each of the two zones between which the leakage is being measured. The technique is to maintain a constant indoor-outdoor pressure difference in the primary zone while simultaneously varying the pressure in the second zone with respect to the primary zone. Furbringer, Roecker and Roulet [9] used a similar approach called the "Guarded Zone Pressurization Technique" to test the airtightness of a large administrative building in 1988. Feustel [10] also investigated the use of this approach for non-residential buildings in a 1988 study, prepared for the U.S. Department of Energy and the Lawrence Berkeley Laboratory.

Modera and Herrlin used MOVECOMP, a multi-zone air movement model, to evaluate the technique and to analyze wind induced uncertainties. The building chosen for the reference simulations was a multifamily building typical of those built around the turn of the century in U.S. cities. The main conclusion drawn by the authors is that wind plays an important role in uncertainties associated with interzonal leakage measurements. At wind speeds above 5 m/s, even perfect pressure and flow measurements cannot provide uncertainties smaller than 10 %. The report states that an outdoor pressure reference that minimizes measurement fluctuations is very important in reducing uncertainties. The report also highlights the importance of subtleties in measurement protocol, the leakage distribution and the type of wind under which the test is made.

2.3 Airtightness Survey of Row Houses In Calgary, Alberta

This 1990 paper prepared by J. A. Love [11], presents data on the airtightness of row houses in Calgary, Alberta. The approach used is similar to the technique defined by Modera and Herrlin [8] in which blower doors are used to simultaneously depressurize adjacent zones. The results of the tests with and with depressurization are used to differentiate the leakage through partition walls from the leakage through the exterior envelope.

The report addresses the logistical difficulties encountered by the test crews. Testing often required repeat visits because occupants failed to provide access despite prior arrangement. Similar problems were also encountered during the ISOLACTION program and can generally be expected when concurrent access to several building units is required. These difficulties are often underestimated prior to testing and must be taken into consideration when evaluating alternative test methods (the less access required the better).

Contrary to the R2000 row houses tested by Sheltair [5], partition wall air leakage was significant. For 24 Calgary row houses, party wall leakage ranged from 17 to 52 % of total leakage and averaged 37 %. The houses were built between 1965 and 1982 using wood framed construction. Party wall construction varied from project to project but was either concrete block construction or wood stud with fire stop. The flow exponent was calculated with and without partition wall leakage, using the multi-point test to the CAN/CSGB-149.10 standard. The mean value was 0.65 with a standard deviation of 0.06 with party leaks and 0.68 with a standard deviation of 0.1 without partition leaks. This result lends support to the use of 0.65 as a typical value for building leakage, commonly used when doing a one-point blower door test.

2.4 Pressure Diagnostics: Diagnosing Complex Leakage Paths

This 1992 guide by Michael Blasnik and Jim Fitzgerald [12] presents methods for diagnosing complex air leakage paths using blower door induced pressures. These methods can be used to estimate the airtightness characteristics of intermediate spaces adjacent to the main test zone. These intermediate spaces can be garages, attics, basements, rooms or other units. Two of the procedures presented in this report could be used for testing small multi-unit buildings.

The two procedures of interest are based on what the authors call "the fundamental principal of series leakage":

> *"The ratio of the pressure difference across the interior and exterior surfaces of a series leak is a direct function of the ratio of their air leaks."*

For example, if a house with a garage is depressurized to 50 Pa and the house/garage leakage area is equal to the garage/outside leakage area, then the pressure difference to the garage will be midway or 25 Pa. If the garage pressure is closer to the house pressure than to the outside pressure, then the leakage area from the house to the garage is larger than the leakage area from the garage to the outside. A single pressure difference measurement provides qualitative information about the relative tightness of the air barriers in a series path, but another measurement is required to obtain quantitative values.

The two methods used to quantify series leakage areas are described below:

Method 1: Opening a Door

This method consists of making a first air flow measurement, usually expressed in *liter/second at 50 Pa pressure difference* (l/s50), for the main unit and measuring the pressure difference in the adjacent zone. A second measurement is then taken with a door or window in the adjacent zone opened to the outside (zone pressure equal to the outside pressure) or open to the main zone (zone pressure equal to the main unit pressure). The second measurement quantifies the impact of removing one of the air barriers in the leakage path. The change in the l/s50 is a function of how well the air barrier resisted air leakage. The flow coefficient is assumed to be a typical value for building leaks (n=0.65). The method works best when the increase in l/s50 can be well measured (at least 100 l/s50) and when the initial pressure difference is not close to 50 or 0 Pa.

Method 2: Adding a Hole

This method consists of making a first fan flow measurement for the main zone and measuring the initial pressure difference in the adjacent zone. A second fan flow measurement is then taken after adding a hole of known size to one side of the flow path and measuring the change in pressure difference. The change in pressure difference across the leakage path is a function of the change in relative airtightness of the two sides. This method assumes that the added hole behaves as a sharp edged orifice so that orifice flow equations can be used to estimate the added flow. Other leaks are assumed to behave like typical building leaks. According to the authors, this method works best when the initial pressure difference and the subsequent change in pressure difference are in the order of 15 Pa.

The Open Door Method is similar to the Single-Door Method (A) defined by Tuluca and Sherman [13]. The main difference is that the Open Door Method only makes provisions for a main unit and one adjacent zone, whereas Tuluca and Sherman address the more complex issues of developing a data set for more than two zones.

The Adding a Hole Method is essentially a variation of the Open Door Method. Instead of opening windows or doors to vary the configuration, a hole of known size is added. This method is useful when an adjacent zone can not be fully opened to the outside, an attic space for example. The main advantage with this method is that occupants may be less inconvenienced in winter since their apartments are not fully open to the outside.

2.5 Simplified Multizone Blower Door Techniques for Multifamily Buildings

Adrian Tuluca and Max Sherman [13] prepared this study for the New York State Energy Research and Development Authority in 1995. This research focused on the applicability of two door and single door methods for testing the airtightness of New York State apartment buildings. The research investigates whether these methods can be used effectively to measure ELA of both the external shell and the interior partitions. Tests were performed on two buildings containing six apartments each. A summary of the methods is presented below:

Method 1: **Two-Door Method**

This method is similar to the method defined by Modera and Herrlin [8]. The second blower door is used to equalize the pressure between the main unit and the adjacent units, one at a time. The leakage through the outside envelope of the main unit is the total leakage minus the leakage to each neighbor. This method assumes that the flow exponent, n, is constant and that interstitial leakage, through bypasses such as floors, walls and plumbing stacks, is negligible.

Method 2: **Single-Door Method (A)**

Two versions of a single-door technique were tested. In the first version, the blower door is installed in the main unit; opening and closing windows in the other zones varies the leakage configuration. This provides a data set of airflows into the main unit at various pressures from the other units. The flow coefficients are obtained by solving the system of equations. A two-zone case requires only two blower door measurements, one measurement with the windows in the adjacent unit open and another with the windows closed. More complex situations, such as the six-unit buildings tested for this project, require a large number of measurements.

Method 3: **Single-Door Method (B)**

The second version of the single-door test consists of measuring the total leakage of each unit in the building, one at a time. An additional measurement is made in a closed configuration (with the windows in the adjacent units closed) to obtain the pressure difference to each adjacent zone. The data set can then be solved to obtain the flow coefficients for the interior partitions and the external envelope of each unit. The main difference with respect to the first version of the single-door test is that the blower door must be re-installed in each of the units.

When compared to tracer gas measurements, the Two-Door Method provided satisfactory values for both the external and internal leakage areas. However, the report concludes that this technique was time consuming and required extensive access to all the units in the building, making it better suited to research rather than routine weatherization work. The authors recommend using the Two-Door Method to characterize the performance of a sample of buildings, the results could then be extended to the building stock or could be used as a baseline for testing using the Single-Door Method (B).

The report concludes that the Single-Door Method (B) was less accurate than the Two-Door Method but still provided adequate results when the interior partitions were not too tight relative to the exterior shell. The report also concludes that results become unreliable when partitions are tight, but that inter-zonal air leakage is less important in this case. This method was faster than the Two-Door Method, since only one blower door was required and one technician could carry out the test. However, it was still necessary to setup the blower door and perform a test in each unit. The authors feel that at a minimum, this method provides a qualitative assessment of interzonal leakage, which can be used to evaluate air-sealing strategies and detect dangerous situations, such as leakage from a boiler room to apartments. When fully developed, the authors conclude that this method would be suitable for use by weatherization crews.

According to the report, the Single-Door Method (A) did not provide satisfactory results for measuring the air leakage through the external envelope and interior partitions. This method did not require a separate test in each unit and was therefore the fastest and least intrusive to the occupants. However, the poor results lead the authors to discard this technique for use in weatherization programs. The report does not address what caused the poor results, but they were likely linked to the complexity of the test buildings. The report does not consider if this method could be appropriate for smaller buildings.

This report provides valuable insight, principally because it addresses issues relating to the applicability of these tests on older buildings, within the scope of weatherization work. Unlike the Sheltair study, in which the R-2000 buildings had little leakage between units, the buildings in this study had inter-zonal leakage areas of comparable magnitude to the external leakage areas. Nevertheless, it is important to point out that the buildings in this study had six units compared to only two or three units for typical Montreal multiplexes. Also, contrary to the New York buildings tested, Montreal multiplexes have little or no common spaces such as corridors and vestibules. Variances in regional construction practices are also important and should be considered.

3. Theoretical Development of Blower Door Methods

3.1 Overview

Three single blower door methods and the baseline test method are developed in this chapter. The protocols for these methods are based on the author's work experience in the ISOLACTION weatherization program and the review of previous studies, which addressed the issue of blower door testing for multifamily buildings. This chapter does not address basic airflow and blower door theory, as this information is available in numerous textbooks and reference handbooks. The protocols are developed for three building configurations typical to Montreal multiplexes, as illustrated in figure 3.1.

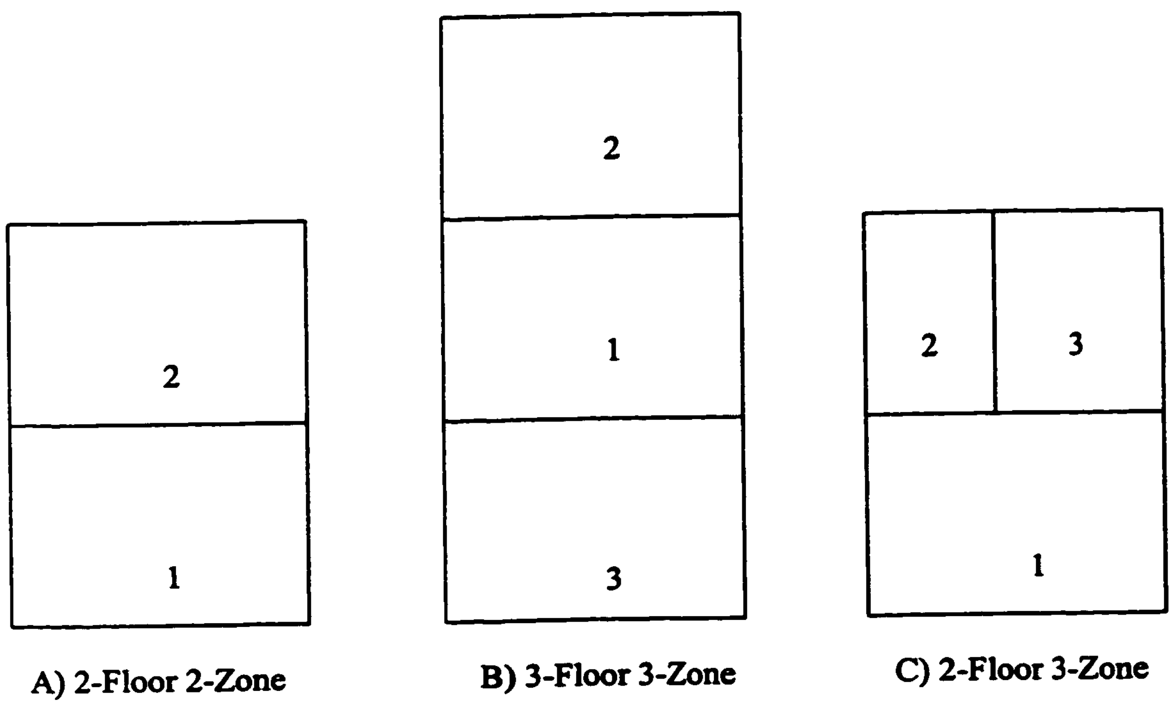

Figure 3.1 Typical Building Configurations for Montreal Multiplexes

The data sets are obtained by balancing airflows through the exterior envelope and the interior partitions, using the power law airflow equation [14]:

$$Q = CP^n$$

where

$Q =$	the airflow through the leakage path, l/s ,
$C =$	the flow coefficient of the leakage path, l/(s*Pa^n),
$P =$	the pressure difference across the leakage path, Pa,
$n =$	the flow exponent of the leakage path, dimensionless.

The flow exponent can be calculated using a multi-point test under whole building depressurization, where fan flows are measured for incremental changes in the zone pressure difference. The value for the flow exponent can vary from 0.5 to 1.0, depending on the characteristics of the leakage paths [15,16,17]. When fitting depressurization test data to buildings, the value of *n* generally lies between 0.6 and 0.7 [14]. The common value used in industry for single point blower door tests is 0.65 [12,18]. Love [11] presented data on the airtightness of row houses in Calgary, Alberta, which indicated that most buildings in the study had flow exponents close to 0.65. A value of 0.65 was used in this thesis for these reasons.

It is assumed in this thesis that the flow coefficient *C* does not vary with the leakage direction through a flow path (no directional valve effect). Although directional valve effects can influence the value of *C*, these differences would be difficult to measure in multifamily buildings with fan pressurization devices. Current standards and blower door manuals do not specify the measurement of the directional valve effect when establishing the airtightness of buildings [2,18], previous studies on blower door testing of multifamily buildings also assume that the directional valve effect can be neglected [5,7,11,12,13]. Accounting for the directional valve effect would double the unknown variables, making the methods more complex and less suitable within the scope of a weatherization program.

The data sets for each of the configurations consist of a set of linear equations, which can be solved by one of several linear algebra techniques. An Excel spreadsheet program was developed by the author to solve the data sets for the unknown flow coefficients C using Cramer's rule [19,20]. The field data, the calculations and the results are presented in the appendix. Other valuable results, such as the equivalent leakage area (ELA), normalized leakage area (NLA), liters per second at 50 Pa pressure difference (l/s50) and air change at 50 Pa pressure difference (ACH50), are derived from the calculated flow coefficients and are also presented in the appendix.

3.2 Area Weighted Pressure Difference Method

The Area Weighted Pressure Difference Method is similar to the Pressure Drop Method described by Sheltair [5]. Air leakage through interior partitions is estimated by measuring the pressure difference in adjacent units and then making an assumption regarding the leakage characteristics of the adjacent units.

The method developed here differs from the Pressure Drop Method described by Sheltair in that the exterior leakage of the units are assumed to be linearly proportional to their exterior envelope areas. This assumption is made to account for the fact that dwelling units in Montreal multiplexes vary in size and shape. In addition, airflow through the exterior surfaces of an adjacent unit is assumed to be equal to the airflow through the partition shared by that unit and the test unit (no bypasses).

3.2.1 Configuration A) 2-floor 2-zone

In this configuration, the blower door is installed in the largest unit or the unit suspected of having the most air leakage (usually the ground floor unit). A pressure tap is installed in the adjacent zone to measure the pressure difference. The test is performed at a reference pressure difference of 50 Pa in the main zone with respect to the outside. The protocol is illustrated in figure 3.2.

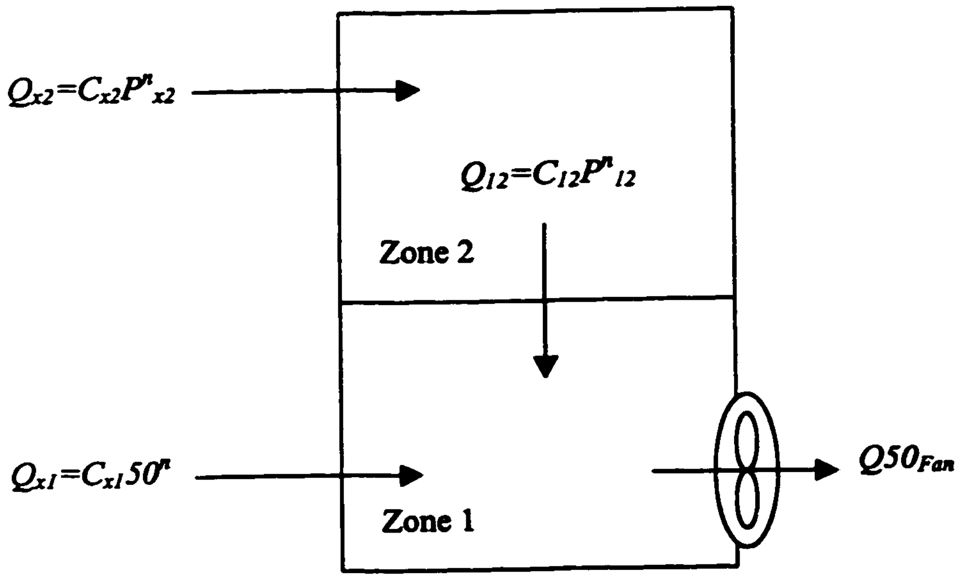

Figure 3.2 Protocol for 2-floor 2-zone configuration - Area Weighted Pressure Difference Method

Where $Q50_{Fan}$ = fan flow at 50 Pa, l/s

Q_{x1} = airflow between exterior and zone 1, l/s,

Q_{x2} = airflow between exterior and zone 2, l/s,

Q_{12} = airflow between zone 2 and zone 1, l/s,

C_{x1} = the flow coefficient between exterior and zone 1, l/(s*Pa^n),

C_{x2} = the flow coefficient between exterior and zone 2, l/(s*Pa^n),

C_{12} = the flow coefficient between zone 1 and zone 2, l/(s*Pa^n),

P_{12} = pressure difference between zone 1 and zone 2, Pa,

Px_2 = pressure difference between exterior and zone 2, Pa,

n = the flow exponent of the leakage path, 0.65, dimensionless.

Balancing the flows for zones 1 and 2 gives us the following equations:

$$C_{x1}50^n + C_{12}P_{12}^n = Q50_{Fan} \qquad (1)$$

$$C_{x2}P_{x2}^n + C_{12}P_{12}^n = 0 \qquad (2)$$

The assumption that air leakage is proportional to envelope area provides us with the third equation required.

$$C_{x1}\left(\frac{1}{A_1}\right) - C_{x2}\left(\frac{1}{A_2}\right) = 0 \qquad (3)$$

Where A_1 and A_2 are the exterior envelope areas of zones 1 and 2 respectively. This system of equations with 3 unknowns (flow coefficients C) can be readily solved using linear algebra techniques.

3.2.2 Configuration B) 3-floor 3-zone

In this configuration, the blower door is installed in zone 1 and pressure taps are installed in the two adjacent zones. The zone 1 is brought to a pressure difference of 50 Pa with respect to the outside. This configuration has two more flow paths than the previous configuration. This simple model assumes that zones 2 and 3 are not connected. However, ISOLACTION experience has shown that these two zones are usually connected to some degree through interstitial spaces such as plumbing shafts and skylights. The protocol and flow paths are illustrated in figure 3.3.

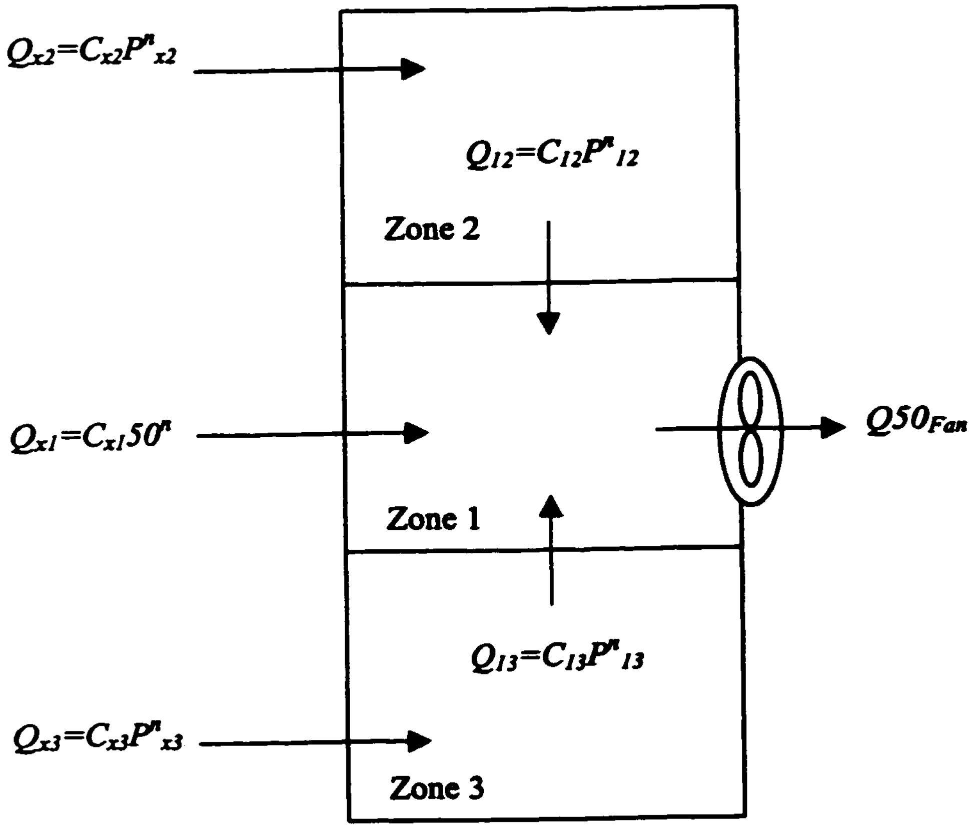

Figure 3.3 Protocol for 3-floor 3-zone configuration - Area Weighted Pressure Difference Method

Balancing the flows for zones 1 and 2 provides the three following equations:

$$C_{x1}50^n + C_{12}P_{12}^n + C_{13}P_{13}^n = Q50_{Fan} \qquad (4)$$

$$C_{x2}P_{x2}^n + C_{12}P_{12}^n = 0 \qquad (5)$$

$$C_{x3}P_{x3}^n + C_{13}P_{13}^n = 0 \qquad (6)$$

Two more equations are obtained with the assumption that leakage is proportional to building envelope area.

$$C_{x1}\left(\frac{1}{A_1}\right) - C_{x2}\left(\frac{1}{A_2}\right) = 0 \qquad (7)$$

$$C_{x1}\left(\frac{1}{A_1}\right) - C_{x3}\left(\frac{1}{A_3}\right) = 0 \qquad (8)$$

Equations 4 through 8 can be solved to obtain the five unknown flow coefficients.

3.2.3 Configuration C) 2-floor 3-zone

The Area Weighted Pressure Difference Method, as defined here, can not be used to solve this particular configuration. On a theoretical level, this configuration has more unknowns than equations and would therefore require an additional assumption. On a practical level, the pressure difference between the two 2nd floor zones, zones 2 and 3, would probably be too small to produce valid results in estimating the flow coefficient of the partition separating these two zones. A simple way around this problem is to treat the building in the same manner as the 3-floor 3-zone configuration (see figure 3.1c). In other words, we assume that there is no connection between zones 2 and 3.

3.2.4 Field Testing Procedure

The field testing procedure for the Area Weighted Pressure Difference Method is summarized below.

1) Measure building volume, floor areas and envelope areas.
2) Install blower door in the main unit and prepare the building for testing, according to accepted industry practice and the blower door manual instructions.
3) Depressurize the main zone to 50 Pa (accounting for base pressure difference).
4) Measure the fan flow and the pressure difference to each adjacent zone (accounting for measured base pressure differences and change in air density if required).
5) Record all measurements and process the data to obtain the required results using the Excel spreadsheet (see appendix).

3.3 Unit Method

The Unit Test Method is similar to the Single-Door Method (B) defined by Tuluca and Sherman [12]. This test consists of measuring the total leakage of each unit in the building, one unit at a time, and measuring the pressure differences to adjacent units. The data set can then be solved to obtain the flow coefficients for the interior partitions and the external envelope of each unit.

3.3.1 Configuration A) 2-floor 2-zone

The first test is performed with the blower door installed in the bottom unit and a pressure tap installed in the adjacent zone. The test is then repeated with the blower door installed in zone 2. The protocol and flow paths are illustrated in figure 3.4.

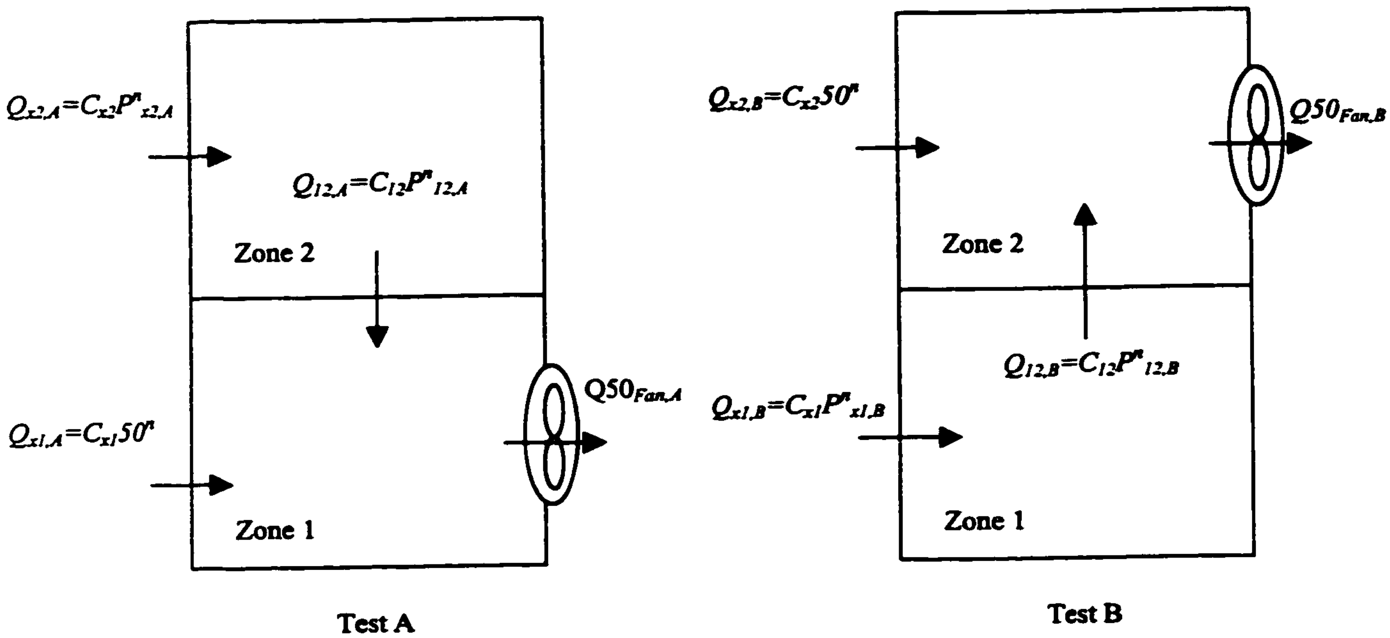

Figure 3.4 Protocol for 2-floor 2-zone configuration – Unit Method

Balancing the flows for zones 1 and 2, for test A, gives us the following equations:

$$C_{x1}50^n + C_{12}P_{12,A}^n = Q50_{Fan,A} \qquad (9)$$

$$C_{x2}P_{x2,A}^n + C_{12}P_{12,A}^n = 0 \qquad (10)$$

The 3rd equation is obtained by balancing the flows in test B for zone 2:

$$C_{x2}50^n + C_{12}P_{12,B}^n = Q50_{Fan,B} \qquad (11)$$

Equations 9 through 11 can be solved to obtain the flow coefficients C.

It should be noted that a 4th equation could have been obtained by balancing the flows in test B for zone 1. An over-determined system of equations may prove useful when some of the equations have high uncertainty levels. For example, if the pressure difference between the adjacent zones in test A is only 5 Pa but is 20 Pa in test B, it would be preferable to use test B to formulate the 3rd equation.

3.3.2 Configuration B) 3-floor 3-zone

A first test is performed with the blower door installed in zone 1, with pressure taps installed in the other two zones. The test is repeated with the blower door installed in zone 2 and then in zone 3. The protocol and flow paths are illustrated in figure 3.5.

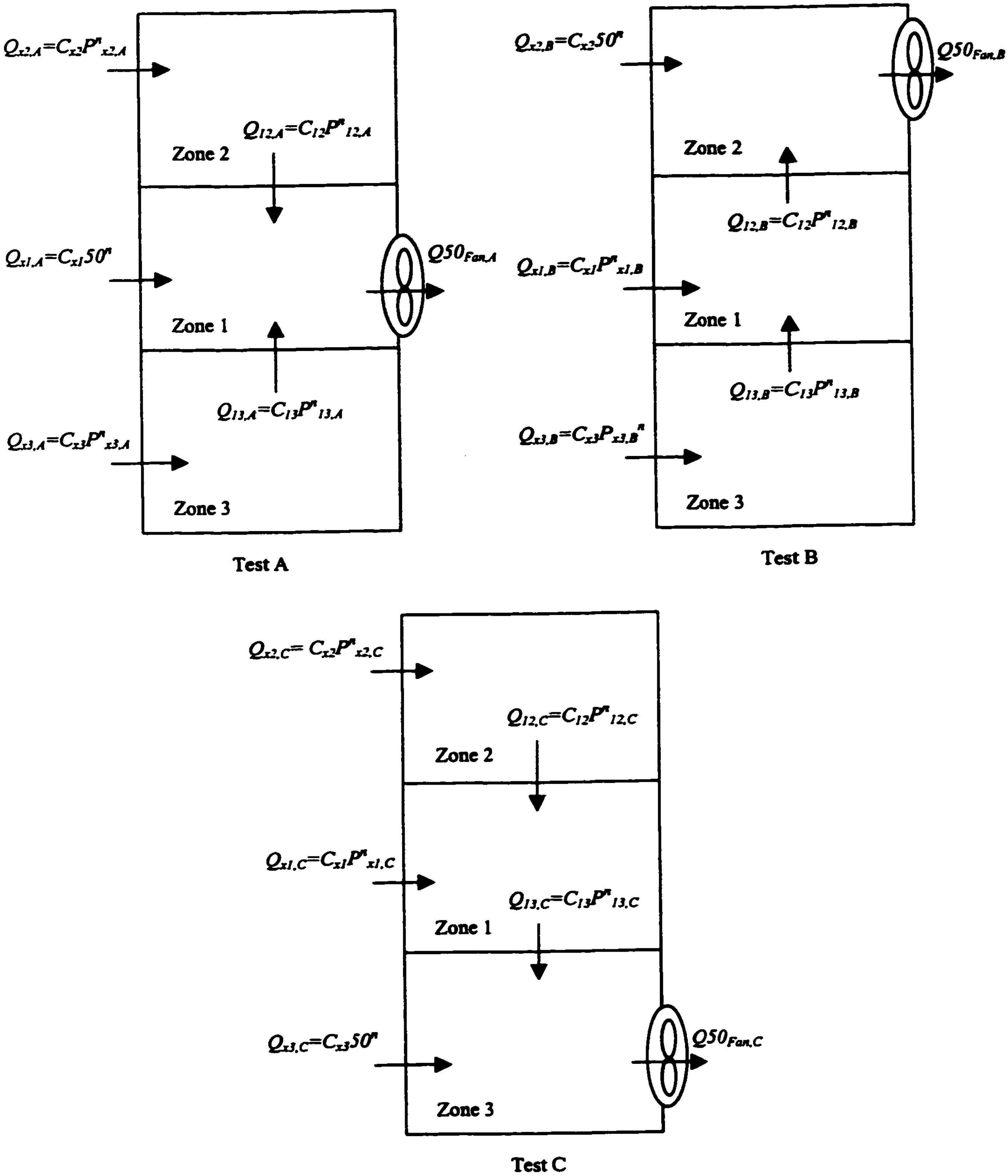

Figure 3.5 Protocol for 3-floor 3-zone configuration – Unit Method

Balancing the flows for zones 1,2 and 3, for test A, gives us the following equations:

$$C_{x1}50^{n} + C_{12}P_{12,A}^{n} + C_{13}P_{13,A}^{n} = Q50_{Fan,A} \tag{12}$$

$$C_{x2}P_{x2}^{n} + C_{12}P_{12,A}^{n} = 0 \tag{13}$$

$$C_{x3}P_{x3}^{n} + C_{13}P_{13,A}^{n} = 0 \tag{14}$$

The 4th and 5th equations are obtained by balancing the flows in the zones with the blower door (main zone) in tests B and C:

$$C_{x2}50^{n} + C_{12}P_{12,B}^{n} = Q50_{Fan,B} \tag{15}$$

$$C_{x3}50^{n} + C_{13}P_{13,C}^{n} = Q50_{Fan,C} \tag{16}$$

Equations 12 through 16 can be solved to obtain the flow coefficients C. Four additional equations could have been formulated by balancing the flows in the zones without the blower door in tests B and C. However, since one of the zones is not directly adjacent to the zone with the blower door, some of the pressure differences could be small and less reliable.

3.3.3 Configuration C) 2-floor 3-zone

The basic procedure is the same as for the 3-floor 3-zone configuration. However, this configuration introduces a 6th unknown, the flow coefficient between zones 2 and 3. The protocol and flow paths are illustrated in figure 3.6.

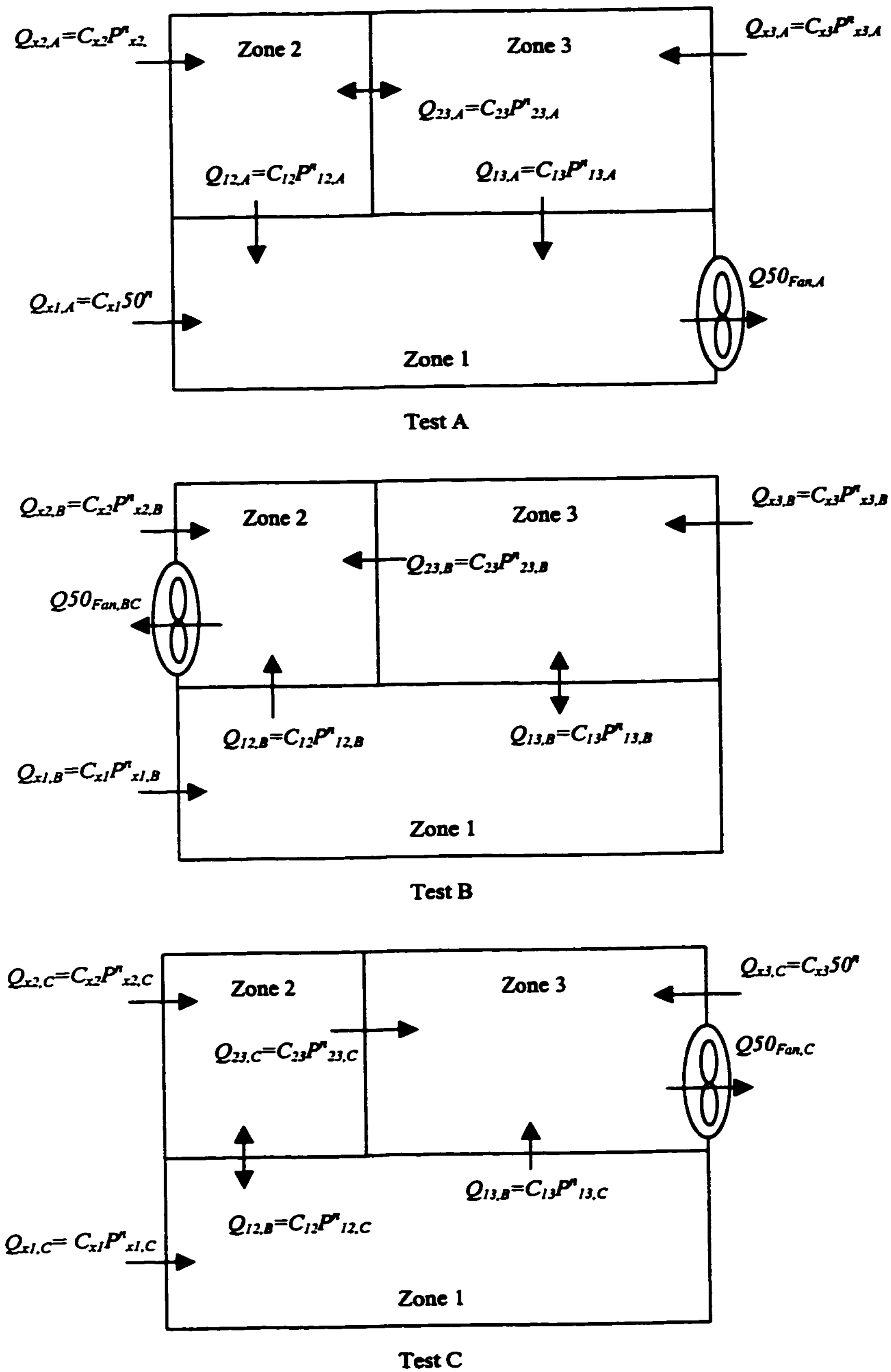

Figure 3.6 Protocol for 2-floor 3-zone configuration – Unit Method

The data set for this configuration consists of six equations with six unknowns. Three equations are obtained from the flow balance of the main zone in tests A, B and C.

$$C_{x1}50^n + C_{12}P_{12,A}^n + C_{13}P_{13,A}^n = Q50_{Fan,A} \qquad (17)$$

$$C_{x2}50^n + C_{12}P_{12,B}^n + C_{23}P_{23,B}^n = Q50_{Fan,B} \qquad (18)$$

$$C_{x3}50^n + C_{13}P_{13,C}^n + C_{23}P_{23,C}^n = Q50_{Fan,C} \qquad (19)$$

Because we have an over-determined system, the three other equations can be selected from a possible six. Equations based on large pressure differences are more reliable; therefore the selection process is based on the pressure readings obtained on site. The objective is to formulate the equations using the largest possible pressure difference between adjacent zones. For example, consider the following hypothetical data:

	Pressure difference 1-2	Pressure difference 2-3	Pressure difference 1-3
Test A	15 Pa	1 Pa	14 Pa
Test B	15 Pa	20 Pa	5 Pa
Test C	8 Pa	22 Pa	14 Pa

In this scenario, test C gives the best data, followed by test B. Two equations are formulated with a flow balance of the adjacent zones in test C and a third equation is obtained from test B:

$$C_{x1}P_{x1,C}^{n} + C_{12}P_{12,C}^{n} + C_{13}P_{13,C}^{n} = 0 \tag{20}$$

$$C_{x2}P_{x2,C}^{n} + C_{12}P_{12,C}^{n} + C_{23}P_{23,C}^{n} = 0 \tag{21}$$

$$C_{x1}P_{x1,B}^{n} + C_{12}P_{12,B}^{n} + C_{13}P_{13,B}^{n} = 0 \tag{22}$$

3.3.4 Field Testing Procedure

The field testing procedure for the Unit Test Method is summarized below.

1) Measure building volume, floor areas and envelope areas.
2) Install blower door in the main unit and prepare the building for testing, according to accepted industry practice and the blower door manual instructions.
3) Depressurize the main zone to 50 Pa (accounting for measured base pressure differences).
4) Measure the fan flow and the pressure difference to each adjacent (accounting for measured base pressure differences and change in air density if required).
5) Repeat step 3 and 4 with the blower door installed in the other building units.
6) Record all measurements, select which tests provide the most appropriate pressure differences and define the data set accordingly. Process the data to obtain the required results using the Excel spreadsheet.

3.4 Open/Closed Method

This method is similar to the Single-Door Method (A) defined by Tuluca and Sherman [13] and the Open Door Method defined by Blasnik and Fitzgerald [12]. The test consists of varying the airflow configuration of the building by opening and closing windows (or doors) in the zones adjacent to the main test unit. It is important that enough windows are open so that the pressure in the open zone is equal to the outside pressure, thereby removing one of the air barriers in the leakage path.

3.4.1 Configuration A) 2-floor 2-zone

The first test is performed with the blower door installed in the bottom unit and a pressure tap installed in the adjacent zone. The test is then repeated with zone 2 open to the outside. The protocol and flow paths are illustrated in figure 3.7.

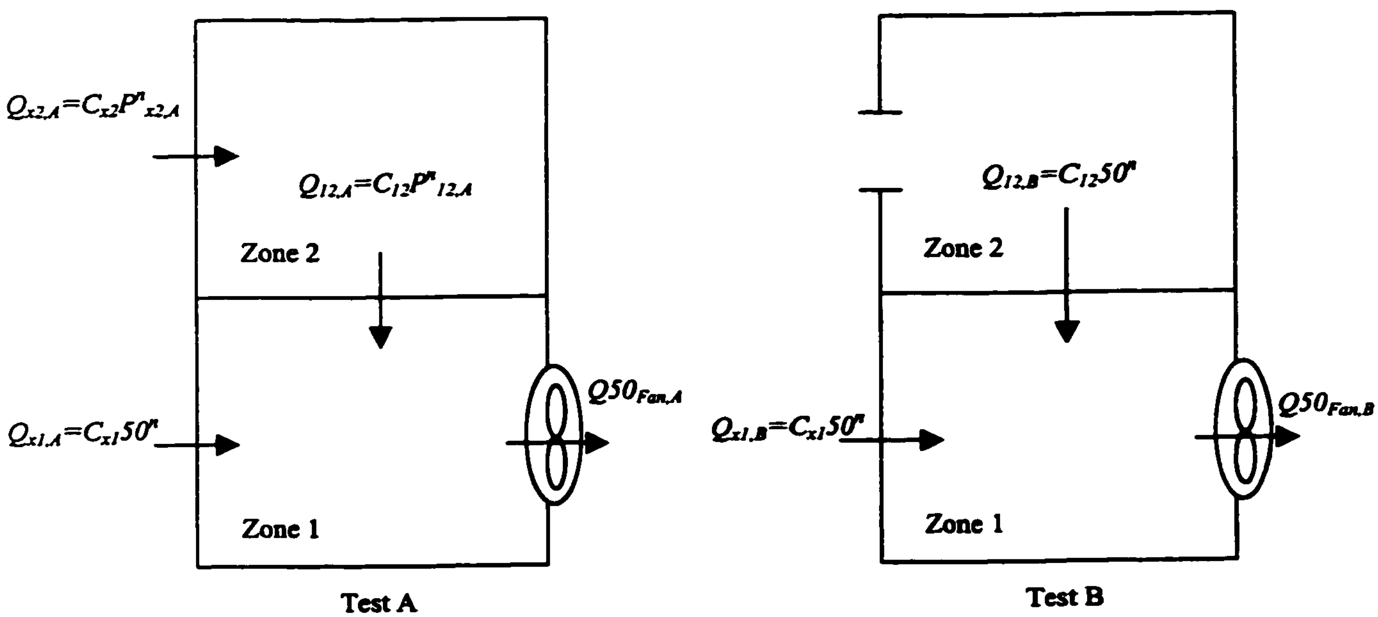

Figure 3.7 Protocol for 2-floor 2-zone configuration – Open/Closed Method

Balancing the flows for zones 1 and 2, for test A, gives us the following equations:

$$C_{x1}50^{n} + C_{12}P_{12,A}^{n} = Q50_{Fan,A} \qquad (23)$$

$$C_{x2}P_{x2,A}^{n} + C_{12}P_{12,A}^{n} = 0 \qquad (24)$$

The 3rd equation is obtained by balancing the flows in the main zone in test B:

$$C_{x1}50^{n} + C_{12}50^{n} = Q50_{Fan,B} \qquad (25)$$

Equations 23 through 25 can be solved to obtain the flow coefficients C.

3.4.2 Configuration B) 3-floor 3-zone

The first test is performed with the blower door installed in zone 1, with pressure taps installed in the other two zones. A second test is then performed with the windows open in zone 2 and closed in zone 3. Finally, a third test is performed with the windows open in the zone 3 and closed in zone 2. The protocol and flow paths for this configuration are illustrated in figure 3.8.

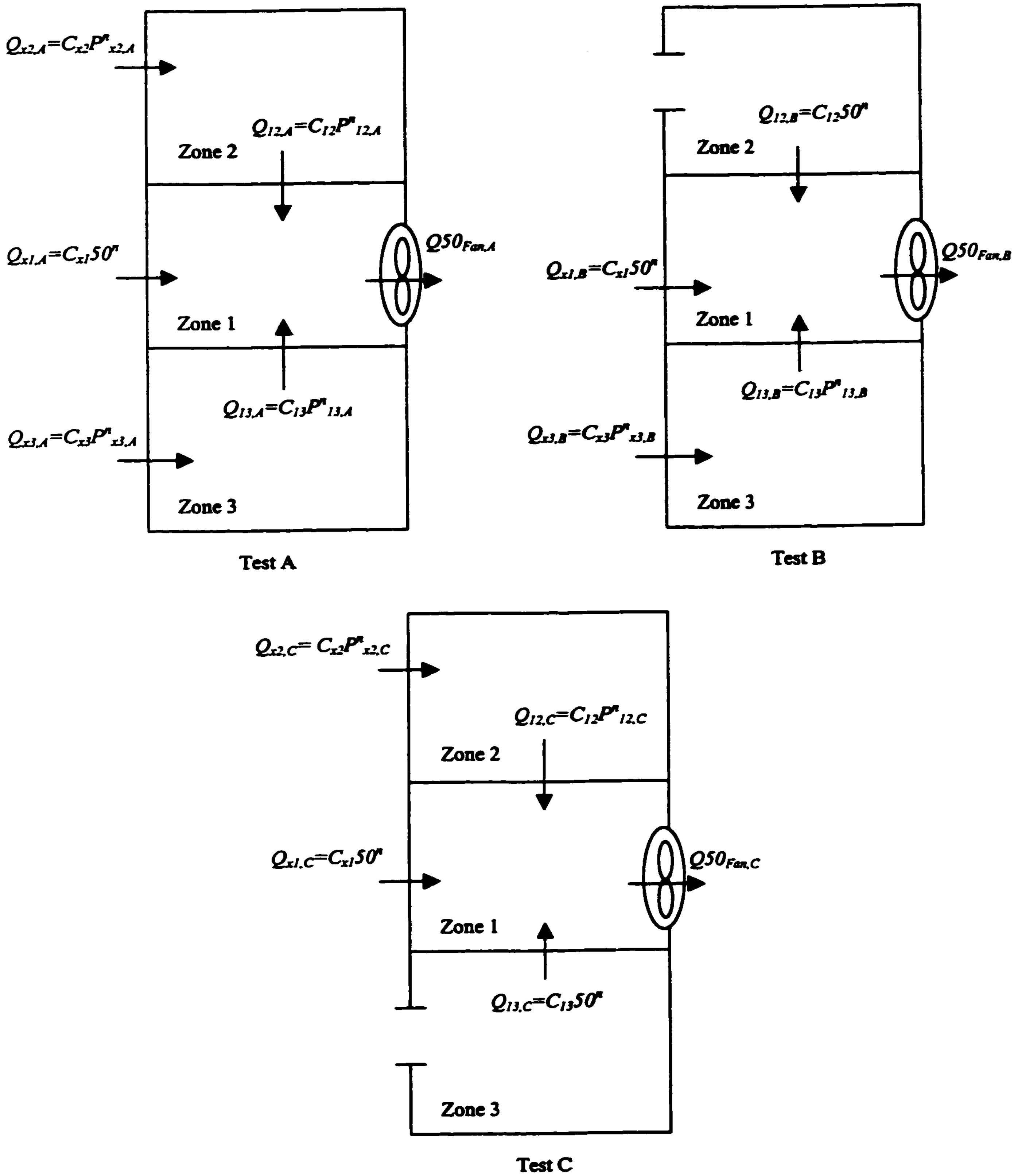

Figure 3.8 Protocol for 3-door 3-zone configuration - Open/Closed Method

Balancing the flows for zones 1,2 and 3, for test A, gives the following equations:

$$C_{x1}50^{n} + C_{12}P_{12,A}^{n} + C_{13}P_{13,A}^{n} = Q50_{Fan,A} \quad (26)$$

$$C_{x2}P_{x2,A}^{n} + C_{12}P_{12,A}^{n} = 0 \quad (27)$$

$$C_{x3}P_{x3,A}^{n} + C_{13}P_{13,A}^{n} = 0 \quad (28)$$

The 4th and 5th equations are obtained by balancing the flows in zone 1 for test B and C:

$$C_{x1}50^{n} + C_{12}50^{n} + C_{13}P_{13,B}^{n} = Q50_{Fan,B} \quad (29)$$

$$C_{x1}50^{n} + C_{12}P_{12,C}^{n} + C_{13}50^{n} = Q50_{Fan,C} \quad (30)$$

Equations 26 through 30 can be solved to obtain the flow coefficients C.

3.4.3 Configuration C) 2-floor 3-zone

The basic procedure is the same as for the 3-floor 3-zone configuration. However, in this configuration a 6th unknown is introduced; the flow coefficient between zones 2 and 3. The protocol and flow paths are illustrated in figure 3.9.

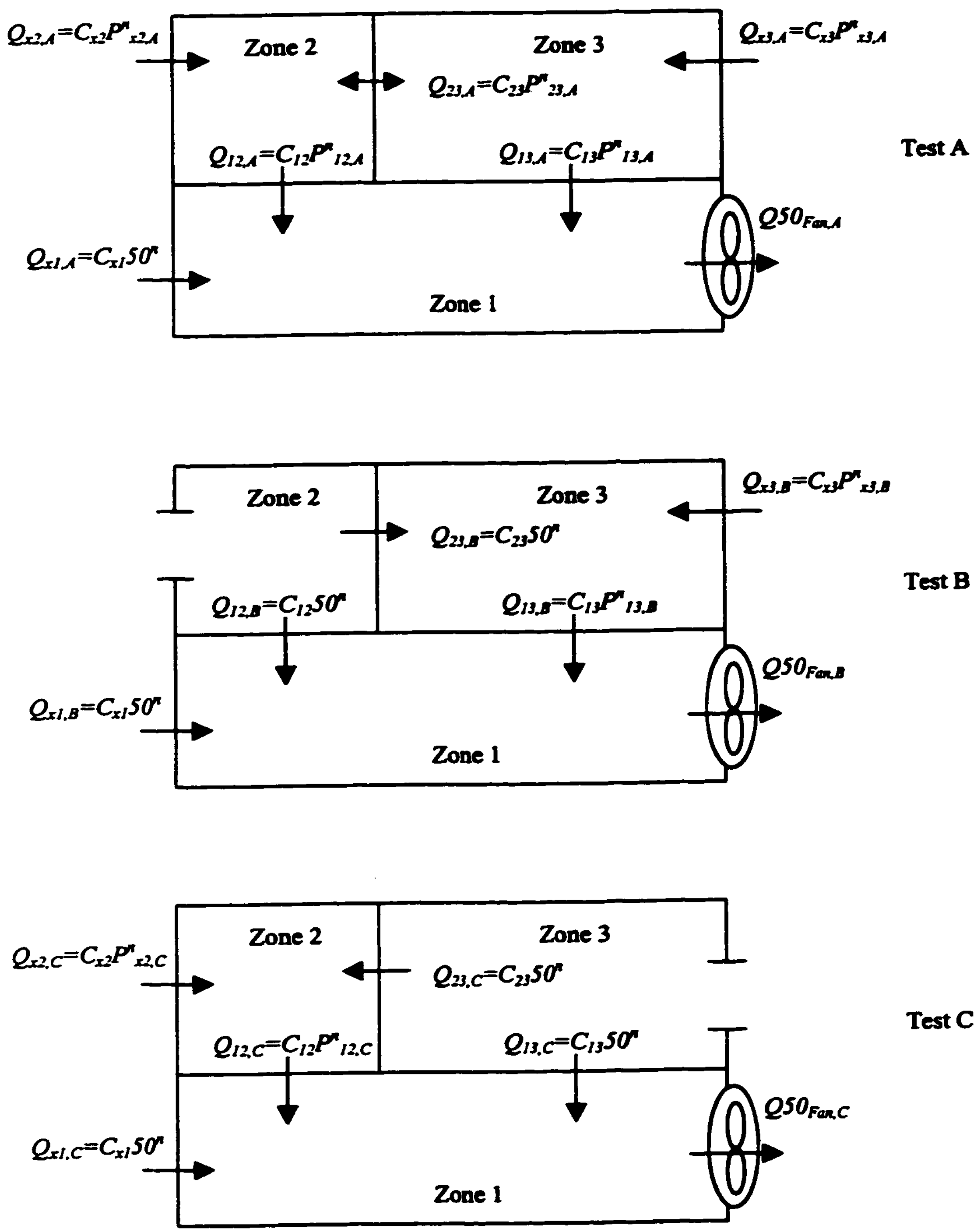

Figure 3.9 Protocol for 2-floor 3-zone configuration - Open/Closed Method

The protocol allows us to formulate up to seven independent equations for the six unknown variables. The equations required for the data set are selected to avoid equations containing small pressure difference values. Two equations are obtained from Test A. The choice of which 2nd story zone to use for an equation will be based on their respective pressure differences with respect to zone 1. For example, if zones 2 and 3 have pressure differences of 14 and 8 Pa respectively, then zone 2 would be selected.

Balancing the flows for zone 1 and zone 2 in test A gives us the following equations:

$$C_{x1}50^n + C_{12}P_{12,A}^n + C_{13}P_{13,A}^n = Q50_{Fan,A} \qquad (31)$$

$$C_{x2}P_{x2,A}^n + C_{12}P_{12,A}^n + C_{23}P_{23,A}^n = 0 \qquad (32)$$

The next two equations are derived from balancing the flows in zones 1 and 3 for test B:

$$C_{x1}50^n + C_{12}50^n + C_{13}P_{13,B}^n = Q50_{Fan,B} \qquad (33)$$

$$C_{x3}P_{x3,B}^n + C_{13}P_{13,B}^n + C_{23}P_{23,B}^n = 0 \qquad (34)$$

The 5th and 6th equations are obtained by balancing the flows in zone 1 and 2 for test C:

$$C_{x1}50^n + C_{13}50^n + C_{12}P_{12,C}^n = Q50_{Fan,C} \qquad (35)$$

$$C_{x2}P_{x2,C}^n + C_{12}P_{12,C}^n + C_{23}P_{23,C}^n = 0 \qquad (36)$$

Equations 31 through 36 can be solved to obtain the flow coefficients C.

3.4.4 Field Testing Procedure

The field testing procedure for the Open/Closed Method is summarized below.

1) Measure building volume, floor areas and envelope areas.
2) Install blower door in the main zone and prepare the building for testing, according to accepted industry practice and the blower door manual instructions.
3) Depressurize the main zone to 50 Pa (accounting for measured base pressure differences).
4) Measure the fan flow and the pressure difference to each adjacent (accounting for measured base pressure differences and change in air density if required).
5) Vary the configuration of the building by opening and closing windows (or doors) in the adjacent zones and repeat steps 3 and 4, making sure that the pressure in the open zone is equal to the outside pressure.
6) Record all measurements, select the zone which provides the most appropriate pressure differences (adjust the data set accordingly), and process the data to obtain the required results using the Excel spreadsheet.

3.5 Two Door Method – Baseline Test

The Two Door Method was used a baseline for the evaluation of the single blower door methods. This approach successfully used by Tuluca and Sherman [10], and Modera and Herrlin [5] to test multifamily buildings. For a two-zone building, a blower door is placed in each zone, giving an accurate measurement of the envelope airtightness. The airtightness of the partition separating the zones is obtained by measuring the increase in fan flow required to maintain one zone at 50 Pa, when the other fan is turned off. A similar approach is used for a three-zone building except that the unknown leakage paths are isolated one at a time using a 50 Pa pressure difference.

3.5.1 Configuration A) 2-floor 2-zone

The protocol and flow paths are illustrated in figure 3.10.

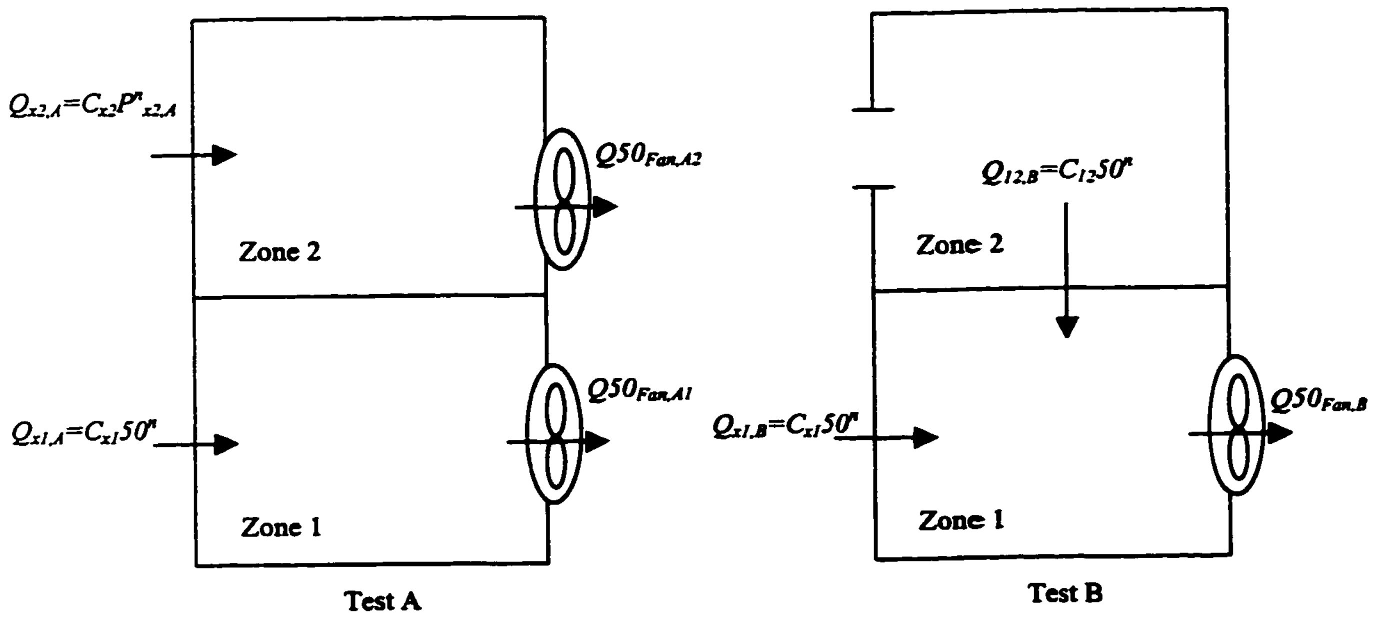

Figure 3.10 Protocol for 2-floor 2-zone configuration - Multiple Door Method

Balancing the flows for zones 1 and 2, for test A, gives us the following equations:

$$C_{x1}50^{n} = Q50_{Fan,A1} \qquad (37)$$

$$C_{x2}50^{n} = Q50_{Fan,A2} \qquad (38)$$

The 3rd equation is obtained by balancing the flows in test B for zone 1:

$$C_{x1}50^{n} + C_{12}50^{n} = Q50_{Fan,B} \qquad (39)$$

Equations 37 through 39 can be solved to obtain the flow coefficients C.

3.5.2 Configuration B) 3-floor 3-zone

For this configuration, the technique is to keep two zones at the same pressure, while simultaneously creating a 50 Pa pressure difference to the 3rd zone. This technique leads to accurate results because the flow rate across a leakage path is measured directly. In other words, we measure the change in fan flow in the primary unit when the pressure difference across the leakage path goes from 50 to zero Pa. Sensitivity to uncertainties in the measured pressure readings is reduced because we always use a large pressure difference. The protocol and flow paths for this configuration are illustrated in figure 3.11.

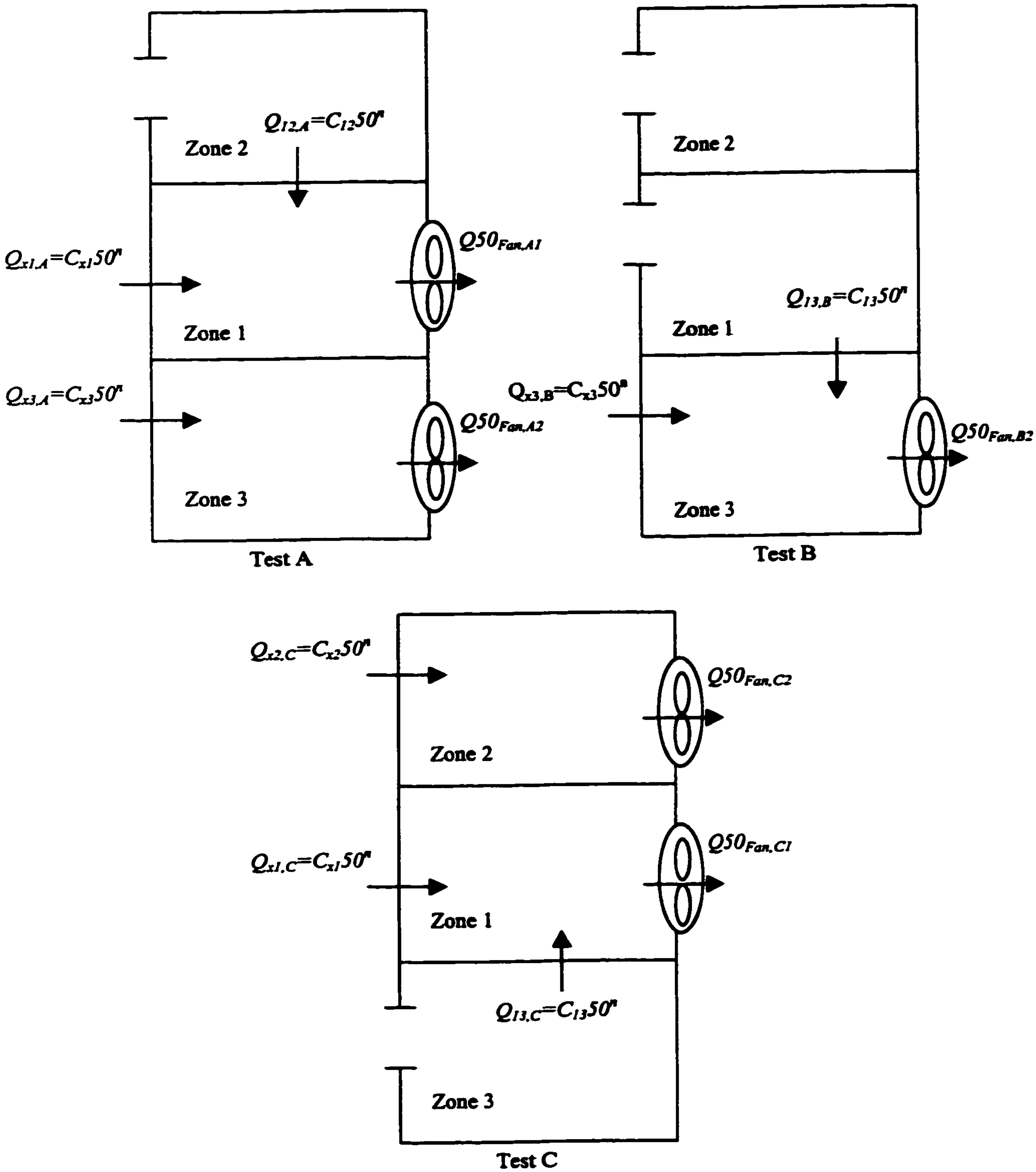

Figure 3.11 Protocol for 3-floor 3-zone configuration - Two Door Method

Balancing the flows for zone1 and 3 in test A gives us the following equations:

$$C_{x1}50^n + C_{12}50^n = Q50_{Fan,A1} \quad (40)$$

$$C_{x3}50^n = Q50_{Fan,A2} \quad (41)$$

The 3rd equation is obtained by balancing the flow in zone 3 for test B:

$$C_{x3}50^n + C_{13}50^n = Q50_{Fan,B2} \quad (42)$$

The 4th and 5th equations are obtained by balancing the flows in zone 1 and 2 in test C:

$$C_{x1}50^n + C_{13}50^n = Q50_{Fan,C1} \quad (43)$$

$$C_{x2}50^n = Q50_{Fan,C2} \quad (44)$$

Equations 40 through 44 can be solved to obtain the flow coefficients C.

3.5.3 Configuration C) 2-floor 3-zone

The approach is similar to the 3-floor 3-zone configuration, except that a 6th unknown is introduced; the flow coefficient between zones 2 and 3. The protocol and flow paths are illustrated in figure 3.12.

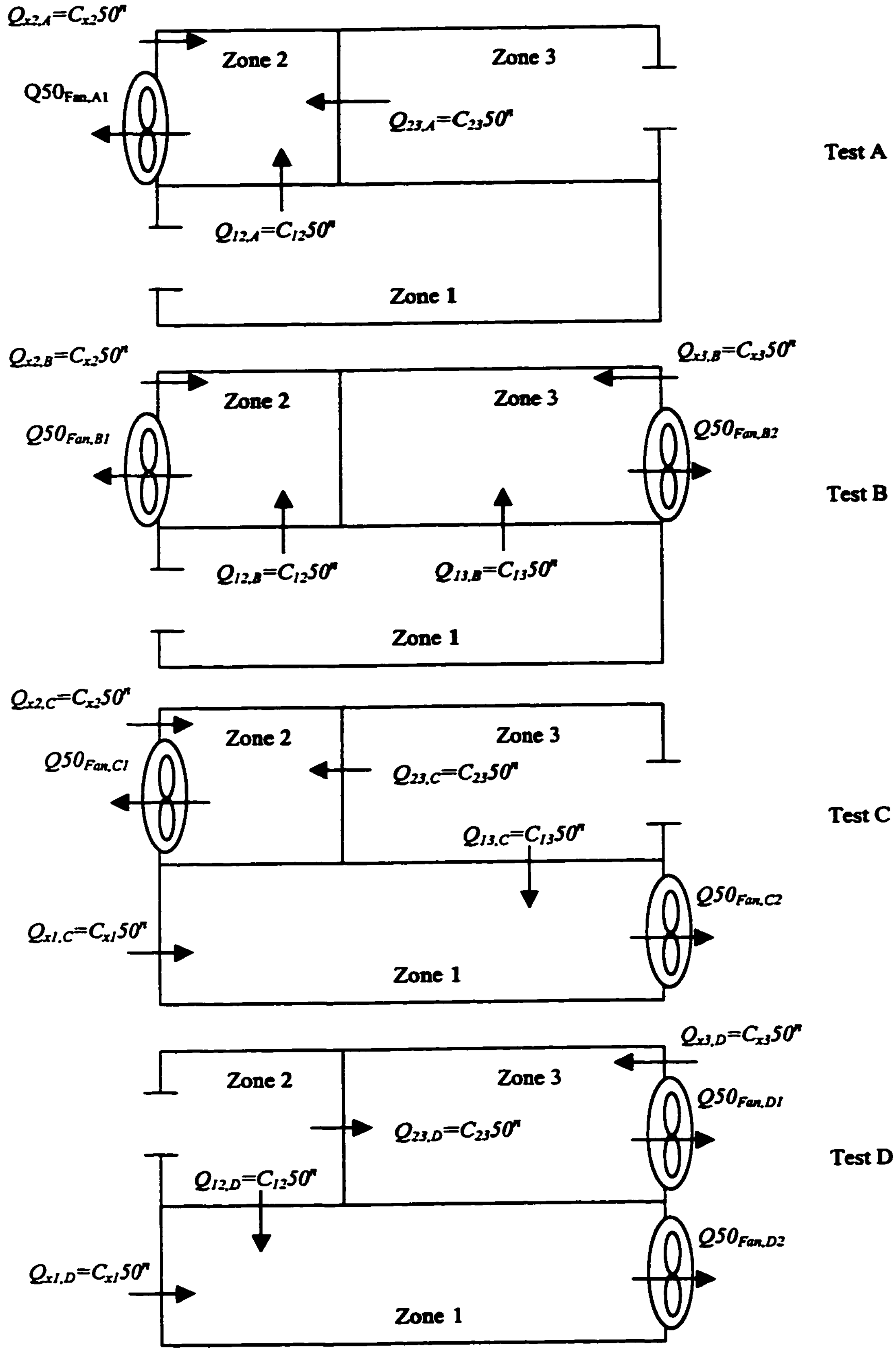

Figure 3.12 Protocol for 2-floor 3-zone configuration – Two Door Method

Balancing the flows for zones 2 and 3, for test A, gives us the following equations:

$$C_{x2}50^{n} + C_{12}50^{n} = Q50_{Fan,A1} \qquad (45)$$

$$C_{x3}50^{n} + C_{13}50^{n} = Q50_{Fan,A2} \qquad (46)$$

The 3rd and 4th equations are obtained by balancing the flows in zone 1 and 3, for test B:

$$C_{x1}50^{n} + C_{12}50^{n} = Q50_{Fan,B1} \qquad (47)$$

$$C_{x3}50^{n} + C_{23}50^{n} = Q50_{Fan,B2} \qquad (48)$$

The 5th and 6th equations are obtained by balancing the flows in zone 1 and 2, for test C:

$$C_{x1}50^{n} + C_{13}50^{n} = Q50_{Fan,C1} \qquad (49)$$

$$C_{x2}50^{n} + C_{23}50^{n} = Q50_{Fan,C2} \qquad (50)$$

3.5.4 Field Testing Procedure

The field testing procedure for the Two Door Method is summarized below.

1) Measure building volume, floor areas and envelope areas.
2) Install the blower doors in the units according to the protocol. Prepare the building for testing, according to accepted industry practice and the blower door manual.
3) Depressurize the appropriate zones to 50 Pa and measure the fan flow for each blower door (accounting for base pressure differences and change in air density if required).
4) Vary the configuration according to the protocol and repeat step 3.
5) Process the data to obtain the required results using the Excel spreadsheet.

4. Field Evaluation

4.1 Field Test Results

The field test results for the four test buildings are summarized in tables 4.1 through 4.4. These tables present the ELAs of the exterior envelopes and interior partitions obtained with the single door methods in comparison to the multi-door method (baseline). A complete compilation of the data, including pressures, flow measurements, building takeoffs and calculations, is presented in the appendix.

4.1.1 Building #1: 1040 St-Aubin

This detached 2-floor 3-unit building was built in 1965 and is located in Ville St-Laurent (figure 4.1). The ground floor unit also occupies the finished basement. Two other units are located on the 2^{nd} floor. Total heated floor space is approximately 501 m^2. Of this total 334 m^2 are for the ground floor unit, 100 m^2 for larger 2^{nd} floo unit and 67 m^2 for the smaller 2^{nd} floor unit. The building was tested as both a 2-floor 2-zone configuration and a 2-floor 3-zone configuration (see figure 3.1). A common stairway was used to combine the 2^{nd} floor units into a single zone for the first series of tests. Each unit was treated as a separate zone for the second series of tests. The interior garage was considered as an unheated space and left open to the outside during testing.

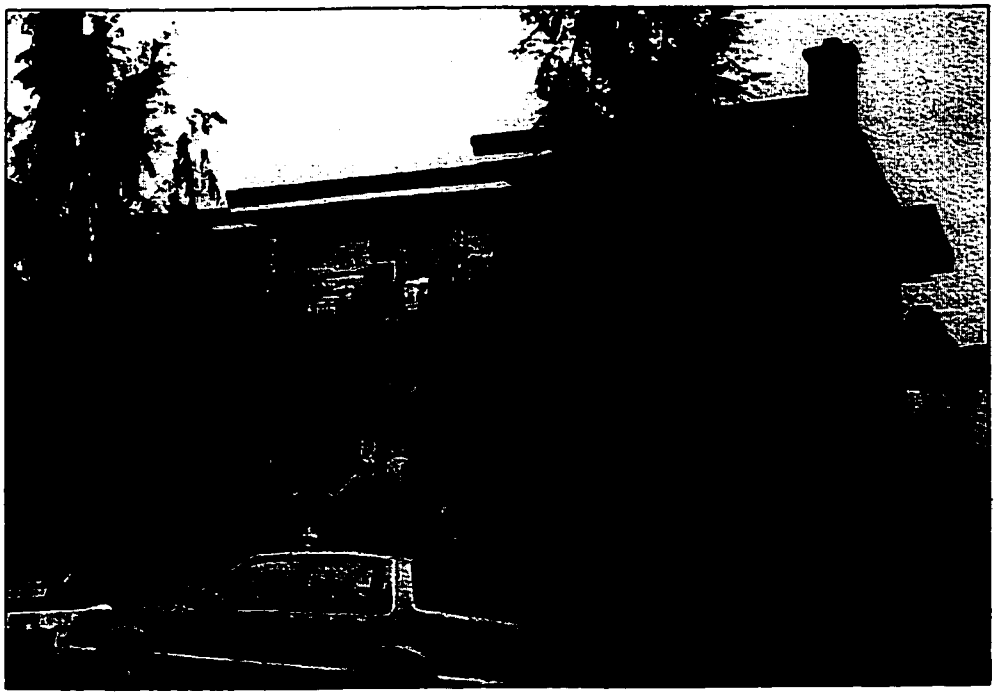

Figure 4.1 Building #1: 1040 St-Aubin

Table 4.1-A ELAs (cm^2) for Building #1: Data Set #1 (2-floor 2-zone)

Leakage Path [1]	Blower Door Method						
	Two Door (Baseline)	Area Weighted Pressure difference		Unit		Open/Closed	
	ELA (cm^2)	ELA (cm^2)	% diff.[2]	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.
X-1	2095	1842	-12.1%	1969	-6.1%	1254	-40.1%
X-2	1655	2131	28.8%	1820	10.0%	3579	116.2%
1-2	911	1044	14.5%	891	-2.2%	1752	92.3%
X-All	3751	3974	5.9%	3789	1.0%	4833	28.9%

[1] X-1= Exterior to zone 1, X-2 = exterior to zone 2, 1-2 = zone 1 to zone 2, X-All = exterior to building
[2] % difference = (ELA – ELA Baseline)/ELA Baseline

Table 4.1-B ELAs (cm^2) for Building #1: Data Set #2 (2-floor 3-zone)

Leakage Path	Blower Door Method						
	Two Door (Baseline)	Area Weighted Pressure difference		Unit		Open/Closed	
	ELA (cm^2)	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.
Ext-Z1	2199	1857	-15.6%	2009	-8.6%	1679	-23.7%
Ext-Z2	1208	1437	18.9%	1406	16.3%	1456	20.5%
Ext-Z3	348	711	104.7%	435	25.2%	1361	291.6%
Z1-Z2	427	704	64.7%	527	23.4%	665	55.6%
Z1-Z3	447	476	6.5%	468	4.8%	755	68.9%
Z2-Z3	153	NA[1]		141	-7.9%	180	17.8%
Ext-All	3755	4006	6.7%	3851	2.5%	4496	19.7%

1 NA = Not applicable (see section 3.1.3)

4.1.2 Building #2: 8399 Dunant

This semi-detached 3-unit building, located in St-Leonard, was built in 1969 (figure 4.2). The total heated floor area is 355 m^2. The ground floor unit also occupies part of the basement (170 m^2). A second unit occupies the 2nd floor (135 m^2) and a third unit (50 m^2) is located in the basement. The building was modeled as a 3-floor 3-zone configuration, with each dwelling unit assigned to one zone. The interior garage was considered as an unheated space and left open to the outside during testing.

Figure 4.2 Building #2: 8399 Dunant

Table 4.2 ELAs (cm^2) for Building #2 (3-floor 3-zone)

Leakage Path	Blower Door Method						
	Two Door (Baseline)	Area Weighted Pressure difference		Unit		Open/Closed	
	ELA (cm^2)	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.
X-1	1789	1736	-2.9%	1808	1.1%	1423	-20.4%
X-2	1864	2610	40.0%	2031	8.9%	2736	46.7%
X-3	399	368	-7.7%	547	37.0%	837	109.8%
1-2	920	888	-3.5%	691	-24.9%	931	1.2%
1-3	537	315	-41.3%	467	-12.9%	716	33.4%
X-All	4052	4714	16.3%	4385	8.2%	4996	23.3%

4.1.3 Building #3: 25501 Cousineau

This semi-detached 2-story building has two dwelling units (figure 4.3). It was built in 1957 and is located in the Cartierville district of Montreal. The principle dwelling unit occupies the ground floor and the basement (190 m^2). A second unit occupies the 2^{nd} floor (85 m^2). The total heated floor area is 285 m^2. The building was modeled as a 2-floor 2-zone configuration, with each unit representing one zone.

Figure 4.3 Building #3: 25501 Cousineau

Table 4.3 ELAs (cm^2) for Building #3 (2-floor 2-zone)

Leakage Path	Blower Door Method						
	Two Door (Baseline)	Area Weighted Pressure difference		Unit		Open/Closed	
	ELA (cm^2)	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.
X-1	2155	1570	-27.2%	2150	-0.3%	1580	-26.7%
X-2	682	1879	175.5%	905	32.7%	1862	173.0%
1-2	1059	1650	55.8%	795	-25.0%	1634	54.3%
X-All	2838	3449	21.6%	3055	7.7%	3442	21.3%

4.1.4 Building #4: 5465 Coolbrook

This detached building was built in 1967 and is located in the NDG district of Montreal (figure 4.4). The building has a total heated floor area of 345 m^2. The principle unit occupies the ground floor and the basement (230 m^2). A second unit occupies the second floor (115 m^2). The building was modeled as a 2-floor 2-zone configuration.

Figure 4.4 Building #4: 5465 Coolbrook

Table 4.4 ELAs (cm^2) for Building #4 (2-floor 2-zone)

	Blower Door Method						
Leakage Path	Two Door (Baseline)	Area Weighted Pressure difference		Unit		Open/Closed	
	ELA (cm^2)	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.	ELA (cm^2)	% diff.
X-1	1194	859	-28.1%	960	-19.6%	900	-24.6%
X-2	715	879	22.9%	712	-0.5%	811	13.4%
1-2	930	904	-2.8%	732	-21.3%	835	-10.3%
X-All	1909	1738	-9.0%	1672	-12.5%	1711	-10.4%

4.2 Discussion of Results

This section presents an assessment of the test results obtained for the four buildings. The results for the single door methods are compared to the baseline results for the ELA values of the total building envelope, the envelope of the individual units, and the interior partitions. The suitability of the single door methods is also evaluated using the criteria of practicality, time required and robustness.

4.2.1 Area Weighted Pressure Difference Method

For the Area Weighted Pressure Difference Method, the ELA values for the total exterior envelope were fairly close to the baseline values for all five data sets. The differences relative to the baseline values ranged from -9.0 % for Building #4 to 21.6 % for Building

#3. The unit-per-unit values and the interior partition values were more divergent with respect to the baseline values.

The accuracy of the Area Weighted Pressure Difference Method is dependent on how uniform the actual leakage areas are on a unit-per-unit basis, since the assumption of a uniform leakage distribution is used to set up the flow equations in the data set. Table 4.5 compares the NLA value obtained from the Area Weighted Pressure Difference Method to the variable values calculated using the Two Door Method.

Table 4.5: Comparison of NLA Values (cm^2/m^2)

	NLA – Area Weighted Pressure Difference Method (cm^2/m^2)	NLA – Two Door Method (cm^2/m^2)			
Building	All zones	Zone 1	Zone 2	Zone 3	Overall
1(A)	7.1	8.0	5.5	-	6.7
1 (B)	7.1	8.4	6.0	3.5	6.7
2	10.5	10.8	7.5	11.4	9.0
3	11.1	15.2	4.0	-	9.1
4	3.9	5.4	3.2	-	4.3

Table 4.5 indicates that the NLA values for the upper units (zones 2) were consistently smaller than for the units on the first floor (zones 1). Although a larger sample of buildings would be required to establish conclusive trends on leakage distribution, the results suggest that it would be possible to refine the assumption to reflect the average characteristics of a local building stock. The required data could be obtained from multi-door tests of a sample of buildings and used to calibrate the data set for the Area

Weighted Pressure Difference Method. This would be possible when weatherization programs target neighborhoods containing similar buildings built in the same time period.

The Area Weighted Pressure Difference Method can not provide accurate results unless the building is close to the assumed exterior leakage pattern. This also means that this method can not be used to quantify the effectiveness of weatherization work (post-retrofit), since we do not know how the retrofit work changes the leakage distribution. Another drawback worth mentioning is that an accurate measure of the exterior envelope area is required to obtain valid results. The Unit Method and the Open/Closed Method do not need this measurement to obtain the l/s50 or the ELA, which may be the only values required by the weatherization crew.

The Area Weighted Pressure Difference Method is best suited to estimate the leakage characteristics of pre-retrofit buildings in neighborhoods where the building stock is uniform. It can also provide a qualitative assessment of how well the units are connected. Of the three single-door methods tested, the Area Weighted Pressure Difference Method was the fastest and easiest to carry out. The blower door is setup only once, in the largest unit or the one suspected of having the most leakage. The technician requires only limited access to the adjacent zones to install a pressure tap and ensure that all windows are closed. The risk of human error is greatly reduced because only one flow measurement and one or two pressure measurements are required. In addition, the simplicity of this method ensures that suspected errors are easy to verify and correct.

4.2.2 Unit Method

The Unit Method yielded very good results when used to calculate the ELA of the total exterior envelope. Compared to the baseline values, the results ranged from -12.5 % difference for Building #4 to 8.2 % difference for Building #2. The exterior ELA values on a unit-per-unit basis and the ELA values for interior partitions were more divergent with respect to the baseline values, but were by far the best of the three single door methods. Particularly good results were obtained for Building #1A (table 4.1-A), where all results were within 10 % of the baseline values.

The Unit Method requires a separate blower door test in each of the units, making it more time consuming, complex and intrusive than the Area Weighted Pressure Difference Method. There is also a notable difference in the time and effort required for 3-unit buildings compared to 2-unit buildings. However, these drawbacks could be reduced once the technicians are familiar with the equipment and the testing protocol.

The Unit Method provides robust results that are not greatly affected by small variations in measured readings, which can be caused by the wind, equipment accuracy or human error. By manipulating the data entered in the Excel spreadsheet, it can be demonstrated that small variations in either the fan flows or the pressure readings do not have a large impact on the final results. For example, the measured fan flow in Test A for Building #1A was at 1667 l/s. Changing this value to 1817 l/s (9 % increase) causes the total ELA to change from 3789 cm^2 to 4032 cm^2, a 6 % increase (figure 4.5). Similarly, the initial pressure difference across the partition was 30 Pa, changing this value to 33 Pa (10 % increase) causes the total ELA to change from 3789 cm^2 to 4043 cm^2, a 7 % increase (figure 4.6).

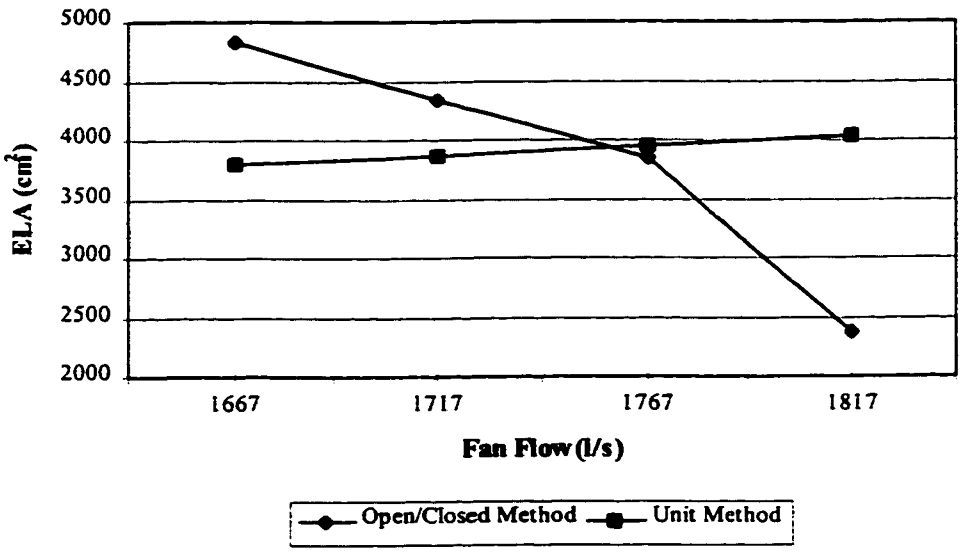

Figure 4.5 ELA as a Function of Fan Flow in Test A (Building 1A)

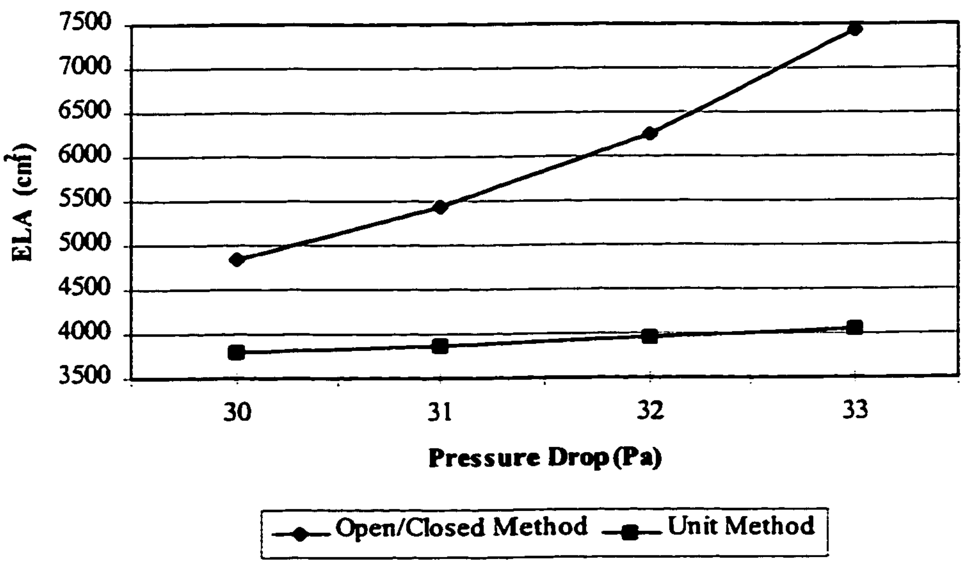

Figure 4.6 ELA as a Function of Pressure difference in Test A (Building 1A)

The Unit Method is intuitive in nature because a separate fan flow is obtained for each unit. Even before treating the collected data, the technician can make an approximate estimate of what the results will be. For example, in a 2-unit building with a relatively tight floor between units, the technician should expect a total building l/s50 that is slightly less than the sum of the two fan flows. The intuitive nature of the protocol and the robustness of the results would reduce the time required to verify questionable data.

4.2.3 Open/Closed Method

The Open/Closed Method provided approximate results for the ELA of the total exterior envelope. Compared to the baseline values, the total ELA values ranged from a -10.4 % difference for Building #4 to a 28.9 % difference for Building #1. Except for building #4, the ELA values of the interior partitions and the exterior envelopes on a unit-per-unit basis did not correspond to the baseline values. These results were the most divergent of the three single door methods compared to the baseline values.

The inaccurate results are probably linked to the fact that the simple model used to develop the data set does not account for the bypasses found in real buildings. These bypasses take the form of plumbing stacks, wall spaces, chimneys, skylights and attic spaces. The model can not account for bypass behavior when units are opened to the outside.

The Open/Closed Method is sensitive to small variations in readings, which may have contributed to the poor results. This is especially true when the difference in fan flow between the open and closed configurations or the measured pressure difference across an air barrier is small. This sensitivity can be demonstrated by manipulating the data entered in the Excel spreadsheet. For example, the measured fan flow in Test A for Building #1A was 1667 l/s, changing this to 1817 l/s (9 % increase) causes the total ELA to change from 4833 cm^2 to 2380 cm^2 (51 % reduction). In comparison, the same change applied to the Unit Method caused only a 6 % increase (figure 4.5). Changing the pressure difference across the partition from 30 Pa to 33 Pa (10 % increase) causes the total ELA to change from 4833 cm^2 to 7430 cm^2, a 54 % increase (figure 4.6). The impact of these changes on the ELA of the partitions and of the envelope on a unit-per-unit basis is even greater.

A major drawback with the Open/Closed Method is that the protocol is not intuitive, especially for the 3-zone configurations. Although the protocol is based on solid mathematical fundamentals, it is akin to a black box in which you feed values in and get values back without knowing why. Unlike the Unit Method, technicians can not estimate the outcome of the results based on the measurements. This lack of insight could increase the time spent checking results and repeating tests to verify data. The Open/Closed Method is more complex and time consuming than the Area Weighted Pressure Difference Method. It is slightly less time consuming than the Unit Method, simply because the blower door does not have to be moved around. However, opening windows could inconvenience the occupants on cold winter days. As was the case for the

Unit Method, the complexity increases for 3-unit buildings with respect to 2-unit buildings.

4.2.4 Other Considerations

Two of the tested buildings were attached. Since the protocols are developed for detached buildings, leakage across the firewall was assumed to be negligible. This is a reasonable assumption when the firewall has no intentional openings, which is normally the case unless unusual characteristics such as connected crawlspaces exist. In practice, it would be difficult to measure inter-building leakage in attached buildings. The procedure would be too complex because of the large number of zones. Also, gaining access to adjacent buildings and ensuring proper test conditions would involve logistical difficulties. Therefore, it is recommended that inter-building leakage should be considered negligible, unless evidence to the contrary is detected during the inspection.

The protocols were defined with a pressure difference of 50 Pa in the main zone with respect to the outside. This is the value commonly used for blower door tests in the industry. However, it may be convenient in certain situations to use another pressure difference. For example, it may not be possible to reach 50 Pa if the building is very leaky or very large. In this case, a lower pressure difference could be used as a basis for the tests. This situation occurred for one of the buildings tested for this thesis (Building 1), in this case a pressure difference of 40 Pa was used for the tests.

The accuracy and repeatability of blower door readings depends on the effect of weather conditions. The wind can make it difficult to measure pressure differences and thereby cause inaccurate blower door test results. In addition, when the blower door fans are exposed to the wind, the wind will interact directly with the fan itself. The stack effect can also cause a significant pressure differential across the envelope. For these reasons, it is preferable to test buildings under calm conditions and with small inside-outside temperature differences. Standard CAN/CGSB-149.10 [2] recommends that tests should not be performed when the wind speed exceeds 20 km/h. It is recommended that the operator take time averaged pressure readings and that the operator account for the base pressures across the air barriers when recording pressure differences.

The repeatability of blower door measurements may also be influenced by seasonal variations in moisture content in envelope construction materials. Weatherization work can also lead to higher moisture content levels in the envelope unless mechanical ventilation is used to offset the reduced air flux through the envelope. Occupant behavior and lifestyle also influence indoor humidity levels and further complicate matters. At this point, the impact of moisture content variations in the envelope for the multifamily buildings addressed in this thesis remains an open question.

As was discussed in Section 3.1, the flow exponent n generally lies between 0.6 and 0.7 [14], and a value of 0.65 was used in this thesis. Although this assumption is considered appropriate within the scope of this thesis, it is important to evaluate the sensitivity of the test methods to the value of n. For this purpose, the value of n was varied incrementally from 0.6 to 0.7 in the Excel program for one of the buildings tested (Building 1A). The results are presented in figure 4.7.

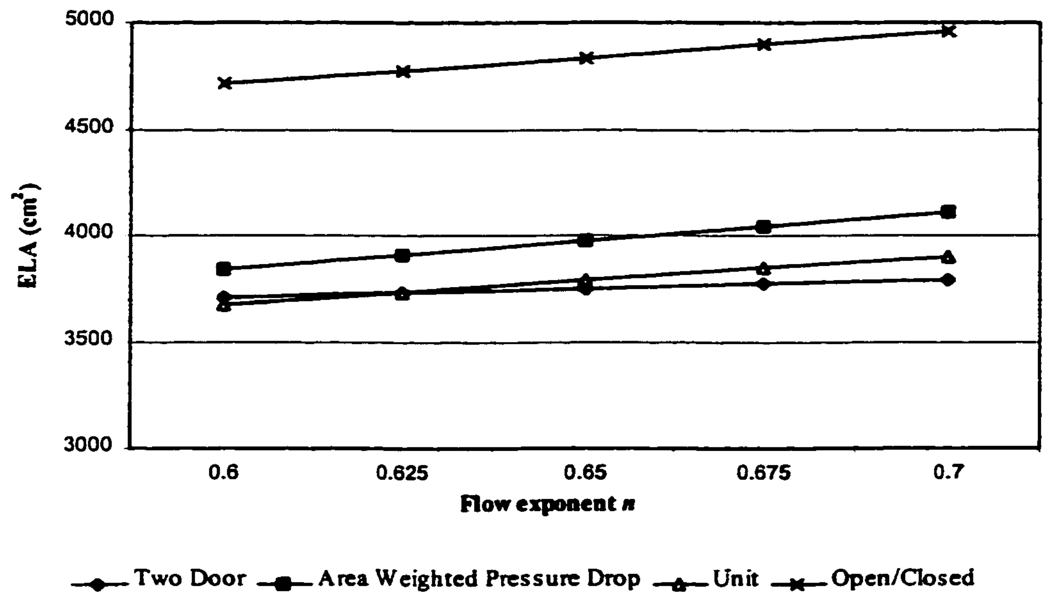

Figure 4.7 ELA as a Function of Flow Exponent (Building 1A)

The results indicate that within the range of interest, none of the methods can be considered sensitive to the value of *n*. The Two Door Method was the least sensitive with a 2.2 % increase in the ELA when the value of *n* went from 0.6 to 0.7, compared to increases of approximately 6 % for all three single door methods.

5. Conclusion

5.1 Summary and Conclusions

This thesis developed and evaluated three single blower door methods, which can be used to establish the leakage characteristics of both the exterior envelope and the interior partitions of two or three-unit buildings. These methods rely on airflow measurements using only one blower door, combined with pressure measurements in adjacent zones. Field tests were performed on four pre-1970 buildings in the Montreal area, typical of the local building stock. The results were analyzed in comparison to baseline values obtained using multiple blower doors.

The Unit Method, which requires a fan flow measurement in each unit, compared favorably with the baseline results. This method provided values that were within 12.5 % of the baseline for the ELA of the building shell in all the tested buildings. Its interzonal and unit-per-unit ELA values were more divergent, but were on average within 25 % of the baseline values. At a minimum, the results provide an approximate estimate of how well the units are connected and how the leakage area is distributed. The main strength of this method is that the results are robust and intuitive. Small discrepancies in the fan flow and the pressure readings will not significantly change the results. The intuitive nature of the protocol makes it appropriate for weatherization crews and would reduce the time required to validate questionable results.

The Area Weighted Pressure Difference Method uses a simple approach, based on the assumption of a uniform leakage distribution for the exterior envelope. This method provides approximate results for the overall ELA of the tested buildings and a qualitative assessment of how well the units are connected. The refinement of the assumption to better reflect the actual leakage distribution can improve the accuracy of this method. This method is best suited to test the airtightness of pre-retrofit buildings in neighborhoods where the building stock is uniform, but is inappropriate to measure the effectiveness of weatherization work. The main advantages of this method are its simplicity and speed.

The Open/Closed Method, which changes flow configurations by opening and closing the units to the outside, can not be used dependably to estimate the airtightness of multifamily buildings. This method is very sensitive to small changes in measured readings, especially when the difference in fan flow between the open and closed configurations or the measured pressure difference across an air barrier is small. In addition, the lack of intuitiveness in the protocol makes it unsuitable for use by weatherization crews.

The contribution of this thesis is the development of blower door methods, which can be used to estimate both the external and the interzonal air leakage in 2 and 3-unit multifamily buildings using only one blower door. This represents significantly more valuable information than is currently obtained with the whole building depressurization technique. These results can be used to estimate the impact of retrofit measures on natural ventilation, to establish the need for mechanical ventilation and to estimate potential energy savings.

5.2 Implications for Weatherization Programs

The recent emergence of the renovation market in Canada has increased the interest in blower door testing as part of weatherization services and programs. These programs often target low-rise multifamily buildings since they are usually less insulated and airtight than single-family dwellings. However, retrofitting these buildings raises many concerns about indoor air quality, ventilation requirements and the cost. Although these issues also apply to single-family detached houses, they are more complex in multifamily buildings due to interzonal air movement. For these reasons, it is important to estimate how energy retrofits impact both the external and the interzonal air movement in multifamily buildings.

The implications of this research work for weatherization programs will depend on the scope, constraints and liabilities of the agency overseeing the program. Some of the specific issues are the building selection process, the estimation of cost effectiveness and potential energy savings, ensuring adequate air change rate (natural or mechanical ventilation), and time and budget constraints.

Utility bills are often used in weatherization programs to identify the least efficient buildings in a certain region. The selected buildings are then visited to ensure that they meet all the program requirements for structural integrity, electrical safety and accessibility. At this point, the potential for energy savings is confirmed through a visual inspection combined with quantitative measurements, such as a blower door test. Because this is only a screening process, time and cost are more important than accuracy. The Area Weighted Pressure Difference Method may be suitable to screen these pre-retrofit buildings in neighborhoods where the building stock is uniform. The Unit Method would be more appropriate for atypical buildings.

Weatherization programs usually have a cost-effectiveness target in terms of "kWh saved per dollars spent". An accurate estimation of the building airtightness is part of the information needed to justify cost-effectiveness. These expenses must be added to the total cost of the weatherization work. Therefore, keeping these extra expenses to a minimum is a priority. In this respect, the Unit Method provides reasonably accurate results, while requiring fewer resources than a multi-door test.

Much progress has been made in recent years in understanding how a building works as an integrated system. We now realize that changes made to one particular component of the building can also influence the performance of several other components. The implications for weatherization programs are important. The sponsoring agency is not only responsible for the work done, but also for the impact this work has on the building as a system. For example, air sealing allows us to save on energy costs, but it also has an impact on ventilation and humidity levels. Sealing a leaky building reduces the fresh air supply, which in turn increases humidity levels. This may then lead to condensation, mold and air quality problems. Another example is the added structural load caused by insulating an attic space. Not only must the weight of the insulation be considered, but also the extra snow load caused by the reduced heat loss through the roof.

Ventilation is a critical issue because of its impact on health. The program sponsor must ensure that the weatherization work does not lead to inadequate ventilation [21,22,23]. Ventilation is a particularly complex issue in multifamily buildings. Multi-zone airflow models are needed to analyze the natural and mechanical ventilation rates on a unit-per-unit basis. However, current models such as CONTAM [24] and COMIS [25] were designed as research tools, rather than for use on site by weatherization crews [26,27]. The value of blower door data is limited without the availability of simple and effective multi-zone airflow models. Ideally, weatherization crews should be equipped with simple graphical airflow models that allow blower door results to be evaluated on site.

Current building codes and standards do not address the specific issues relating to post-retrofit ventilation in multifamily buildings. Therefore, the responsibility and liability issues for the renovation market remain unclear. The emergence of the renovation market will create a shift in the research effort towards these issues in the near future. The results of this study can contribute to the development of standards for determining the airtightness of multifamily buildings.

5.3 Recommendations for Future Research Work

This thesis work was initiated to partly address the growing interest in the measurement and analysis of airtightness characteristics of older multifamily buildings. These buildings represent a great potential for energy savings and will be targeted by weatherization programs in the near future. Insulating and sealing measures can change how these buildings behave as a system by making the envelope more airtight. This can lead to unexpected problems such as poor indoor air quality and condensation due to higher indoor humidity levels. Providing adequate mechanical ventilation may be considered necessary in certain cases.

Future research could investigate the effectiveness of exhaust fans as a means to increase outdoor air supply in multifamily buildings. Older buildings usually have no mechanical ventilation. It is either too difficult or too expensive to install a balanced ventilation system with ducts to the main zones in these buildings. For this reason, exhaust fans are usually considered as the most appropriate ventilation option following retrofit work. However, the quantity of outdoor air drawn through the envelope by these fans on a unit-per-unit basis is not well understood and would make an interesting research topic. Ventilation could be examined on a unit-per-unit basis using hourly weather files for various locations. Other factors that could be considered are fan location, the airtightness of the envelope and of interior partitions. This research would contribute to our knowledge of ventilation for the segment of the existing building stock which is most likely to be targeted for energy retrofits and weatherization programs in the near future.

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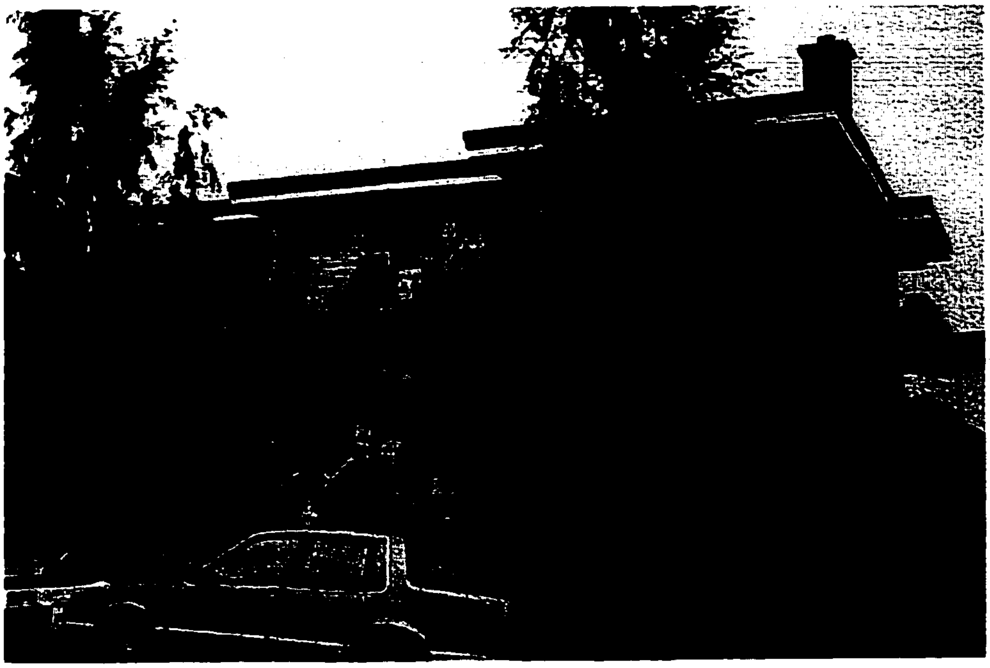
Appendix

Field Data and Calculations

General Information:

Building No.:	**1A**	Date of test:	20-May-99
Address:	1040 St-Aubin	Outdoor temp.:	20 C
	St-Laurent	Indoor temp.:	20 C
Construction year:	1965	Conditions:	Light wind
Owner:	L.J. Ottoni		
Configuration:	2F-2Z		



Takeoffs:

	[illegible]	Zone 2	[illegible]	[illegible]
Floor Area (m2)	334	167		501
Envelope [illegible]	261	302		563
Volume (m3)	840	434		1274

Area Weighted Pressure Drop Method | n= 0.65 | **(Building #1A)**

	Base	Gauge	Adjusted	
Q50fan (l/s):		1667	[redacted]	
Px1 (Pa):	0.0	-40	[redacted]	*
Px2 (Pa):	0.0	-10	[redacted]	
P12 (Pa):	0.0	-30	[redacted]	
At/A2			[redacted]	
At/A1			[redacted]	

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set									
Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]		[redacted]		[redacted]
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Unit Method

	Base	Test A Gauge	Adjusted	Test B Gauge	Adjusted
Q50fan (l/s):		1667	[redacted]	1595	[redacted]
Px1 (Pa):	0.0	-40	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0.0	-10	[redacted]	-40	[redacted]
P12 (Pa):	0.0	-30	[redacted]	-32	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set									
Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]		[redacted]		[redacted]
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Open/Closed Method

	Base	Test A Gauge	Adjusted	Test B Gauge	Adjusted
Q50fan (l/s):		1667	[redacted]	1851	[redacted]
Px1 (Pa):	0.0	-40	[redacted]	-40	[redacted]
Px2 (Pa):	0.0	-10	[redacted]	0	[redacted]
P12 (Pa):	0.0	-30	[redacted]	-40	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set									
Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]		[redacted]		[redacted]
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Multiple Door Method

	Base	Test A Gauge	Test A Adjusted	Test B Gauge	Test B Adjusted
Q50fan-1 (l/s):		1290	[redacted]	1851	[redacted]
Q50fan-2 (l/s):		1019	[redacted]	[redacted]	[redacted]
Px1 (Pa):	0.0	-40	[redacted]	-40	[redacted]
Px2 (Pa):	0.0	-40	[redacted]	[redacted]	[redacted]
P12 (Pa):	0.0	[redacted]	[redacted]	-40	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]		[redacted]		[redacted]
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

*** Due to the size and leakiness of the building, it was not possible to use 50 Pa as a basis for the tests, therefore a pressure of 40 Pa was used instead**

General Information

Test Number:	**1B**	Date of test:	20-May-99
Building Address:	St-Aubain	Outdoor temp.:	20
	St-Laurent	Indoor temp.:	20
Construction Year:	1965	Conditions:	Light wind
Owner:	L.J. Ottoni		
Configuration:	2F-3Z		

Takeoffs:

	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	334	100	67	501
[illegible]	261	202	100	563
[illegible]	840	260	174	1274

(Building #1B)

Area Weighted Pressure Drop Metho n= 0.65

	Base	Guage	Adjust	
Q50fan (l/s):		1724	[redacted]	
Px1 (Pa):	0	-40	[redacted]	*
Px2 (Pa):	0	-10	[redacted]	
Px3 (Pa):	0	-14	[redacted]	
P12 (Pa):	0	-30	[redacted]	
P13 (Pa):	0	-26	[redacted]	
At/A1			[redacted]	
At/A2			[redacted]	
At/A3			[redacted]	

Cx1	Cx2	Cx3	C12	C13	Qfan
[redacted]					

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A-	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A-	[redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x3	[redacted]	A-	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]				
C23:	[redacted]	l/s50-23:	[redacted]	ELA-23	[redacted]				
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A	[redacted]

Unit Method n= 0.65

	Base	Test A Guage	Adjust	Test B Guage	Adjust	Test C Guage	Adjust
Q50fan (l/s):		1724	[redacted]	1251	[redacted]	613	[redacted]
Px1 (Pa):	0	-40	[redacted]	-4	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0	-10	[redacted]	-40	[redacted]	[redacted]	[redacted]
Px3 (Pa):	0	-14	[redacted]	[redacted]	[redacted]	-40	[redacted]
P12 (Pa):	0	-30	[redacted]	-36	[redacted]	[redacted]	[redacted]
P13 (Pa):	0	-26	[redacted]	-1	[redacted]	-35	[redacted]
P23 (Pa):	0	-4	[redacted]	-37	[redacted]	-36	[redacted]

Cx1	Cx2	Cx3	C12	C13	C23	Qfan
[redacted]						

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A-	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A-	[redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x3	[redacted]	A-	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]				
C23:	[redacted]	l/s50-23:	[redacted]	ELA-23	[redacted]				
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A	[redacted]

Open/Closed Method | **n= 0.65** | **(Building #1B)**

	Base	Test A Guage	Adjust	Test B Guage	Adjust	Test C Guage	Adjust
Q50fan (l/s):		1724	[redacted]	1828	[redacted]	1852	[redacted]
Px1 (Pa):	0	-40	[redacted]	-40	[redacted]	-40	[redacted]
Px2 (Pa):	0	[redacted]	[redacted]	[redacted]	[redacted]	-8	[redacted]
Px3 (Pa):	0	[redacted]	[redacted]	-10	[redacted]	[redacted]	[redacted]
P12 (Pa):	0	-30	[redacted]	-40	[redacted]	-32	[redacted]
P13 (Pa):	0	-26	[redacted]	-30	[redacted]	-40	[redacted]
P23 (Pa):	0	[redacted]	[redacted]	-10	[redacted]	-8	[redacted]

Cx1	Cx2	Cx3	C12	C13	C23	Qfan
[redacted]						

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A- [redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A- [redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x3	[redacted]	A- [redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]			
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]			
C23:	[redacted]	l/s50-23:	[redacted]	ELA-23	[redacted]			
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A [redacted]

Multiple Door Method | **n= 0.65**

	Base	Test A Guage	Adjust	Test B Guage	Adjust	Test C Guage	Adjust
Q50fan1 (l/s):		1101	[redacted]	1007	[redacted]	838	[redacted]
Q50fan2 (l/s):		[redacted]	[redacted]	489	[redacted]	[redacted]	[redacted]
Px1 (Pa):	0	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0	-40	[redacted]	-40	[redacted]	-40	[redacted]
Px3 (Pa):	0	[redacted]	[redacted]	-40	[redacted]	[redacted]	[redacted]
P12 (Pa):	0	-40	[redacted]	-40	[redacted]	[redacted]	[redacted]
P13 (Pa):	0	[redacted]	[redacted]	-40	[redacted]	[redacted]	[redacted]
P23 (Pa):	0	-40	[redacted]	[redacted]	[redacted]	-40	[redacted]

Cx1	Cx2	Cx3	C12	C13	C23	Qfan
[redacted]						

	Base	Test D Guage	Adjust
Q50fan1 (l/s):		308	[redacted]
Q50fan2 (l/s):		1617	[redacted]
Px1 (Pa):	0	-40	[redacted]
Px2 (Pa):	0	[redacted]	[redacted]
Px3 (Pa):	0	-40	[redacted]
P12 (Pa):	0	-40	[redacted]
P13 (Pa):	0	[redacted]	[redacted]
P23 (Pa):	0	-40	[redacted]

*** Due to the size and leakiness of the building, it was not possible to use 50 Pa as a basis for the tests, therefore a pressure of 40 Pa was used instead**

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A- [redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A- [redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x3	[redacted]	A- [redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]			
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]			
C23:	[redacted]	l/s50-23:	[redacted]	ELA-23	[redacted]			
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A [redacted]

General Information:

Building No.:	**2**	Date of test:	22-May-99
Address:	8399 Dunant	Outdoor temp	22
	St-Leonard	Indoor temp.:	22
Construction year:	1965	Conditions:	Light wind
Owner:	Gino Gerbasi		
Configuration:	3F-3Z		

Takeoffs:

	[illegible]	[illegible]	[illegible]	[illegible]
Floor Area	170	135	50	355
Envelope Area	165	248	35	448
Volume	440	329	122	891

Area Weighted Pressure Drop Method

n=	0.65

	Base	Gauge	Adjust
Qfan (l/s):		1954	[redacted]
Px1 (Pa):	0.0	-50	[redacted]
Px2 (Pa):	0.0	-8	[redacted]
Px3 (Pa):	0.0	-22	[redacted]
P12 (Pa):	0.0	-42	[redacted]
P13 (Pa):	0.0	-28	[redacted]
At/A1			[redacted]
At/A2			[redacted]
At/A3			[redacted]

Cx1	Cx2	Cx3	C12	C13	Qfan
[redacted]					

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x	[redacted]	A50-2	[redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x	[redacted]	A50-3	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]				
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Unit Method

n=	0.65

	Base	Test A Gauge	Adjust	Test B Gauge	Adjust	Test C Gauge	Adjust
Qfan (l/s):		1954	[redacted]	1843	[redacted]	677.0	[redacted]
Px1 (Pa):	0.0	-50	[redacted]	-14	[redacted]	-10.0	[redacted]
Px2 (Pa):	0.0	-8	[redacted]	-50	[redacted]	[redacted]	[redacted]
Px3 (Pa):	0.0	-22	[redacted]	[redacted]	[redacted]	-50.0	[redacted]
P12 (Pa):	0.0	-42	[redacted]	-36	[redacted]	[redacted]	[redacted]
P13 (Pa):	0.0	-28	[redacted]	[redacted]	[redacted]	-40.0	[redacted]

Cx1	Cx2	Cx3	C12	C13	Qfan
[redacted]					

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x	[redacted]	A50-2	[redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x	[redacted]	A50-3	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]				
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Open/Closed Method | n= 0.65

	Base	Test A Gauge	Adjust	Test B Gauge	Adjust	Test C Gauge	Adjust	Cx1	Cx2	Cx3	C12	C13	Qfan
Qfan (l/s):		1954	[redacted]	2025	[redacted]	2150.0	[redacted]						
Px1 (Pa):	0.0	-50	[redacted]	-50	[redacted]	-50.0	[redacted]	[redacted]					
Px2 (Pa):	0.0	-8	[redacted]	0	[redacted]	-4.0	[redacted]	[redacted]					
Px3 (Pa):	0.0	-22	[redacted]	-22	[redacted]	0.0	[redacted]	[redacted]					
P12 (Pa):	0.0	-42	[redacted]	-50	[redacted]	-46.0	[redacted]	[redacted]					
P13 (Pa):	0.0	-28	[redacted]	-28	[redacted]	-50.0	[redacted]	[redacted]					

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x	[redacted]	A50-2	[redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x	[redacted]	A50-3	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]				
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Two Door Method | n= 0.65

	Base	Test A Gauge	Adjust	Test B Gauge	Adjust	Test C Gauge	Adjust	Cx1	Cx2	Cx3	C12	C13	Qfan
Qfan1 (l/s):		1928	[redacted]	[redacted]	[redacted]	1655.0	[redacted]						
Qfan2 (l/s):		284	[redacted]	666	[redacted]	1327.0	[redacted]						
Px1 (Pa):	0.0	-50	[redacted]	[redacted]	[redacted]	-50.0	[redacted]	[redacted]					
Px2 (Pa):	0.0	[redacted]	[redacted]	[redacted]	[redacted]	-50.0	[redacted]	[redacted]					
Px3 (Pa):	0.0	-50	[redacted]	-50	[redacted]	[redacted]	[redacted]	[redacted]					
P12 (Pa):	0.0	-50	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]					
P13 (Pa):	0.0	[redacted]	[redacted]	-50	[redacted]	-50.0	[redacted]	[redacted]					

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x	[redacted]	A50-2	[redacted]
Cx3:	[redacted]	l/s50-x3:	[redacted]	ELA-x3	[redacted]	NLA-x	[redacted]	A50-3	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
C13:	[redacted]	l/s50-13:	[redacted]	ELA-13	[redacted]				
		l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

General Information:

Building No.:	3	Date of test:	27-May-99
Address:	12501 Cousineau	Outdoor temp.:	18
	Montreal	Indoor temp.:	18
Construction year:	1955	Conditions:	Light wind
Owner:	Nicolas Gill		
Configuration:	2F-2Z		

Takeoffs:

	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	190	95		285
[illegible]	142	170		312
[illegible]	464	232		696

Area Weighted Pressure Drop Method **n=** **0.65** **(Building #3)**

	Base	Gauge	Adjusted
Q50fan (l/s50):		1655	[redacted]
Px1 (Pa):	0.0	-40	[redacted]
Px2 (Pa):	0.0	-18	[redacted]
P12 (Pa):	0.0	-22	[redacted]
At/A2			[redacted]
At/A1			[redacted]

Cx1	Cx2	C12 Qfan
[redacted]		

Solution set

Cx1:	[redacted]	**l/s50-x1:**	[redacted]	**ELA-x1**	[redacted]	**NLA-x1**	[redacted]	**A50-1**	[redacted]
Cx2:	[redacted]	**l/s50-x2:**	[redacted]	**ELA-x2**	[redacted]	**NLA-x2**	[redacted]	**A50-2**	[redacted]
C12:	[redacted]	**l/s50-12:**	[redacted]	**ELA-12**	[redacted]				
Cx-all	[redacted]	**l/s50-x:**	[redacted]	**ELA-x**	[redacted]	**NLA-x**	[redacted]	**A50**	[redacted]

Unit Method

	Base	Test A Gauge	Adjusted	Test B Gauge	Adjusted
Q50fan (l/s50):		1655	[redacted]	989	[redacted]
Px1 (Pa):	0.0	-40	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0.0	-18	[redacted]	-40	[redacted]
P12 (Pa):	0.0	-22	[redacted]	-33	[redacted]

Cx1	Cx2	C12 Qfan
[redacted]		

Solution set

Cx1:	[redacted]	**l/s50-x1:**	[redacted]	**ELA-x1**	[redacted]	**NLA-x1**	[redacted]	**A50-1**	[redacted]
Cx2:	[redacted]	**l/s50-x2:**	[redacted]	**ELA-x2**	[redacted]	**NLA-x2**	[redacted]	**A50-2**	[redacted]
C12:	[redacted]	**l/s50-12:**	[redacted]	**ELA-12**	[redacted]				
Cx-all	[redacted]	**l/s50-x:**	[redacted]	**ELA-x**	[redacted]	**NLA-x**	[redacted]	**A50**	[redacted]

Open/Closed Method

	Base	Test A Gauge	Adjusted	Test B Gauge	Adjusted
Q50fan (l/s50):		1655	[redacted]	1979	[redacted]
Px1 (Pa):	0.0	-40	[redacted]	-40	[redacted]
Px2 (Pa):	0.0	-18	[redacted]	0	[redacted]
P12 (Pa):	0.0	-22	[redacted]	-40	[redacted]

Cx1	Cx2	C12 Qfan
[redacted]		

Solution set

Cx1:	[redacted]	**l/s50-x1:**	[redacted]	**ELA-x1**	[redacted]	**NLA-x1**	[redacted]	**A50-1**	[redacted]
Cx2:	[redacted]	**l/s50-x2:**	[redacted]	**ELA-x2**	[redacted]	**NLA-x2**	[redacted]	**A50-2**	[redacted]
C12:	[redacted]	**l/s50-12:**	[redacted]	**ELA-12**	[redacted]				
Cx-all	[redacted]	**l/s50-x:**	[redacted]	**ELA-x**	[redacted]	**NLA-x**	[redacted]	**A50**	[redacted]

Multiple Door Method

	Base	Test A Gauge	Test A Adjusted	Test B Gauge	Test B Adjusted
Q50fan-1 (l/s50):		1327	[redacted]	1979	[redacted]
Q50fan-2 (l/s50):		420	[redacted]	[redacted]	[redacted]
Px1 (Pa):	0.0	-40	[redacted]	-40	[redacted]
Px2 (Pa):	0.0	-40	[redacted]	[redacted]	[redacted]
P12 (Pa):	0.0	[redacted]	[redacted]	-40	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

General Information:

Building No.:	4	Date of test:	June 13,1999
Address:	5465 Coolbrook	Outdoor temp.:	29
	Montreal	Indoor temp.:	27
Construction year:	1950	Conditions:	Light wind
Owner:	Hiroshi nakamura		
Configuration:	2F-2Z		

Takeoffs:

	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	230	115		345
[illegible]	220	225		445
[illegible]	560	280		840

Area Weighted Pressure Drop Method **n= 0.65** **(Building #4)**

	Base	Gauge	Adjusted
Q50fan (l/s50):		989	[redacted]
Px1 (Pa):	0.0	-50	[redacted]
Px2 (Pa):	0.0	-23	[redacted]
P12 (Pa):	0.0	-22	[redacted]
At/A2			[redacted]
At/A1			[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Unit Method

	Base	Test A Gauge	Adjusted	Test B Gauge	Adjusted
Q50fan (l/s50):		989	[redacted]	979	[redacted]
Px1 (Pa):	0.0	-50	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0.0	-23	[redacted]	-50	[redacted]
P12 (Pa):	0.0	-22	[redacted]	-43	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Open/Closed Method

	Base	Test A Gauge	Adjusted	Test B Gauge	Adjusted
Q50fan (l/s50):		989	[redacted]	1171	[redacted]
Px1 (Pa):	0.0	-50	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0.0	-23	[redacted]	-50	[redacted]
P12 (Pa):	0.0	-22	[redacted]	-50	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]

Multiple Door Method

	Base	Test A Gauge	Test A Adjusted	Test B Gauge	Test B Adjusted
Q50fan-1 (l/s50):		850	[redacted]	[redacted]	[redacted]
Q50fan-2 (l/s50):		509	[redacted]	1171	[redacted]
Px1 (Pa):	0.0	-50	[redacted]	[redacted]	[redacted]
Px2 (Pa):	0.0	-50	[redacted]	-50	[redacted]
P12 (Pa):	0.0	[redacted]	[redacted]	-50	[redacted]

Cx1	Cx2	C12	Qfan
[redacted]			

Solution set

Cx1:	[redacted]	l/s50-x1:	[redacted]	ELA-x1	[redacted]	NLA-x1	[redacted]	A50-1	[redacted]
Cx2:	[redacted]	l/s50-x2:	[redacted]	ELA-x2	[redacted]	NLA-x2	[redacted]	A50-2	[redacted]
C12:	[redacted]	l/s50-12:	[redacted]	ELA-12	[redacted]				
Cx-all	[redacted]	l/s50-x:	[redacted]	ELA-x	[redacted]	NLA-x	[redacted]	A50	[redacted]