AN INNOVATIVE AIRTIGHTNESS TEST PROCEDURE FOR SEPARATING ENVELOPE AIR LEAKAGE FROM INTERIOR PARTITION AIR LEAKAGE IN MULTI-ZONE BUILDINGS

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ABSTRACT

An Innovative Airtightness Test Procedure For Separating Envelope Air Leakage From Interior Partition Air Leakage In Multi-Zone Buildings

Gary Proskiw

A new airtightness test procedure has been developed for separating exterior envelope air leakage from interior partition leakage, when testing a single zone within a multi-zone building. Historically, envelope leakage from a single zone within a multi-zone building could only be measured if exact equalization was achieved of the pressure differentials across all interior partition surfaces using a masking blower(s). Experimentally, this has proven to be problematic with the result that the procedure is seldom used. The new technique, called the "Parallel Flow Airtightness Test" method (PFAT) permits partition leakage to be measured and subtracted from the total leakage of the test zone thereby allowing the exterior envelope leakage to be isolated and quantified. However, instead of requiring exact equalization of the interior partition pressure differentials, the new technique only requires that they be modified from their original values. Experimentally, this is a much easier condition to achieve and offers significant advantages to practitioners.

As part of this thesis, the PFAT test procedure was proposed, validated in a series of laboratory trials and then applied to three different buildings to assess its practicality under real-world conditions. Using the results of the laboratory and field work, guidelines were then developed for applying the methodology to other structures.

Under laboratory conditions (with no wind or indoor-to-outdoor pressure differentials to account for), the PFAT method was capable of measuring the exterior envelope air leakage with a maximum error of about 2% at 75 Pa, when a second blower was used to modify the pressure regimes in the adjacent, buffer zone. When the pressure regimes in the buffer zone were modified by simply sealing or unsealing a duct to the buffer zone, the accuracy of the procedure degraded significantly, producing errors of up to 26%.

The field trials were then carried out on three multi-zone buildings in Winnipeg. From these trials it was concluded that the procedure seems well suited to field work and offers advantages, in terms of time and equipment, over the traditional pressure-masking technique. However, greater skill and better planning are required relative to that needed for a conventional, single-zone airtightness test. Overall, it was concluded that for many applications the PFAT method provides a workable method of separating interior partition air leakage from exterior envelope building.

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NOMENCLATURE

A	Area (m^2)
ac/hr	Air changes per hour (1/hour)
C	Flow coefficient (L/s•Pa^n)
C_p	Pressure coefficient (dimensionless)
d	Deviation
D	Diameter (m)
ELA	Equivalent Leakage Area (m^2)
f	Friction factor (dimensionless)
g	Gravitational constant (m/s^2)
g_c	Conversion factor (kg•m/m^2)
H	Height (m)
L	Length (m)
L	Litres
m	Metres
n	Flow exponent (dimensionless)
NLA	Normalized Leakage Area (cm^2/m^2)
NLR	Normalized Leakage Rate (L/s•m^2)
Pa	Pascals
Q	Flow rate (L/s or m^3/s)
R_e	Reynolds number
s	Seconds
T	Temperature (°C)
V	Velocity (m/s)
ΔP	Pressure differential (Pa)
v	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Standard deviation

CHAPTER 1

INTRODUCTION

1.1 AIR LEAKAGE IN BUILDINGS

One of the most significant developments in the field of building science over the last 25 years has been the recognition of the critical role which air leakage plays in determining a structure's performance, durability, functionality and longevity. Excess air leakage can lead to a host of problems including accelerated envelope degradation, increased energy costs, reduced comfort as well as increased noise, dirt and pollutant transfer from the outdoors. In Canada, the financial impact of envelope air leakage has been estimated at several hundred million dollars per year with much of this amount attributed to premature envelope failure due to air exfiltration/moisture deposition. Obviously, a building's airtightness can have a critical role in determining the performance of the structure.

For air leakage to occur two requirements must be satisfied: a physical opening must be present in the building envelope and a pressure differential must exist across the opening. Unintentional cracks, holes and other discontinuities are always present although their size and flow characteristics can vary dramatically over the building envelope and among different structures. These leakage paths invariably occur because most of the materials used in construction are semi-permeable to air flow and, more importantly, the major connections between major building elements (such as the wall/foundation intersection or the window/wall joint) are almost never airtight with the result that air leakage is free to occur whenever a pressure differential exists. In fact, the objective of so-called "airtight" construction practices is not to eliminate air leakage since this would be far too ambitious a goal, but rather to control it within acceptable limits.

There are three driving forces which can induce air leakage in a building: wind action, stack effect and mechanical systems. Wind action is the most easily recognized. A wind blowing against a building creates a positive pressure differential on the windward side of the structure which induces air infiltration, i.e. air flows from the outdoors, across the building envelope, and into the structure. On the leeward side the opposite occurs, a negative pressure differential is generated (relative to the indoors) which causes air exfiltration, i.e. the flow of interior air through the envelope to the outdoors. The magnitude of the wind-induced pressure differential is proportional to the square of the wind velocity; therefore, if the wind speed doubles the pressure differentials increase by a factor of four. Wind-induced pressure differentials can range as high as a couple of thousand Pascals (Pa) under extreme wind conditions although more typical values would be in the order of 10 to 100 Pa. Fortunately, extreme pressure differentials are normally of short duration (a handful of seconds). Since the wind-induced pressure differential varies dramatically over the building envelope, predicting the leakage rate at a specific location is generally quite difficult.

The second air leakage driver, the stack effect, is created by the temperature differential between the indoors and outdoors and is so-named because its behaviour replicates that of a chimney or stack. For example, in winter the air inside the building is warmer, and hence has a lower density, than the ambient air which causes a pressure differential to be created over the lower portions of the building which induces air infiltration. Over the upper portions of the structure, the reverse occurs with the result that the stack effect generates air exfiltration over the upper portion of the building. The magnitude of the stack effect depends on the temperature differential between the indoors and outdoors and the height of the building. As both variables increase, so does the stack effect. Typical values for the stack-induced pressure differential in low-rise Canadian buildings under winter conditions are in the order of 5 to 15 Pa for low-rise residential construction although this can increase to well over 100 Pa for taller commercial-type structures.

The third driving force for air leakage is operation of the building's mechanical systems. Any mechanical device which is capable of exhausting or supplying air across the building envelope will generate pressure differentials between the indoors and outdoors and thereby induce air leakage through the envelope. Devices in this category include exhaust and supply fans, Heat Recovery Ventilators, make-up air ducts, relief air ducts and other components which might be included as part of the ventilation system. It also includes other mechanical devices not normally considered part of the ventilation system such as clothes dryers and indoor barbeques which exhaust to the outdoors. The magnitude of mechanical system-induced pressure differentials varies greatly but is typically in the range of -25 Pa to + 25 Pa, depending on the direction of the net air flow across the envelope.

The magnitude of the net pressure differential created by these three forces varies with time and with location on the envelope and is the algebraic sum of the individual pressure differentials created by the three drivers. Given the nature of these forces, it is obvious that the pressure differentials acting on a building envelope can vary significantly in terms of magnitude and direction.

Wind and, to a lesser extent, stack-induced air leakage tend to be highly dynamic in their behaviour since they are predominately controlled by naturally occurring factors such as wind speed and direction, and by ambient temperature. Mechanically induced air leakage is generally more stable in nature since most mechanical systems operate under relatively steady-state conditions for extended periods of time. It is also the only one of the three driving forces which can be controlled by the building's occupants.

The pattern of air leakage over the building envelope is determined by the distribution of cracks, holes and other discontinuities as well as the pressure differential at each location. Contrary to popular belief, most air leakage in buildings does not usually occur through the doors and windows but is distributed over the envelope in a very non-uniform pattern. Generally speaking, most leakage occurs at the major joints, intersections and penetrations in the envelope. For example, in residential construction one of the major leakage locations is often the wall/foundation intersection because three major components meet at this location (exterior wall, floor system and the foundation) and hence there is opportunity for leakage to occur if these joints are not adequately detailed and constructed to control leakage. Opaque building envelope components such as walls and ceilings generally demonstrate extremely low leakage rates through the actual component although significant leakage can occur at the intersections of these components with other elements or where elements pass through the opaque sections (such as service penetrations or windows).

In most cases, the leakage paths are not geometrically simple holes or cracks in the envelope through which air can easily flow. In practice, they are often complex, even byzantine matrices with both parallel and series flow passages which are interconnected to other leakage pathways in unpredictable ways. While the flow characteristics of simple pathways can often be easily described, those present in most building envelopes are much more complex and are normally identified through empirical testing of the complete structure without any commentary on the behaviour of specific leaks.

1.2 CHARACTERIZING AIR LEAKAGE IN BUILDINGS

It has been said (by some anonymous sage) that "you don't understand something until you can quantify it". Accepting this pearl of wisdom, we are led to the conclusion that understanding air leakage, and its effects, requires quantified knowledge of the building's air leakage characteristics. The capability to actually measure the airtightness of a building and provide an objective, quantified description of this value was first developed in Scandinavia during the 1960's or 1970's with the development of the "blower door" - a test rig suitable for field use which could be used to perform an airtightness test on smaller structures such as detached houses. The rig consisted of large capacity blower which was mounted into a temporary frame installed in a suitable doorway. With the blower running, the entire envelope was subjected to air leakage into the house (air infiltration), typically to indoor-to-outdoor pressure differentials of up to about 75 Pa. The only place where air was able to exit the building was at the blower where a nozzle or orfice plate could be located to measure the exhaust air rate. Since the exhaust flow rate through the nozzle had to equal the rate at which air was leaking into the structure, it became possible to measure the blower exhaust flow rate and thereby know the rate of air movement into the house. By measuring the amount of air leakage at various indoor-to-outdoor pressure differentials, the leakage characteristics of the building could be characterized. Since then, test procedures have been developed and standardized by such bodies as the Canadian General Standards Board (CGSB), the American Society for Testing and Materials (ASTM) as well as a number of

European standards-writing bodies.

These procedures and equipment work well for houses and other small buildings. However, as the structure becomes larger and more complex (and demonstrates higher leakage rates), most commercially available test equipment will not have adequate capacity to properly test the structure. In the case of very large buildings, the air flow capacity which is available may only be a small fraction of that which is required.

One result of this situation is that the body of airtightness knowledge available on smaller buildings such as houses is dramatically more extensive than it is for larger buildings. At present, reliable airtightness data exists for roughly 250,000 Canadian houses while the equivalent number for large, commercial-style buildings for which data is available in the literature is less than 200 - worldwide. This creates some significant problems.

Without quantified knowledge of the air leakage characteristics of a building, an array of important information will remain unknown (and unknowable). For example:

- How does the subject building's airtightness compare to those of other structures of similar size, age, construction, etc.?
- Does the building meet mandated airtightness requirements as defined by the building code or other standards?
- If computer-based, energy or ventilation models are being used, what inputs should be employed to describe the envelope's leakage characteristics?
- If the building has been retrofitted, how much has the retrofit improved the airtightness characteristics?
- Is the building vulnerable to envelope degradation due to air exfiltration/moisture deposition within the envelope?
- What will be the energy impact of uncontrolled air leakage and to what extent can it be mitigated by sealing measures?

While broad similarities may appear to exist among buildings in terms of their air leakage characteristics, experience has clearly demonstrated the difficulty of predicting the behaviour of a specific building. This is most pronounced with older structures which tend to much leakier than new construction. Differences in leakage behaviour are also affected by the type of building, the style of construction, type of cladding, maintenance history, location, builder experience, etc. Even among newly constructed, detached houses it is very difficult for even an experienced airtightness tester to accurately predict leakage behaviour since such large variations can occur. In fact, field testing has repeatedly shown that the measured airtightness of even ostensibly similar buildings can vary dramatically - by as much as an order of magnitude.

The air leakage characteristics of buildings are seldom treated as a performance variable - i.e. one which must be specified during the design phase and then met during the construction phase. With the exception of a relatively small number of houses and a few commercial buildings which are designed and constructed to specific, quantitative airtightness standards, the air leakage characteristics of most Canadian buildings was, and is, a by-product of the construction process. In other words, the air leakage rate is viewed as something to be merely accepted after the fact, rather than as a measured performance variable which can be compared to a specified design requirement. The only major exceptions are those houses constructed to the R-2000 Standard, or equivalent, (which collectively represent less than 1% of new construction) and non-residential buildings constructed to requirements such as the C-2000 Standard or the Commercial Building Incentive Program (which have an even smaller market penetration than R-2000 houses). One result of this situation is that there is only a modest demand for airtightness testing services in Canada.

While testing detached houses is relatively straightforward exercise, as the building becomes larger testing becomes much more problematic due to the physical requirements for blowers which must now move comparatively large quantities of air. For example, at present there are a few hundred blower doors in use in Canada (to be discussed later). These can handle all but the largest (or more correctly, the leakiest) houses as well as some small commercial-type buildings. However, their maximum flow capacity is about 2,500 L/s (5300 ft^3/min) which is well below that required for testing most commercial buildings. In fact, as will be discussed later most commercial buildings are leakier, per unit size, than comparably sized houses. One option for larger buildings is to utilize multiple, residential blower doors to develop sufficient flow capacity. While this technique has worked with reasonable success, it does dictate significant equipment, manpower and organizational requirements. Other options have also been investigating utilizing very large capacity blowers however these have only seen very limited application, usually just for research purposes. As a result, many large buildings simply cannot be tested using commercially available procedures, equipment and expertise. New ideas are needed to give these buildings the opportunity to benefit from airtightness testing and thereby improve the structure's overall performance.

1.3 ORGANIZATION

Chapter 1 of this thesis provides a brief introduction to air leakage theory and principles as well as airtightness testing of buildings with a particular emphasis on larger, multi-zone buildings.

Chapter 2 defines the problem in more detail and examines the rationale for the research. Chapter 3 reviews the theoretical basis for the Parallel Flow Airtightness Test method. and the laboratory test rig used in its development, while Chapter 4 reviews the laboratory trials in more detail.

Chapter 5 discusses the field trials which were used to evaluate the new procedure while Chapter 6 discusses the results of the laboratory and field trials.

Chapter 7 provides a detailed, step-by-step description of the procedure and is intended for use by those who wish to use the new method. Chapter 8 summarizes the conclusions and recommendations from this work. Finally, the need for future work on the development of the procedure is considered in Chapter 9.

For readers less familiar with the theory and practice of air leakage in buildings, Appendix A describes the basic physics of the phenomenon, the affects which it can produce and how air leakage rates are commonly measured in greater detail than has been discussed here. It also provides a description of how air leakage data are reported and reviews typical air leakage characteristics of actual buildings using measured data from several hundred tests. It also contains a discussion of equipment and performance airtightness standards currently in use around the world.

Appendix B contains the data from, and results of, the laboratory testing described in Chapter 4.

CHAPTER 2

RATIONALE FOR THE RESEARCH

2.1 MEASURING THE AIRTIGHTNESS OF SINGLE-ZONE BUILDINGS

To understand the need for the research described in this thesis, it is necessary to review the procedures currently used for quantifying building airtightness. The concept of measuring, or characterizing, the air leakage of a building is a relatively new tool for building scientists; in fact, the first airtightness tests were only performed in Canada about 30 years ago. The protocol for measuring the airtightness of single-zone buildings has been established and formalized by a number of standards-writing bodies including the Canadian General Standards Board (CGSB-149.10 - “Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method”) and the American Society for Testing and Materials (ASTM E 779 - “Standard Test Method for Determining Air Leakage Rate by Fan Pressurization”). CGSB-149.10 (which was first published in 1986) is the primary airtightness testing standard used in Canada while ASTM E 779 is more widely used in the United States. A number of other test standards have also been developed in locations such as Europe. Although these standards all have slight differences from each other, they follow the same basic protocol.

Figure 1 shows the basic test configuration used for performing an airtightness test on a detached, single-zone building such as a house. First, a device colloquially known as a “blower door” is installed in a suitable doorway. The blower door consists of an adjustable frame with a fabric or solid insert and a large capacity fan which is used to exhaust air from the building (although most commercial models also feature a reversible blower so that air can be supplied, rather than exhausted). The blower door is designed to provide a relatively tight seal to the existing door frame although some supplemental taping may be required. The blower uses an adjustable speed control to modulate the flow rate thereby producing any desired indoor-to-outdoor pressure differential within the flow range of the equipment. Air flow rates through the blower are typically measured using a nozzle or offce plate assembly installed directly onto the blower with the entire unit calibrated at the factory. Most commercial units include a series of nozzles or orfice plates to provide flow measuring capability over a wide range of air flow rates. Maximum flow rates for current models sold in North America are about 2,500 L/s (5,300 ft^3/min).

To perform the test, all exterior doors (other than the one occupied by the blower door) and windows are closed and any other intentional holes in the building envelope (such as exhaust or supply air ducts) are temporarily sealed. All interior doors are opened so the building has no appreciable internal flow resistance and can legitimately be treated as a single zone. Some type of pressure measuring device, such as a digital micromanometer is used to determine the indoor-to-outdoor pressure differential. To minimize data scatter, restrictions are usually placed on the maximum wind speed under which the test can be performed, typically no more than 20 km/hr.

Once the test set-up is complete, the blower is activated to establish the initial pressure differential. In the case of CGSB-149.10, a value of 50 Pa ± 2.5 Pa is used. Under normal stack effect in winter, an indoor-to-outdoor pressure differential of approximately 5 Pa is developed for each storey of the structure. Thus for detached houses and similar buildings, 50 Pa is sufficiently high that the entire building envelope will be subjected to air infiltration. As a result, the only location where air is physically leaving the building is at the calibrated blower door - where it can be measured. The rate of envelope leakage must therefore equal the rate at which air is exhausted by the blower door. Once the pressure and flow rate have stabilized (which typically takes a few seconds), the values of both are recorded. The flow rate is then reduced by about 5 Pa (to 45 Pa) and a new flow rate and pressure differential established and then recorded. This process is repeated over a range of indoor-to-outdoor pressure differentials ranging from 50 Pa to 15 Pa.

Some blower door manufacturers now also offer automated units which control the fan speed and record the appropriate pressure data so that the operator is no longer required to actively intervene in the process. With the aid of a laptop computer, these units basically perform the entire test.

Experience has shown that air flow through a porous structure, such as a building envelope or components which make up the building envelope, follows a mathematical relationship which can be described using a power equation of the form...

$$Q = C\,\Delta p^{n} \qquad (1)$$

where:

Q = air flow rate (L/s)

C = flow coefficient ($L/s \cdot Pa^{n}$)

ΔP = indoor-to-outdoor pressure differential (Pa)

n = flow exponent (dimensionless)

Although Eq. (1) is not derived from first principles, such as the Continuity equation or Bernoulli's theory, it has been found to work remarkably well. Establishing the correlation shown in Eq. (1) is accomplished by first determining the logarithms of the flow rate and pressure differential data measured during the test. When the logarithms are plotted, the result is a linear equation from which the two unknowns (C and n) can be calculated. Correlation coefficients (r) of 0.99 or better can usually be achieved from the plot of air flow rate versus indoor-to-outdoor pressure differential. In fact, CGSB-149.10 requires that the correlation coefficient exceed 0.99 for the test to be considered valid.

CGSB-149.10 also places important restrictions on permitted values for the flow exponent (n) in Eq. (1). For the test to be valid, n must have a value between 0.5 and 1.0. As explained in Appendix A, the lower limit represents the case of pure orfice flow and would describe the case of a building with physically large holes. The upper limit describes the case of laminar flow which might occur through a number of small diameter flow passages. Actual building envelopes have leakage characteristics which are between these two extremes and reflects the diverse nature of the flow paths through the envelope. These restrictions on the flow exponent are mentioned here because they will be used in the Parallel Flow Airtightness Test method.

Airtightness test data analysis is usually carried out using manufacturer-supplied software packages which are structured to comply with the data treatment and analysis procedures specified in the parent standards. The time required to complete the analysis is usually about 10 minutes once the required information has been assembled.

Aside from the quantitative determination of the structure's air leakage characteristics, the test also provides an opportunity to perform a qualitative assessment of the envelope to determine the location of the air leaks and give an indication of their relative magnitudes (minor, major, etc.). In many instances, this information is as valuable as the actual quantitative results since it provides valuable guidance on where corrective actions are required (in new construction) or remedial work (in retrofits) is needed.

Over the last quarter of a century, this methodology has been successfully employed hundreds of thousands of times on Canadian buildings such that there is now a large and ever-growing body of knowledge about the air leakage characteristics of buildings against which the results of current tests can be compared.

The test method is relatively quick (usually taking between one and two hours on site), requires equipment which is moderately priced (approximately $5,000), is easy to transport (a sub-compact car is adequate) and does not require extensive expertise or education since most practitioners can be given adequate training in one or two days. The test can be performed at any time of the year and does not require unusual environmental conditions to be successfully completed. As mentioned, the maximum wind speed permitted by the CGSB procedure is 20 km/hr; no limitations are placed on the indoor or outdoor temperatures.

2.2 MEASURING THE AIRTIGHTNESS OF MULTI-ZONE BUILDINGS

While single-zone airtightness tests can be described as easy to plan, perform and analyse, the situation becomes much more complex as the building becomes significantly larger than (say) a detached house. Basically, the problem is the difficulty of obtaining sufficient air-moving capacity to sufficiently depressurize (or pressurize) the structure coupled with the need to control operation of the buildings's doors and windows and mechanical systems. The sheer size of most multi-zone buildings and hence the amount of envelope leakage which can be expected is usually much greater than can normally be handled with a conventional blower door. Either very larger blowers or multiple blowers must be used. Also, the air leakage rate per unit area of building envelope is usually much greater in multi-zone buildings than it is for detached houses (Proskiw, 2001). A few blower door manufacturers are now producing multiple units which are basically two or three conventional blower assemblies ganged together to fit into a single doorway. While this can increase the total air-moving capacity by a factor of perhaps five or six, even this is inadequate for many large buildings.

In the 1980's, the National Research Council of Canada developed equipment for performing airtightness tests on large buildings (Shaw, 1980). It featured a trailer-mounted blower system with an airflow capacity of about 23 m^3/s (50,000 ft^3/min). The blower was connected to the building using a 0.9 m (3') flexible ductwork arrangement and a temporary plywood door plug. Unfortunately, it has only seen limited use and then only as a research tool. In fact, the rig was last seen by the author languishing in the parking lot of NRC in Ottawa. At about the same time, a similar device was built by the (then) National Bureau of Standards in the United States. Their system consisted of a 7.5 m^3/s (16,000 ft^3/min) axial fan which was powered by a 7,000 W, 230 V single-phase, gasoline-powered generator (Hunt, 1984). Flow rates were measured using a pitot static flow monitoring assembly with built-in flow straighteners mounted approximately one fan diameter upstream of the fan. Both of these systems were workable and were successfully used on a number of buildings. However, given the complexity and cost of the rigs they were regarded as research tools only and were not really envisioned as engineering equipment which could be routinely used for commercial applications. Since practitioners generate most of the data on airtightness, the net result has been a very limited knowledge base on large building airtightness. For example, while airtightness data has been documented for hundreds of thousands of Canadian houses, the equivalent amount of data has been accumulated for only a few hundred buildings - world wide.

Another issue which can cause problems is that many multi-zone buildings are much taller than houses which means the stack effect can be significantly larger such that the blower may not be able to adequately depressurize the structure.

In addition, when conducting an airtightness test absolute control over the building is normally required since doors and operable windows have to be kept closed, interior doors kept open and sealing of intentional openings attended to. All of this takes time, often considerable amounts of time and normally dictates that the occupants vacate the building. Given that most multi-zone buildings are normally occupied by large numbers of people, this can create very real practical problems. For example, consider the difficulty of attempting to conduct an airtightness test on a Multi-Unit Residential Building (MURB) or hotel. These types of buildings are normally occupied 24 hours per day and have operable windows. How can the testing agency be confident that the occupants have not intentionally or accidentally opened one or more of the windows - even a slight amount? Even continuous, exterior observation of the building before, during and after the test would not likely be adequate. Calculations have shown that with even a very small percentage of the operable window area open, the air leakage characteristics of the building will be dominated by the open windows - not the building envelope (Proskiw, 2006).

One way of dealing with the limitations of performing whole building airtightness tests on multi-zone buildings is to test a single zone within the structure and extrapolate the results to the entire structure. This approach has the advantage of being logistically much simpler (and cheaper) and precludes the need for expensive equipment and personnel requirements needed to operate multiple blower assemblies. Also, absolute control over the building is not required, only the zone which is actually being tested and perhaps one or two adjacent zones. Obviously, the limitation of this approach is that only a small (but hopefully representative) sample of the building envelope is being tested. Further, all of the envelope's details may not be represented in the single test zone. A version of this approach has been successfully used by the author on dozens of occasions to perform qualitative examinations on single zones within a large building. It is commonly used to identify the locations of air leaks in retrofit situations where the intent is to retrofit the envelope. Obviously, this requirement dictates that information be obtained regarding where the air leaks are situated so that remedial efforts can be designed.

To illustrate, consider the case of a hotel which is suffering envelope distress due to air exfiltration and interstitial moisture deposition. While conducting a complete airtightness test on the entire building would be very expensive, time-consuming and subject to all the limitations described above, a qualitative examination of a single room or a small number of rooms can be easily performed in a few hours by mounting the blower door in the doorway to the test suites By depressurizing the room, the location and relative magnitudes of air leaks can be assessed with relative ease and the remedial package designed. Leakage across internal partitions, floors and ceilings can be ignored and just the air leakage across the building envelope assessed. .While this technique does not provide a quantitative determination of the leakage characteristics of the envelope, it does provide very valuable information on the existing behaviour of the envelope and permits retrofit dollars to be directed where they will produce the maximum benefit.

To summarize, airtightness testing of single-zone buildings to provide both a quantitative assessment of the leakage characteristics and a qualitative determination of the locations of air leaks is a well-established, reliable and very modestly priced endeavour. In contrast, testing an entire large, multi-zone building is certainly possible but only after some significant issues have been dealt with:

- Very large, high-capacity blowers (possibly with their own power supplies) are normally required and these may not even be commercially available.
- Absolute control over the building is needed to insure inadvertent door and window openings do not take place or that intentional seals are not disturbed.
- Considerable time is normally required with a number of trained personnel needed to successfully carry out the test.
- The cost of the test can be considerable.

The ability to quantitatively test a single-zone within a multi-zone building would significantly increase the flexibility and opportunities for airtightness tests on large buildings. Being able to produce quantitative as well as qualitative results, at reasonable cost, would increase the utility of airtightness testing for this class of structure. It would be particularly beneficial for existing buildings since they are normally occupied which precludes whole building testing or at least makes it highly problematic. It is worth noting that while no formal statistics are available on the subject, it is certain that hundreds of Canadian, multi-zone buildings have been retrofitted over the last 20 years to correct problems with their building envelopes. Most of these retrofits have been required well before the normal life expectancy of either the building or the envelope had been reached (in some cases these retrofits have been required on structures which were only a few years old). Collectively, they represent an expenditure of several billions of dollars. Obviously, anything which can be done to improve the assessments of these buildings and the design of their retrofits could be hugely beneficial. Therefore, let us consider the issues involved in performing a quantitative airtightness test on a single zone within a multi-zone building.

2.3 PROBLEM STATEMENT

Consider Fig. 2 which shows a building comprised of Zone A (the test zone) and Zone B (the additional space). Although they are shown as having the same floor area in the schematic representation, in practice the two zones might be considerably different from each other in terms of area and volume. Let us assume that the envelope leakage through Zone A (Q_A) is of interest. If a blower door is set up in Zone A exhausting to the outdoors then the air flow through the orfice plate (or other flow-measuring system) used by the blower door consists of Q_A and Q_B (the envelope leakage through Zone B). However, since Q_A cannot be isolated from Q_B, we have no way of determining either variable.

Historically, the only means of solving this problem has been to use the "Balanced Fan Depressurization Technique" developed by Shaw and Reardon of the National Research Council (Reardon, Kim and Shaw, 1987). The details of this technique are described in detail in Appendix A, but basically it involves using a second, masking blower to neutralize the pressure differential across the interior surfaces which separate the test zone from the rest of the building. In other words, for each indoor-to-outdoor pressure differential established in Zone A, a second blower is used in Zone B which exhausts air to the outdoors at a sufficient rate to neutralize the pressure differential across the interior partitions. Thus, all of the air flow measured at the blower door in Zone A is envelope leakage through Zone A (the quantity of interest). In a relatively small structure with moderate leakage, the masking blower should be able to neutralize the pressure differential across the interior partitions providing sufficient care and skill are exercised. Unfortunately, as the size - or more correctly the leakage - of the second (non-test) zone becomes larger, the required capacity of the masking blower can become excessive. Given that virtually all of the blowers used today for airtightness testing in Canada and the United States are those developed for residential applications, with maximum flow capacities of about 2,500 L/s (5,300 ft^3/min), virtually all researchers and practitioners will not have the necessary equipment to perform such tests.

Although it may not be obvious from Fig. 2, another problem arises. The two blower systems have a tendency to interfere with one another such that small balancing adjustments made to one tends to cause fluctuations in the flow rate of the second - which requires adjustment of the second blower - which then causes the original blower to change its flow rate - and so on. While this sounds like a minor problem, the author has used this technique in the field and found that blower interaction can be a surprisingly annoying and a difficult problem to deal with since it is necessary to carefully maintain a zero pressure differential across the interior partitions. In some cases, more than two blowers may be required with this technique. For example, if a single suite in a hotel or apartment block is being tested, pressure masking would be required for the suite above, below and on both sides of the test suite - a total of one test suite and four masking blowers. This produces multiple interference patterns among the blowers which can best be described as akin to trying to hold five, greased, squirming children in your arms at one time. Easy to describe on paper but very difficult in practice.

The key problem with the masking blower approach is that the pressure differential across interior partitions has to be maintained at exactly zero - not simply reduced or moderated to some degree.

To deal with this problem, a new test method (which is the subject of this thesis) has been developed which can isolate exterior building envelope air leakage from interior partition leakage in certain multi-zone buildings, but which does not require exact equalization of the partition pressure differentials – only that the pressure differentials can be modified by a second fan. As a result, the required air-moving capacity of the second blower is significantly reduced, even to the extent that residential blower doors can be successfully used in many commercial building applications. Further, since exact pressure equalization is not required across the partitions, flow balancing during the test is simplified. This new procedure has been termed the "Parallel Flow Airtightness Test" method. Interaction between the primary and masking blower is also reduced since exact neutralization of the partition surfaces pressure differential is not required.

This thesis describes the theory, development and evaluation of the "Parallel Flow Airtightness Test" (PFAT) method for measuring the air leakage in a single zone of a multi-zone building.

2.4 OBJECTIVES

The research described in this thesis was carried out to further the development of the Parallel Flow Airtightness Test method. Its specific objectives were:

1. To develop and evaluate the new procedure.
2. To validate the method under laboratory conditions and define its limitations, data requirements and analysis methods.
3. To apply the procedure to three multi-zone buildings thereby identifying its utility and practicality under real-world conditions.
4. To prepare a formal methodology for performing the test.

CHAPTER 3

DEVELOPMENT OF THE PARALLEL FLOW AIRTIGHTNESS TEST METHOD

3.1 OVERVIEW OF THE DEVELOPMENT PROJECT

The original concept for the Parallel Flow Airtightness Test method dates back to when the candidate was performing pre-renovation testing on one zone of an institutional building scheduled to receive a major renovation to its building envelope to reduce unintentional air leakage. Originally, the scope of work for the testing program included only qualitative air leakage examinations of the building envelope (for determining the locations and relative strengths of the leakage pathways). However, during the course of performing this work, the basic concept for the PFAT test method was conceived, developed and subsequently used to test the zone of interest within the overall structure (Proskiw, 2003).

The development work consisted of two phases. The first was construction and utilization of a laboratory test facility which could be used to replicate, from a fluid mechanics perspective, the air leakage characteristics of a two-zone structure. Using this test rig, the capabilities of the PFAT method could be explored in more detail under controlled conditions (zero wind and zero indoor-to-outdoor temperature differentials) and with various test configurations. Further, the design of the test rig permitted the "envelope" leakage characteristics of the two zones to be adjusted (as desired) and measured, thereby providing information on the accuracy of the new procedure.

In addition, the test rig allowed inter-zone air leakage to be measured (the significance of which will be explained shortly). This was a critical advantage which the test rig offered since it had been recognized that a fundamental weakness of any field testing program was that it could not provide data on the amount of inter-zone leakage and hence the accuracy of the PFAT method. The test rig eliminated this problem by providing independent quantification of the inter-zone leakage.

The second phase of the project consisted of applying the new procedure to a sample of actual buildings. These tests provided insight on the overall practicality of the procedure under field conditions. For this phase, the new technique was applied to three multi-zone buildings of varying size, construction and occupancy. Using the results of these two phases, a series of observations and conclusions were developed on the accuracy, practicality and utility of the PFAT method. Suggestions were also proposed for further development work.

3.2 DESCRIPTION OF THE TEST METHOD

The PFAT method solves the problem of separating exterior envelope air leakage through the test zone from partition leakage (between the test and buffer zones) by using two blower doors set up in the configuration shown in Fig. 3. Zone A is the test zone and Zone B represents the buffer zone. The first blower door (the "primary blower door") is set up in the test zone and is used to exhaust air from Zone A to either Zone B or to the outdoors. The second blower door is located in the buffer zone and exhausts directly to the outdoors.

To perform the test, the primary blower door is activated and used to achieve an "initial" pressure differential across the exterior envelope ($\Delta P_{A\ initial}$) and the interior partition ($\Delta P_{B\ initial}$), both of which are measured and recorded. The indoor-to-outdoor pressure differential in Zone B is then altered by turning on the masking blower door. This changes the pressure differential across the envelope of the test zone partitions (ΔP_B) and, as a result, the flow rate through the primary blower door (Q_T).

Next, the air flow rate through the primary blower door is adjusted until $\Delta P_{A\ initial}$ equals $\Delta P_{A\ final}$. This produces the "final" condition. Since the air flow rate across a flow restriction is proportional to the pressure differential across the restriction (Eq. (1)), $Q_{A\ initial}$ must equal $Q_{A\ final}$ and the resulting change in air flow through the primary blower door must be due solely to the change in leakage across the partitions. Expressed mathematically...

$$Q_T = Q_A + Q_B \tag{2}$$

where:

Q_T = air flow rate measured at the primary blower door

Q_A = air leakage across the exterior envelope in Zone A

Q_B = air leakage across the interior partitions between Zones A and B

So, $Q_{T\ initial} = Q_{A\ initial} + Q_{B\ initial}$

and $Q_{T\ final} = Q_{A\ final} + Q_{B\ final}$

thus, $\Delta Q_T = Q_{T\ initial} - Q_{T\ final}$

$= (Q_{A\ initial} + Q_{B\ initial}) - (Q_{A\ final} + Q_{B\ final})$

but, $\Delta P_{A\ initial} = \Delta P_{A\ final}$

so $Q_{A\ initial} = Q_{A\ final}$

thus $\Delta Q_T = Q_{B\ initial} - Q_{B\ final}$

since $Q = C\Delta P^n$

$\Delta Q_T = C_P \Delta P^{np}{}_{B\ initial} - C_P \Delta P^{np}{}_{B\ final}$ or

$$\boxed{\Delta Q_T = C_P(\Delta P^{np}{}_{B\ initial} - \Delta P^{np}{}_{B\ final}) \qquad (3)}$$

where:

C_p = flow coefficient of the partitions

n_p = flow exponent of the partitions

Therefore, by operating the primary blower door to produce an initial set of pressure differentials, and then activating the secondary blower door to modify these values, we can produce one equation of the form shown in Eq. (3). Of the five terms in Eq. (3), three are known (ΔQ_T, $\Delta P_{B\ initial}$, $\Delta P_{B\ final}$) and two are unknown (C_p and n_p). We now have one equation in two unknowns - a situation for which there is not an explicit solution.

However, we can repeat this exercise using a new, initial flow rate through the primary blower door. This produces a new flow rate differential when the secondary blower door in Zone B is activated (ΔQ_T) and a new set of values for, $\Delta P_{B\ initial}$ and $\Delta P_{B\ final}$. This leaves us with a new equation, again with three known and two unknown variables. However, by proper manipulation of these two equations in two unknowns, a solution can be found.

Equations of the form shown in Eq. (3) in which the unknown variable(s) are contained in an exponent are known as transcendental equations. Unfortunately, direct algebraic solutions of transcendental equations can be difficult to obtain. However, an iterative, trial and error approach can be used which permits solutions to be determined.

Using Eq. (3) - with different values for ΔQ_T, $\Delta P_{B\,initial}$ and $\Delta P_{B\,final}$ and dividing the first version of the equation by the second, C_p cancels out and we are left with one equation in one unknown (n_p).

$$\frac{[\Delta Q_T]_1}{[\Delta Q_T]_2} = \frac{C_P[(\Delta P^{np}{}_{B\,initial} - \Delta P^{np}{}_{B\,final})]_1}{C_P[(\Delta P^{np}{}_{B\,initial} - \Delta P^{np}{}_{B\,final})]_2}$$

$$\frac{[\Delta Q_T]_1}{[\Delta Q_T]_2} = \frac{[(\Delta P^{np}{}_{B\,initial} - \Delta P^{np}{}_{B\,final})]_1}{[(\Delta P^{np}{}_{B\,initial} - \Delta P^{np}{}_{B\,final})]_2} \qquad (4)$$

Since the unknown variable is in the exponents, the simplest solution is to assume an initial value for n_p, substitute it back into the equation and determine if an equality has been achieved. Assuming that an equality is not achieved on the first attempt, then the initial assumed value for n_p is adjusted and the process repeated until closure is achieved (which typically requires five to ten iterations). Once n_p has been determined, C_p can be easily calculated. Although it sounds cumbersome, this process can be performed very rapidly with the aid of a spreadsheet - which is how the calculations were performed in this project.

Thus, using Eq. (4) with different flow rates and pressure differentials, we can produce explicit solutions for the two variables which define the air leakage characteristics of the partitions (n_p and C_p).

To provide greater data integrity, this process is repeated for a number of different sets of conditions to give a series of equations. Obviously, the greater the number of test conditions and equations which are generated, the greater the number of possible pairs of equations which can be combined for solutions. By comparing all possible combinations of the different pairs of equations, a number of explicit estimates of the solution can be found (the term "estimates" is used because these are empirically determined values which are subject to experimental error). This is the classic situation in which we have "n" sets of items which can be combined in a number of different groups of two. The number of possible combinations by which the data equations can be combined for simultaneous solution can be calculated using Eq. (5).

$$\text{Number of combinations} = N! / [2(N-2)!] \qquad (5)$$

where:

N = number of equations generated.

The final step in the process is to conduct a standard blower door test using CGSB-149.10, or equivalent, on Zone A while the doors or windows are kept open in Zone B. This effectively negates the flow resistance of the Zone B envelope and exposes all surfaces in Zone A (both exterior and partition) to the same pressure differential. Since the leakage characteristics of the partitions (C_p and n_p) are now known, Q_B can be determined. As a result, Q_A can be calculated by subtracting Q_B from Q_T (which is measured using the primary blower door).

3.3 BUILDING AIR LEAKAGE SIMULATOR TEST RIG

To evaluate the new test procedure under controlled conditions, a laboratory test rig was constructed. Known as the "Building Air Leakage Simulator", it was designed to replicate, from a fluid mechanics perspective, the air leakage behaviour of a two-zone structure. The rig permitted tests to be performed with zero wind speed and zero indoor-to-outdoor temperature differentials, and also allowed the leakage characteristics of the "building" to be varied, as described below. The rig was located in Winnipeg.

3.3.1 Design And Construction

The basic configuration of the rig is shown in Figs. 4 to 6. It consisted of two chambers, each approximately 1 m^3 in size, which simulated two, interconnected zones of a building. These were identified as Zones A and B, and corresponded to the Zones A and B described above, i.e. Zone A was the primary test zone while Zone B represented an adjoining part of the building which was able to communicate, from an air leakage perspective, with Zone A. The test rig was designed to operate with air flows which roughly approximated the leakage characteristics of a two-zone structure built to a reasonably airtight construction standard, such as those of the R-2000 Standard. Also, the tests were conducted using zone-to-atmosphere pressure differentials similar to those which might be encountered during actual airtightness tests. For example, the maximum Zone A-to-atmosphere pressure differentials used were typically 75 Pa (Pascals) or less.

The two chambers were manufactured from 19 mm (3/4") plywood and their interiors were sealed with a commercial air barrier membrane to reduce extraneous air leakage. All joints were carefully sealed with silicone sealant. The chambers, as well as all ductwork, were then smoke-tested for leakage. Baffles, in the form of metal mesh screens, were installed in the two boxes to provide better distribution of the air flow over the cross-sectional area of the boxes.

Various sheet metal ducts were then installed to connect the two boxes/zones with each other and with the atmosphere, with each duct representing a possible air leakage path. The nominal size of these ducts was 152 mm (6") in diameter

Duct 1 -	Envelope air leakage path between the atmosphere and Zone A.
Duct 2 -	Air leakage path between Zones A and B.
Duct 3 -	Envelope air leakage path between the atmosphere and Zone B.
Duct 4 -	Pathway for mechanically exhausting air from Zone A to atmosphere.
Duct 5 -	Pathway for mechanically exhausting air from Zone A to Zone B.
Duct 6 -	Pathway for mechanically exhausting air from Zone B to atmosphere.

3.3.2 Instrumentation

Ducts 1, 2 and 3 were equipped with adjustable, variable area 152 mm (6") iris dampers which permitted the leakage characteristics to be easily modified. The iris dampers were basically variable area orifices which could be adjusted and locked in position.

Ducts 1, 2 and 3 were equipped with flow straighteners upstream of the flow-measuring stations. The flow straighteners were constructed from ductwork sections, each approximately 0.3 m long, which were filled with plastic straws whose longitudinal axis was aligned with the direction of flow. Using this rig, the behaviour of the new test procedure was evaluated under a wider range of conditions than would otherwise be possible with actual buildings.

Air flow rates in the ducts were measured using permanently installed flow-measuring stations (labelled as C-1 to C-7). These were installed and calibrated in-situ against a flow nozzle which, in turn, was calibrated by the Saskatchewan Research Council. In-situ calibrations were used to account for any localized flow disturbances which might have been introduced by the ductwork and fittings. All air flow measurements were corrected for temperature and atmospheric pressure and the results expressed at standard temperature and pressure (STP), 20 °C and 101.325 kPa. These are the same temperature and pressure conditions at which results are reported using CGSB-149.10.

Four-point pressure taps were installed in the middle sections of the two chambers for measuring zone-to-atmosphere and zone-to-zone pressure differentials. All pressure differentials, including those associated with the flow-measuring stations, were measured using digital micromanometers which resolved to 0.1 Pa or 0.25 Pa. Typical accuracy specifications for these units were +/- 1% of the pressure reading or +/- 2 counts (whichever was greater). Two variable speed blowers were used to simulate the primary blower door (F-1) and the masking blower (F-2) which would normally be used to perform parallel air flow tests. Blower A was normally installed in Duct 2 thereby simulating a blower door installed between Zones A and B. Alternatively, it could also be connected to Duct 4, thereby permitting air to be exhausted directly from Zone A to atmosphere (this is an alternate blower door location for performing the Parallel Flow Airtightness Test). Blower B functioned as the masking blower whose purpose was to alter the pressure differential between Zones A and B during the test. As an alternate method of modifying the Zone A-to-B pressure differential, Duct 6 could simply be capped (sealed) or left open.

Overall, the test rig worked well although considerable effort had to be expended to commission the unit, primarily to calibrate the various flow-measuring stations. In addition, the original blower (a Fantech FR-140) selected for F-2 was found to have inadequate flow capacity and was eventually replaced with a larger unit (a Fantech FR-200).

3.3.3 Test Rig Commissioning

As part of the calibration process, the rig was configured so that various flow rates could be compared, as shown in Table 1. The first comparison consisted of sealing Ducts 1, 3, 4, and 6, and operating blower F-2 to create a run-around configuration through C-3 and C-4. As shown in Table 1, the measured flow rates for C-3 and C-4, expressed at standard temperature and pressure, compared well. The second comparison, shown in Table 1, compared the net rig inflow through C-1 and C-5 with the net outflow through C-2.

One of the main advantages of the test rig was that *it permitted the actual inter-zone leakage to be measured*, which could not be accomplished directly with a real building. To illustrate, consider the configuration shown in Fig. 4, in which F-2 was installed between the two zones. Using the PFAT method, with C-4 equivalent to the orfice of the blower door, the air leakage characteristics of the Zone A to Zone B leakage could be measured. However, this leakage occurred through Duct 2 and could thus be measured using C-3 and compared to the measured value obtained using the new procedure.

Following the commissioning process, the test rig was used to evaluate a number of test configurations, as discussed in Chapter 4. These configurations were defined by the settings of the three iris dampers and by the location of blower F-1 (either exhausting from Zone A to Zone B, or from Zone A to atmosphere).

Table 1

Test Rig Air Flow Checks

Check #1: Comparison of C-3 and C-4.

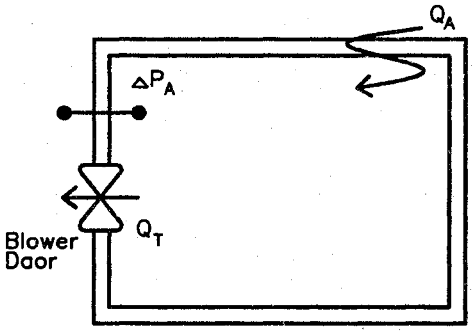
Rig configuration: C-3 and C-4 in the same flow circuit with Ducts 1, 3, 4 and 6 sealed.

C-3 (L/s)	C-4 (L/s)	(C-3 - C-4)/C-3 (%)
31.3	31.5	-0.6
32.6	33.2	-1.8
37.9	38.4	-1.3
40.0	41.5	-3.8
42.0	42.8	-1.9
45.1	45.5	-0.9
48.1	48.8	-1.5
51.0	52.0	-2.0
55.9	56.9	-1.8
61.6	62.2	-1.0
51.0	52.0	-2.0
64.3	65.5	-1.9

Check #2: Comparison of (C-1 + C-5) and C-2.

Rig configuration:

(C-1 + C-5) (L/s)	C-2 (L/s)	$\frac{(C\text{-}1 + C\text{-}5) - C\text{-}2}{(C\text{-}1 + C\text{-}5)}$ (%)
52.0	51.0	1.9
56.2	55.1	2.0
58.8	57.6	2.0
60.9	59.6	2.1
64.2	62.6	2.5
68.2	66.6	2.3
71.9	70.2	2.4
74.6	73.4	1.6
80.1	78.2	2.4
84.7	83.3	1.7



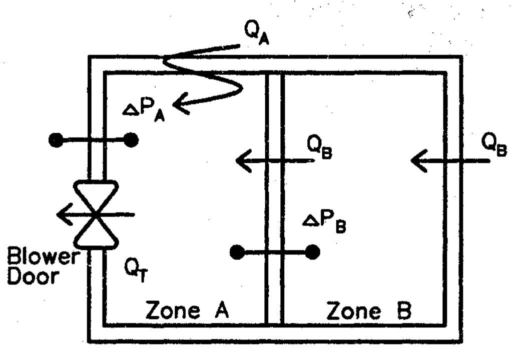
ΔP_A = Pressure differential across exterior envelope

Q_T = Air exhausted by blower

Q_A = Air leakage across exterior envelope

$Q_A = Q_T = C\Delta P^n$

Airtightness Test, Single Zone Case
Fig. 1

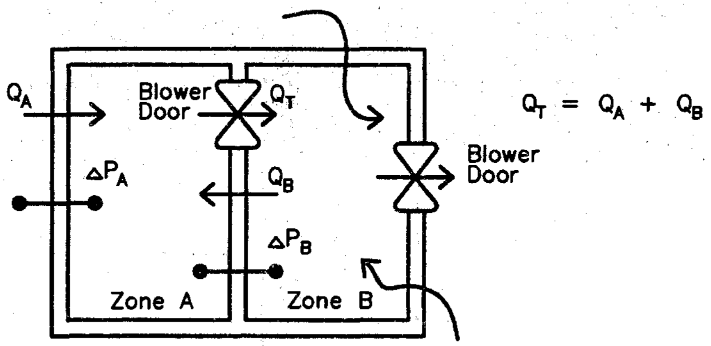


$Q_T = Q_A + Q_B$

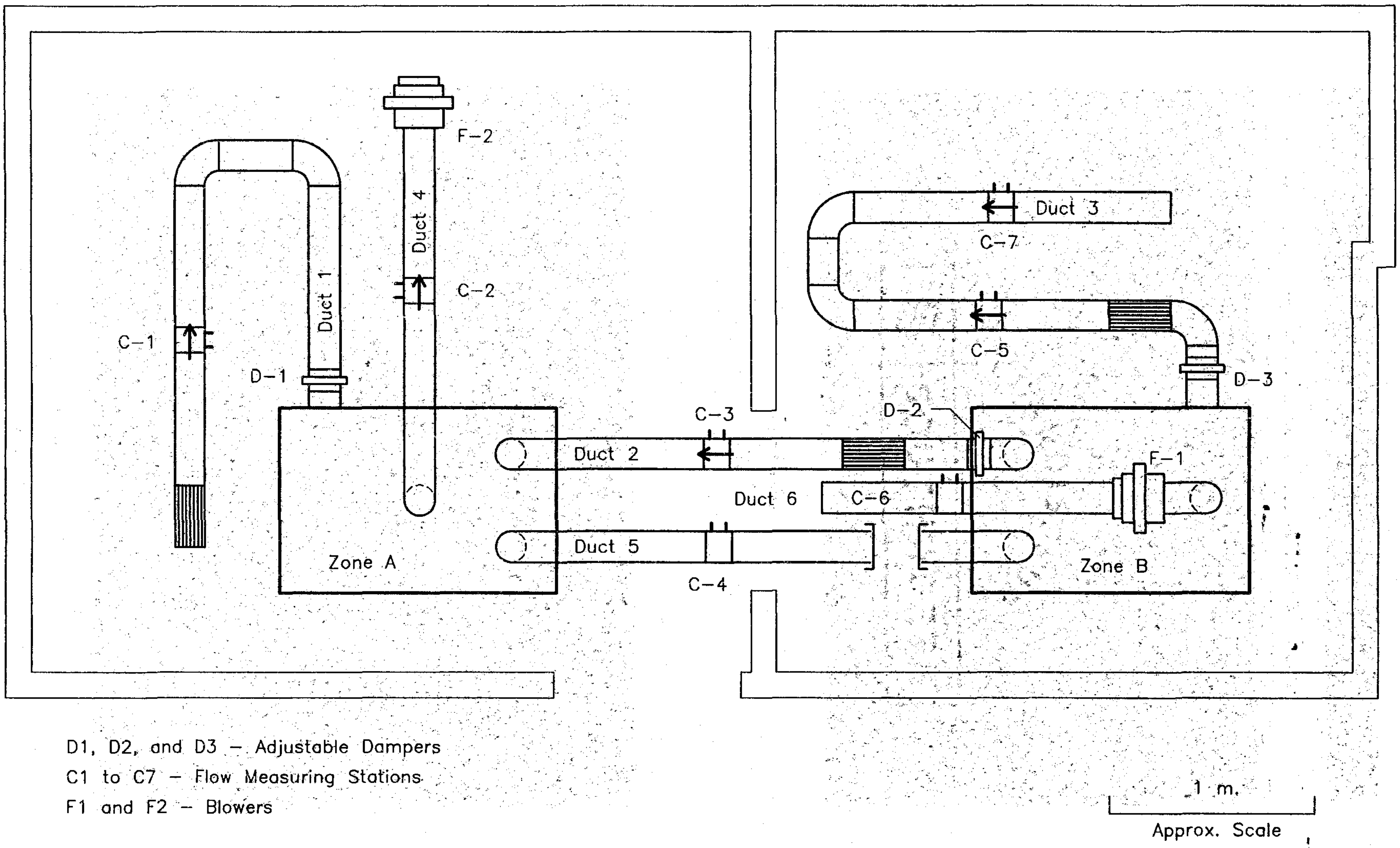
ΔP_B = Pressure differential across interior partition

Q_B = Air leakage across interior partition

Airtightness Test, Multi–Zone Case
Fig. 2

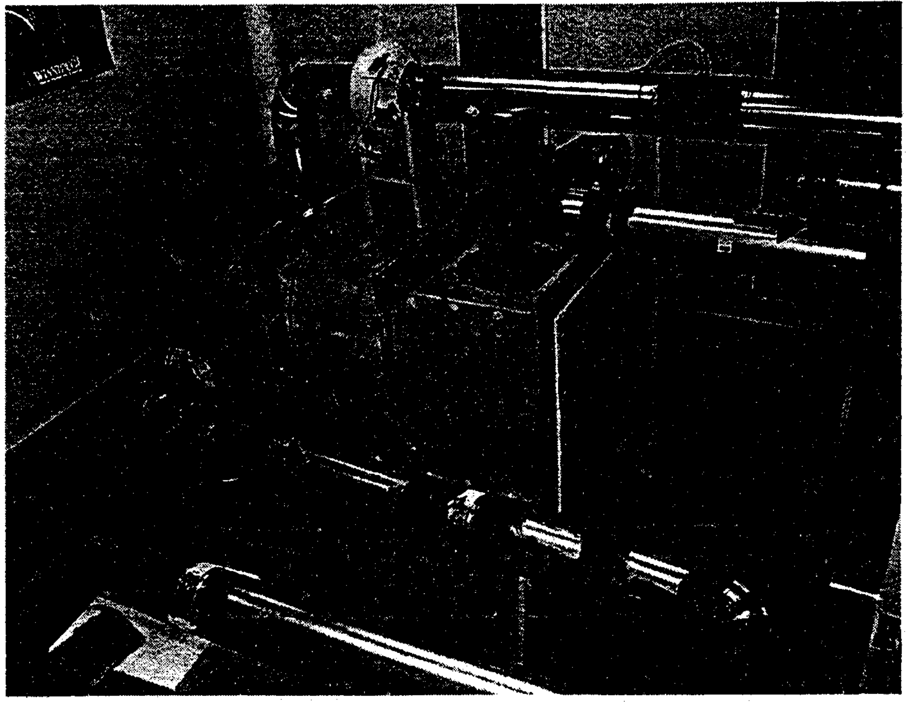


Typical Test Configuration
Fig. 3

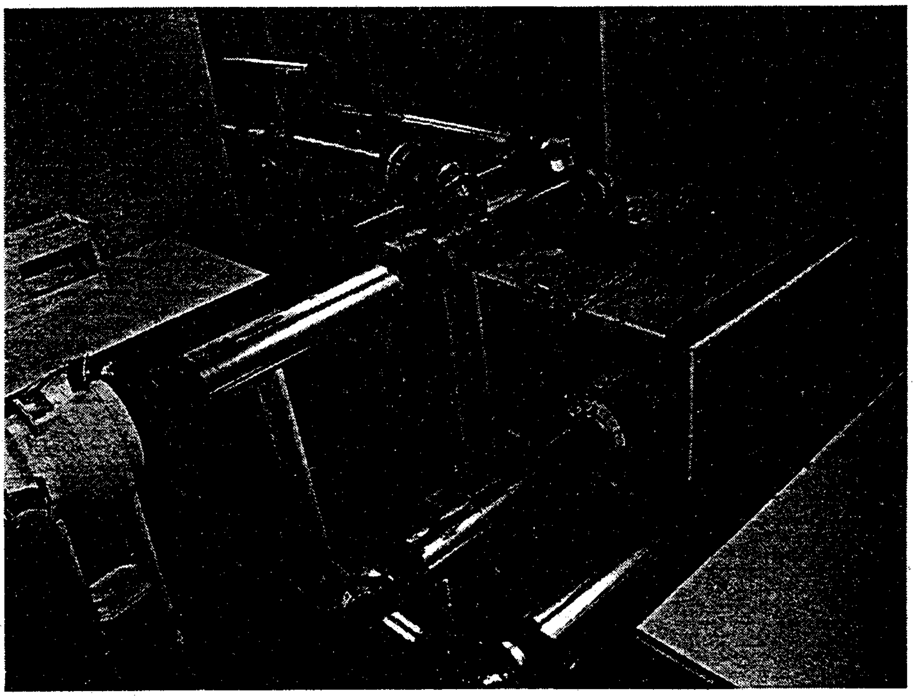


D1, D2, and D3 – Adjustable Dampers
C1 to C7 – Flow Measuring Stations
F1 and F2 – Blowers

Laboratory Test Rig Configuration
Fig. 4



Test Rig
Fig. 5



Test Rig
Fig. 6

CHAPTER 4

LABORATORY TRIALS

4.1 INTRODUCTION

Following completion and commissioning of the Building Air Leakage Simulator, it was used for a series of laboratory trials to explore the proposed test method under various flow conditions. A summary of the test schedule is shown in Table 2. These tests were designed to explore the performance of the new procedure under different sets of leakage conditions between the test zone (Zone A), the buffer zone (Zone B) and ambient. The various conditions were achieved by adjusting the settings of dampers D-1, D-2 and D-3. Two methods of pressure adjustment of Zone B were used: blower-modified and sealing. The first used a blower to alter the pressure in Zone B and corresponded to using a standard blower door or other exhaust device in a real building. The second method consisted of sealing and unsealing the duct between the Zone B and ambient, and corresponded to opening and closing a door or large window between Zone B and the outdoors. If successful, the latter technique would represent a very simple and inexpensive method of achieving pressure modification in the buffer zone and might permit elimination of the second blower.

The remainder of this Chapter summarizes the results of these laboratory trials. The primary yardstick for evaluating the success of these tests was how well the inter-zone air leakage, which occurred through the duct containing C-3 in Fig. 4 could be predicted using the new procedure. A summary of the results is given in Table 3, which shows: the total number of data pairs obtained for each test and the number which met the data acceptance/rejection criterion, the actual and measured C and n values for the inter-zone air leakage, and the actual and measured inter-zone air leakage results at pressure differentials (between Zones A and B) of 10, 50 and 75 Pa. The latter were calculated by first computing the air leakage rates at each pressure differential, for each data point which survived the acceptance/rejection criteria, and then determining the mean value of the survivors.

The data acceptance/rejection process consisted of two steps: a) rejection of all data pairs whose calculated "n" values are outside the range of $0.50 \leq n \leq 1.00$ and b) application of Chauvenet's Criterion. The first step is taken from CGSB-149.10 and reflects the fact that the flow exponent ("n") must have a value between 0.50 and 1.00 to be describing a physically possible flow regime. The lower limit describes the case of pure orifice flow while the upper limit describes pure laminar flow. The derivation of these limits is shown in Appendix A. The rationale for the second step, Chauvenet's Criterion, is discussed in more detail in Chapter 7, but basically involves discarding questionable data points using an objective, statistically based, methodology (ASHRAE, 1986).

"Actual" air flow rates between Zones A and B were calculated by performing a linear regression on the logarithms of the air flow and pressure differential data, developing C and n values to describe this leakage using Eq. (1) and then reporting the results for 10, 50 and 75 Pa, as calculated using the C and n values. Flow measurements were adjusted to STP conditions. This is the same protocol used in CGSB-149.10 and ASTM E 779.

4.2 RESULTS

The complete set of laboratory results are provided in Appendix B. A short description of the individual tests is provided below. Additional discussion is included in Chapter 6.

Test 1.1 (a)

Description: The first two tests were conducted using the smaller, FR-140 blower (F-2) between Zones A and B to replicate the action of the blower door in field applications. Nominal damper positions for D-1, D-2 and D-3 were 100% (i.e., fully open), 60% and 60%, respectively.

Results: The PFAT method was able to predict the air leakage between Zones A and B with errors of -32%, -18% and -14% at pressure differentials of 10, 50 and 75 Pa, respectively. For all three conditions, the new procedure under-estimated the air leakage. The predicted C and n values (which describe the inter-zone air leakage), measured using the new procedure, showed only modest agreement with the actual values measured using C-3.

Test 1.1 (b)

Description: This test was a repeat of Test 1.1 (a) with the same conditions and settings.
Results: Results were roughly the same as Test 1.1 (a), with errors of -48%, -27% and -21% at 10, 50 and 75 Pa, respectively. For all three conditions, the new procedure underestimated the air leakage from Zone A to Zone B. The predicted C and n values, measured using the new method, also showed only modest agreement with the correct values.

Following completion of Test 1.1 (b), it was concluded that the inter-zone blower, F-2, did not have sufficient capacity to adequately modify the pressure differential between the two zones. This fan was then replaced with a larger blower, a model FR-200, which increased the free-stream flow capacity from 71 L/s to 170 L/s, at 50 Pa. The larger blower was used for all subsequent laboratory trials.

Test 1.1 (c)

Description: This was also a repeat of Tests 1.1 (a) and (b), except that the larger inter-zone blower was used and an alternate method of modifying the pressure differential in Zone B was employed. Rather than using a second blower (F-1) to alter the pressure, the exhaust line (which contained F-1) was simply sealed and then unsealed for each data pair. This action replicated opening and closing a large hole in the building envelope of the buffer zone, such as a door or window - thereby eliminating the need for a second blower.
Results: Results were considerably better than those obtained with Tests 1.1 (a) and (b), with errors of 5%, 7% and 7% at 10, 50 and 75 Pa, respectively. Good agreement was also achieved between the predicted and actual C and n values.

Test 1.1 (d)

Description: This was a repeat of Test 1.1 (c) except that the larger, FR-200 blower was for modification of the pressure differential in Zone B, rather than sealing and unsealing the exhaust line containing F-1.

Results: Results were the most accurate obtained to date, with errors of only -6%, -3% and -1% at 10, 50 and 75 Pa, respectively. Good agreement was also achieved between the predicted and actual C and n values.

Test 2.1 (a)

Description: For this next series of tests, damper D-3, which controlled the degree of leakage between Zone B and ambient, was adjusted to have a nominal degree of openness of 30% (rather than 60% in the previous tests). Pressure modification in Zone B for Test 2.1 (a) was achieved by sealing and unsealing the exhaust line containing F-1.

Results: The results of this test were fairly accurate, with errors of 14%, 7% and 5% at 10, 50 and 75 Pa, respectively. Good agreement was also achieved between the predicted and actual C and n values.

Test 2.1 (b)

Description: This was a repeat of Test 2.1 (a) except that blower F-1 was used for modifying the pressure differential in Zone B, rather than sealing and unsealing the exhaust line containing F-1.

Results: The results showed very good agreement, with errors of only 6%, 1% and 0% at 10, 50 and 75 Pa, respectively. Very good agreement was also achieved between the predicted and actual C and n values.

Test 2.2 (a)

Description: For this next series of tests, damper D-2, which controlled the leakage between Zones A and B, was adjusted to have a nominal degree of openness of 30% (rather than 60% in the previous tests). Pressure modification in Zone B for Test 2.2 (a) was achieved by sealing and unsealing the exhaust line containing F-1. The percentage of "good" data points was also the highest achieved to date.

Results: The results were poor compared to those of previous tests, with errors between measured and actual leakage rates of -43%, -28% and -23% at 10, 50 and 75 Pa, respectively. Very poor agreement was achieved between the predicted and actual C and n values.

Test 2.2 (b)

Description: This was a repeat of Test 2.2 (a) except that blower F-1 was used for modification of the pressure differential in Zone B, rather than sealing and unsealing the exhaust line containing F-1.

Results: The results were significantly better than those obtained with Test 2.2 (a), with errors of -3%, -2% and -2% at 10, 50 and 75 Pa, respectively. Good agreement was also achieved between the predicted and actual C and n values.

Test 2.2 (c)

Description: This was a repeat of Test 2.2 (a) and was intended to help assess whether a unique problem had occurred which might have caused the poor results of Test 2.2 (a).

Results: The results were very similar to those achieved with Test 2.2 (a), with errors of -46%, -31% and -26% at 10, 50 and 75 Pa, respectively. Results for the C and n values were also very similar to those of Test 2.2 (a), both of which compared poorly to the actual values.

Test 3.1 (a)

Description: For this next series of tests, blower F-2, which replicated the action of the blower door was repositioned to exhaust from Zone A directly to ambient, rather than into Zone B - as had occurred with all of the previous tests. This is an alternate location for the blower door for actual field tests using the PFAT procedure. Pressure modification in Zone B for Test 3.1 (a) was achieved by sealing and unsealing the exhaust line containing F-1.

Results: The results displayed poor accuracy, with errors between measured and actual leakage rates of -38%, -21% and -16% at 10, 50 and 75 Pa, respectively. Very poor agreement was achieved between the predicted and actual C and n values.

Test 3.1 (b)

Description: This was a repeat of Test 3.1 (a) except that blower F-1 was used for modification of the pressure differential in Zone B, rather than sealing and unsealing the exhaust line containing F-1.

Results: The results were significantly better than those of Test 3.1 (a), with errors of 16%, 4% and 1% at 10, 50 and 75 Pa, respectively. Good agreement was also achieved between the predicted and actual C and n values.

Table 2

Test Schedule And Rig Configuration

Test	Comments	Blower Locations		Lines					Damper Positions		
				C-2	C-3	C-4	C-5	Zone B	D-1	D-2	D-3
1.1 (a) 1.1 (b) 1.1 (c) 1.1 (d)	2-Zone Test with test blower between Zones A and B	C-4 line	Zone B	sealed	open	open	open	open	100%	60%	60%
2.1 (a) 2.1 (b)	2-Zone Test with test blower between Zones A and B	C-4 line	Zone B	sealed	open	open	open	open	100%	60%	30%
2.2 (a) 2.2 (b) 2.2 (c)	2-Zone Test with test blower between Zones A and B	C-4 line	Zone B	sealed	open	open	open	open	100%	30%	30%
3.1 (a) 3.2 (b)	2-Zone Test with test blower exhausting from Zone A to ambient	C-2 line	Zone B	open	open	sealed	open	open	100%	60%	60%

Notes:

1. Damper nomenclature: 100% = fully open, etc.

Table 3
Summary of Laboratory Test Results

Test	Method of Pressure Adjustment	Data Pairs		C (l/s Pan)		n		Q10 (l/s)			Q50 (l/s)			Q75 (l/s)		
		Total	Good	Actual	Calcu -lated	Actual	Calcu -lated	Actual	Calcu -lated	% Diff.	Actual	Calcu -lated	% Diff.	Actual	Calcu -lated	% Diff.
1.1 (a)	Blower (small)	10	3	3.590	2.052	0.610	0.767	14.6	10.0	-32%	39.1	32.1	-18%	50.1	43.3	-14%
1.1 (b)	Blower (small)	10	2	3.262	1.107	0.642	0.853	14.3	7.5	-48%	40.1	29.2	-27%	52.1	41.1	-21%
1.1 (c)	Capping	15	5	3.799	3.709	0.601	0.620	15.2	16.0	5%	39.9	42.5	7%	50.9	54.3	7%
1.1 (d)	Blower	10	3	3.695	3.449	0.607	0.667	14.9	14.0	-6%	39.7	38.7	-3%	50.8	50.4	-1%
2.1 (a)	Capping	15	5	3.802	4.930	0.600	0.561	15.2	17.4	14%	39.8	42.5	7%	50.8	53.3	5%
2.1 (b)	Blower	15	6	3.445	3.878	0.624	0.602	14.5	15.3	6%	39.6	40.1	1%	51.0	51.1	0%
2.2 (a)	Capping	21	10	3.506	1.534	0.582	0.767	13.4	7.6	-43%	34.1	24.5	-28%	43.2	33.1	-23%
2.2 (b)	Blower	15	6	3.535	3.475	0.577	0.591	13.4	13.0	-3%	33.8	33.2	-2%	42.7	42.0	-2%
2.2 (c)	Capping	15	3	3.510	1.343	0.583	0.756	13.4	7.2	-46%	34.3	23.8	-31%	43.4	32.2	-26%
3.1 (a)	Capping	15	8	3.313	1.578	0.637	0.815	14.4	8.9	-38%	40.0	31.5	-21%	51.8	43.6	-16%
3.1 (b)	Blower	21	8	3.099	4.292	0.658	0.597	14.1	16.3	16%	40.6	42.1	4%	53.0	53.5	1%
3.2 (a)	Capping	15	5	3.393	2.263	0.634	0.728	14.6	10.6	-27%	40.5	32.4	-20%	52.3	43.3	-17%
3.2 (b)	Blower	15	5	2.927	3.605	0.670	0.648	13.7	13.4	-2%	40.2	38.6	-4%	52.8	52.6	-0%
3.3 (a)	Capping	15	2	3.378	2.401	0.561	0.638	12.3	9.2	-25%	30.4	24.5	-19%	38.1	31.6	-17%

Notes:

1. Shading indicates that the large blower was used for pressure adjustment.
2. "Actual" values are those which were independently measured using calibrated flow-measuring stations.
3. "Calculated" values are those which were determined using the PFAT method.

CHAPTER 5

FIELD TRIALS

5.1 INTRODUCTION

This Chapter describes the field trials carried out using the Parallel Flow Airtightness Test method. These trials were conducted using three buildings: two indoor swimming pools forming part of larger, multi-zone recreational complexes and a two storey, commercial office building. The two swimming pools had each sustained significant building envelope damage due to air exfiltration/moisture deposition and either received or were scheduled to receive major envelope retrofits to correct the damage. No modifications were carried out on the office building. All three buildings were located in Winnipeg.

It should be noted that some of the refinements to the analysis procedures were developed during the laboratory trials phase, which was conducted after most of the field trials had been completed. Therefore, the analysis of the field results differs slightly from those discussed in other parts of this thesis.

The purpose of the field trials was to evaluate the PFAT under real-world conditions where the controlled features of the laboratory (zero wind, zero indoor-to-outdoor temperature differential, minimal potential for extraneous leakage, etc.) were not available. However, the field trials were not able to provide a quantitative statement on the accuracy of the method (other than in the most general terms) since there was no independent means of measuring the airtightness of those portions of the building envelopes which were of interest. Such independent testing would have required use of the Balanced Fan Depressurization Technique along with high-capacity air-moving and measuring equipment, such as that employed by the National Research Council. In fact, the lack of availability of such equipment was the motivation behind the original development of the PFAT method. Still, the field trials provided good qualitative information on the technique.

5.2 FIELD TEST #1

5.2.1 Building Description

Building #1 was the St. James Civic Centre. This structure was a recreational complex which contained an indoor swimming pool, auditorium, hockey rink, weight-lifting room plus meeting rooms and other ancillary spaces. The swimming pool portion of the building was attached to the rest of the complex on three sides (two interior walls and the floor). The pool room had a floor area of 492 m^2 and volume of 2,730 m^3.

Built approximately 25 years ago, the complex underwent a major renovation in 1999. The most extensive repairs were carried out on the swimming pool portion of the building which underwent a massive building envelope retrofit. Essentially all of the masonry in the two above-grade walls had to be removed because of severe structural degradation caused by repeated freeze-thaw cycling, corrosion of metal fasteners and general degradation of all but the structural steel framework. The retrofit included construction of a new masonry wall system including application of a new, self-adhesive membrane air barrier on the masonry. The new membrane was qualitatively inspected during the construction phase using a blower door, smoke wand and through use of an AIR-SURE air leakage detection device (a.k.a. "bubble gun"). All air leaks identified during the quality assurance process were repaired prior to the airtightness testing. Because of the extreme care taken with the new air barrier, it was felt that the air leakage of the building envelope would be quite low. The airtightness testing (described below) was performed after the retrofit had been completed.

5.2.2 Test Procedure

The primary blower door used for the test was a calibrated, Minneapolis Blower Door. Pressure measurements were performed using a Minneapolis DG-3 Digital Pressure Gauge, resolving to 0.1 Pa with an accuracy of +/- 1% of the pressure reading or +/- 2 counts, whichever is greater. The primary blower door was mounted in one of the doorways separating the pool room from the rest of the complex. This blower door was also used to perform a standard CGSB-149.10 airtightness test on the pool room. By opening the main, doors to the complex as well as the interior doors, the pool room could be treated as a separate, detached space for the purposes of the initial airtightness test. The masking blower door was mounted in the main entrance door of the building. It was cycled on and off to produce the "initial" and "final" pressure differential conditions across the common partitions separating the pool room from the rest of the complex. Although the flow rates through the second blower door were not measured, they were estimated at 2,500 L/s to 3,000 L/s (the freestream capacity of the unit). Flow rates were not measured at the masking blower door since maximum flow capacity was required and the orfice on the blower door would have seriously restricted the air flow rate; also this number was not used in any calculations.

The procedure described above was replicated using various pressure differentials across the exterior envelope to generate six sets of equations of the form shown in Eq. (3), thereby producing 15 unique data pairs. Once the leakage characteristics of the interior partitions were defined (i.e. C and n), the partition leakage was subtracted from the overall six-sided leakage of the pool room calculated using the standard CGSB-149.10 airtightness test procedure to give the leakage of the exterior envelope.

Total time on site to set up and complete the tests was approximately seven hours with two people present. However, the majority of this time was devoted to sealing approximately two dozen ductwork penetrations into the pool room plus several doors and other openings. Once this had been completed and the equipment set up, the time to perform the airtightness tests was about one hour.

5.2.3 Results

Table 4 summarizes the test data. The column headed "Data Pairs" identifies which of the six equations were used to calculate the results. The "C" and "n" columns show the measured airtightness characteristics for the interior partitions, while the Q_{10}, Q_{50} and Q_{75} columns show the derived air leakage rates through the exterior envelope of the pool, computed using the derived n and C values, and the results of the CGSB-149.10, six-sided airtightness test on the pool room only.

Initial examination of the data in Table 4 shows significant variation in the results. In some instances the flow exponent (n) is outside the physically possible range of 0.5 to 1.0. This is reflected in the final results for these cases. However, closer examination of the data shows that all of the "impossible" results (with one exception) were associated with data pairs 1 or 2. If the nine sets of results calculated using these two equations are removed, along with the single set of results calculated using Equations 5 and 6 (since their n value was slightly outside the acceptable range), then five sets of results are left. These are also shown in Table 4. Initially there was concern about why so much of the original data had to be rejected. However, the laboratory studies ultimately showed that this was a typical situation for the procedure.

The remaining five sets of results in Table 4 showed good consistency, particularly at higher pressure differentials. This is encouraging given that the exterior envelope leakage for the pool room was eventually shown to be less than 10% of the partition leakage, i.e. the exterior leakage was calculated as the difference between two large numbers, which is not a desirable situation from an experimental perspective.

Finally, the mean Q_{75} results shown in Table 4 were used to calculate the exterior envelope leakage, interior partition leakage and the pool room's six-sided air leakage, as shown in Table 5.

The leakage rates are expressed using the Normalized Leakage Rate at 75 Pa (NLR_{75}) since it is used in both the Appendix and Commentary of Part 5 of the 2005 National Building Code of Canada to specify recommended maximum air leakage rates for air barrier systems.

Using the swimming pool room's exterior envelope area of 828 m^2 resulted in an NLR_{75} of 0.044 $L/s{\bullet}m^2$ @ 75 Pa. This compares very well to the NBC's maximum, recommended value for air barrier systems (excluding windows - which were present in the pool room) of 0.05 $L/s{\bullet}m^2$ @ 75 Pa for buildings with warm side relative humidities exceeding 55% (such as a pool).

Overall, the results of the field test performed using the new procedure were judged to be encouraging. While two-thirds of the collected data had to be rejected, the remaining data gave results which were both consistent and believable. From a practical perspective, no major problems were encountered using the new procedure in the building.

As an aside, this is one of the buildings included in the literature search on airtightness characteristics of commercial buildings discussed in Appendix A. The results showed that the building (or strictly speaking the one-half of the building envelope which was tested) had the lowest (i.e. tightest) NLR_{75} of any of the 192 buildings identified in the survey. As such, it is the tightest known building envelope tested anywhere in the world, at this time.

5.3 FIELD TEST #2

5.3.1. Building Description

Building #2 was the North End Centennial Pool, whose history and current condition were similar to those of Building #1. Originally constructed about 30 years ago, it contained a swimming pool, change rooms, offices, a senior's complex and auditorium. The latter two sections were added some years after the original construction. The pool room was located at the north end of the structure and was connected to the other portions of the building through its south wall and the floor system. In recent years evidence of building envelope distress became apparent at various locations on the exterior walls of the pool room. This is believed to have been caused, in whole or in part, by air exfiltration and moisture deposition within the wall system. As a result, the building was scheduled for a major retrofit to address these problems. The pool room had a floor area of 1,022 m^2 and volume of 6,853 m^3. In contrast to Building #1, it was anticipated that Building #2 would have a significantly higher air leakage rate.

While Buildings #1 and #2 were similar in their design, construction and history, the major difference between the two was that Building #2 was tested prior to being retrofitted while Building #1 was tested after its renovations were completed.

5.3.2 Test Procedure

The airtightness test utilized the same equipment and basic procedure as used on Building #1. The primary blower door was mounted in one of the doorways separating the pool room from the rest of the complex and used to perform a standard CGSB-149.10 airtightness test on the pool room. By opening the main exterior doors to the complex, the pool room could be treated as a separate, detached space for the purposes of the initial, CGSB-149.10 airtightness test. The masking blower door was mounted in the main entrance door of the building and cycled on and off to produce the "initial" and "final" pressure differential conditions across the partitions separating the pool room from the rest of the complex. Flow rates through the second blower door were not measured, but were estimated to again be between 2,500 L/s and 3,000 L/s (freestream capacity of the unit). This procedure was replicated with various pressure differentials across the exterior envelope to generate six sets of equations of the form shown in Eq. (3), thereby producing 15 unique data pairs. Once the leakage characteristics of the interior partitions were defined (i.e. C and n), the partition leakage was subtracted from the overall six-sided leakage of the pool room calculated using the CGSB-149.10 airtightness test to produce the leakage of the exterior envelope.

Total time on site to set up and complete the tests was approximately four hours with three people present. Again, the majority of this was devoted to sealing various ductwork penetrations into the pool room plus several doors and openings. Once this was completed and the equipment set up, the time to perform all of the airtightness tests was about one hour.

5.3.3 Results

Table 6 summarizes the test data for Building #2. Once again, the column headed "Data Pairs" identifies which of the six equations were used to calculate the results. The "C" and "n" columns show the measured airtightness characteristics for the interior partitions, while the Q_{10}, Q_{50} and Q_{75} columns show the derived air leakage rates through the exterior envelope of the pool, computed using the derived C and n values, and the results of the CGSB-149.10, six-sided airtightness test on the pool room only.

A summary of the pool room's measured exterior envelope leakage, interior partition leakage and six-sided leakage is given in Table 7. These show that the exterior envelope of the pool room displayed a very high air leakage rate. The measured NLR_{75} was 1.16 L/s•m^2 @ 75 Pa, compared with the NBC-recommended value of 0.05 L/s•m^2 @ 75 Pa for high humidity environments (strictly speaking the NBC guidelines only apply to those portions of the envelope which do not contain windows - however the qualitative air leakage examination showed that only a relatively small portion of the overall leakage was occurring through the windows). While it is obviously unreasonable to apply contemporary guidelines to a 30 year old building, the fact that the North End Centennial Pool Room had a leakage rate 23 times the current guideline demonstrates how leaky the envelope was.

5.4 BUILDING #3

5.4.1 Building Description

Building #3 was a two-storey structure with a full basement and a total, useable floor area of approximately 1,040 m^2 (including the basement). It was chosen for the field trials primarily because of its availability and because it was a convenient size to perform the test on. The PFAT method was conducted with a goal of determining the percentage of the total air leakage which occurred through the second storey of the building (i.e. exterior walls, windows and roof), relative to the rest of the building. Such investigations can be useful for determining the distribution of air leakage locations over the building envelope. The second floor had a floor area of 347 m^2 and volume of 1,047 m^3.

5.4.2 Test Procedure

The test equipment and procedure were similar to those used on the other two buildings, except that two methods were used to modify the pressure regimes in the buffer zones (blower operation and door opening/closing). The primary blower door was mounted in one of the doorways separating the second floor from the rest of the building and was also used to perform the CGSB-149.10 airtightness test on the second floor. The masking blower door was mounted in the main entrance door of the building whereas another (single) door was used for the door opening/closing pressure modifications. Flow rates through the second blower door were not measured, but were estimated to be about 500 L/s (1100 ft^3/min).

Using a second blower door for pressure modifications in the buffer zones produced six sets of equations of the form shown in Eq. (3), thereby producing 15 unique data pairs. Using the door opening/closing approach, five equations were generated thereby producing 10 unique data pairs. Once the leakage characteristics of the interior partitions were defined (i.e. C and n), the partition leakage was subtracted from the overall six-sided leakage of the second floor calculated using the CGSB-149.10 airtightness test to give the leakage of the exterior envelope. Total time on site to set up and complete the tests was approximately two hours with two people present. No intentional openings were sealed for any of the tests. The time to perform all of the airtightness tests was about one and a half hours.

5.4.3 Results

Table 8 (a) summarizes the results of the trial on Building #3, using the second blower for pressure modification while Table 8 (b) shows the results when the door opening/closing technique was used. A summary of the second floor's exterior envelope leakage, interior partition leakage and six-sided leakage are provided in Tables 9 (a) and (b).

The trial on Building #3 had a very high rate of data rejection. Using the blower door for pressure modulation, only two of 15 data pairs survived the data acceptance/rejection exercise whereas with the door opening/closing method, only one of 10 survived. A possible explanation for this may be inadvertent operation of the forced air heating system on the lower level of the building which would have affected the pressure balances in the building whenever the furnace blower operated.

The two methods of pressure modification used on Building #3 gave NLR_{75} values for the second floor exterior envelope of 3.44 and 3.96 L/s•m^2 @ 75 Pa, respectively. Although these are based on limited data, it is curious that the door opening/closing technique gave lower air leakage rates than the blower door technique. This is similar to the results from the laboratory trials when the exhaust duct from Zone B was alternatively opened and sealed.

Table 4

Summary Of Test Data - Building #1

Data Pairs		Partition Leakage Characteristics		Exterior Envelope Leakage (L/s)		
		n	C (L/s•Pa^n)	Q_{10}	Q_{50}	Q_{75}
Initial						
1	2	0.53	29.8	-7	38	65
1	3	0.44	48.6	-40	3	34
1	4	0.36	78.9	-85	-44	-10
1	5	6.70	?	?	?	?
1	6	0.04	?	?	?	?
2	3	0.39	61.9	-58	-10	26
2	4	0.18	255	-292	-241	-196
2	5	0.91	5.39	50	85	85
2	6	4.30	?	?	?	?
3	4	0.62	22.2	1	24	36
3	5	0.58	26.2	-6	22	38
3	6	0.64	20.5	5	24	34
4	5	0.57	27.5	-8	19	37
4	6	0.65	19.5	7	27	36
5	6	0.48	44.6	-41	-17	5
Final						
3	4	0.62	22.2	1	24	36
3	5	0.58	26.2	-6	22	38
3	6	0.64	20.5	5	24	34
4	5	0.57	27.5	-8	19	37
4	6	0.65	19.5	7	27	36

Table 5

Summary Of Test Results - Building #1

Component	NLR_{75} (L/s•m^2 @ 75 Pa)
Exterior envelope	0.044
Interior partitions	0.46
Six-sided (exterior envelope & interior partitions)	0.24

Table 6

Summary Of Test Data - Building #2

Data Pairs		Characteristics		Exterior Envelope Leakage (L/s)Partition Leakage		
		n	C (L/s•Pa^n)	Q_{10}	Q_{50}	Q_{75}
Initial						
1	2	0.36	560	1,283	2,290	2,650
1	3	0.64	141	611	1,704	2,206
1	4	0.67	120	566	1,672	2,197
1	5	0.05	9,930	11,138	12,072	12,319
1	6	0.57	195	719	1,789	2,250
2	3	0.82	76	494	1,838	2,559
2	4	0.70	39	194	599	796
2	5	1.10	27	335	1,967	3,072
2	6	0.85	66	468	1,844	2,605
3	4	0.69	65	321	975	1,290
3	5	0.87	64	469	1,893	2,690
3	6	0.78	84	511	1,806	2,482
4	5	0.74	105	578	1,904	2,572
4	6	0.70	114	571	1,763	2,341
5	6	0.93	51	428	1,902	2,769
Final						
3	5	0.87	64	469	1,893	2,690
3	6	0.78	84	511	1,806	2,482
4	5	0.74	105	578	1,904	2,572
4	6	0.70	114	571	1,763	2,341
5	6	0.93	51	428	1,902	2,769

Table 7

Summary Of Test Results - Building #2

Component	NLR_{75} ($L/s \cdot m^2$ @ 75 Pa)
Exterior envelope	1.16
Interior partitions	2.17
Six-sided (exterior envelope & interior partitions)	1.54

Table 8(a)

Summary Of Test Data - Building #3

(Using Blower Door For Pressure Modification)

Data Pairs		Partition Leakage Characteristics		Exterior Envelope Leakage (L/s)		
		n	C (L/s•Pa^n)	Q_{10}	Q_{50}	Q_{75}
Initial						
1	2	2.336	0.0471	10	438	1130
1	3	1.525	1.555	52	606	1125
1	4	0.630	110.9	473	1304	1684
1	5	?	?	?	?	?
1	6	2.525	0.0213	7	415	1156
2	3	0.576	109.4	412	1041	1315
2	4	?	?	?	?	?
2	5	?	?	?	?	?
2	6	2.120	0.1133	15	453	1070
3	4	?	?	?	?	?
3	5	?	?	?	?	?
3	6	1.090	9.874	122	702	1092
4	5	?	?	?	?	?
4	6	0.231	1,107	1885	2734	3002
5	6	?	?	?	?	?
Final						
1	4	0.630	110.9	473	1304	1684
2	3	0.576	109.4	412	1041	1315

Table 8(b)

Summary Of Test Data - Building #3

(Using Door Opening/Closing For Pressure Modification)

Data Pairs		Partition Leakage Characteristics		Exterior Envelope Leakage (L/s)		
		n	C (L/s•Pa^n)	Q_{10}	Q_{50}	Q_{75}
Initial						
1	2	0.843	31.41	219	850	1196
1	3	1.551	1.165	41	503	943
1	4	?	?	?	?	1412
1	5	1.769	0.4459	26	452	925
2	3	3.122	0.0024	3	488	1729
2	4	?	?	?	?	?
2	5	2.356	0.0505	12	508	1321
3	4	?	?	?	?	?
3	5	2.045	0.1586	18	473	1083
4	5	?	?	?	?	?
Final						
1	2	0.843	31.41	219	850	1196

Table 9(a)

Summary Of Test Results - Building #3

(Using Blower Door For Pressure Modification)

Component	NLR_{75} (L/s•m^2 @ 75 Pa)
Exterior envelope	3.44
Interior partitions	4.33
Six-sided (exterior envelope & interior partitions)	2.55

Table 9(b)

Summary Of Test Results - Building #3

(Using Door Opening/Closing For Pressure Modification)

Component	NLR_{75} (L/s•m^2 @ 75 Pa)
Exterior envelope	3.96
Interior partitions	3.45
Six-sided (exterior envelope & interior partitions)	2.55

CHAPTER 6

DISCUSSION OF THE LABORATORY RESULTS AND FIELD TRIALS

6.1 INTRODUCTION

This Chapter discusses the results of the laboratory and field trials, reviews the lessons learned from this work and provides an assessment of the strengths and weaknesses of the Parallel Flow Airtightness Test method.

6.2 OVERALL COMMENTARY ON THE LABORATORY TESTING

As previously mentioned, the primary yardstick for evaluating the success of the laboratory tests was how well the inter-zone air leakage, which occurred through the duct containing Flow Measuring Station C-3 in Fig. 4, could be predicted using the new PFAT procedure. Reviewing Table 3, some interesting observations and comments can be made.

First, when properly applied, the PFAT method was able to separate, with reasonable accuracy, the simulated interior partition air leakage from the exterior envelope leakage in the laboratory trials. For example, when a 75 Pa reference pressure differential was used along with a large capacity blower, the percentage differences between the actual and measured air flows varied from 1% to 2%. Not only were the average percentage differences small, but they were consistently small. As shown in Table 3, the percentage differences for these five tests conducted with the large blower were -1%, 0%, -2%, 1% and 0%, respectively with an average absolute value of less than 1%. Further, the agreement between actual and measured values for the Flow Coefficients (C) and the Flow Exponents (n) for these five tests was also good with mean differences (based on absolute values) of 0.520 (16.5%) for C and 0.036 (5.7%) for the n value.

Examining the actual and measured air flows in Table 3, some of the differences between these two quantities were relatively large (up to 48%). However, most of these instances occurred at low reference pressure differentials (10 Pa or 50 Pa) or when the pressure adjustment in the buffer zone was created using a small blower or by capping and uncapping Duct D-4 (equivalent to opening and closing an outside door to Zone B) in Fig. 4). It is also interesting to note that (based on personal experience) replicate airtightness tests, carefully performed on single-zone structures using established methodologies such as CGSB-149.10 will routinely generate results which show surprising variation in the C and n values even though the resultant, final airtightness parameter (such as the air change rate at 50 Pa or the Normalized Leakage Area at 10 Pa) are quite consistent. This observation makes the results of the laboratory trials even more encouraging.

Another interesting observation from Table 3 is that the rejection rate of data pairs was quite high. For example, if we consider only the five sets of tests in which the large blower was used and which displayed good correlation to the actual inter-zone air leakage, i.e. Tests 1.1 (d), 2.1 (b), 2.2 (b), 3.1 (b) and 3.2 (b), the rejection rates were 70%, 60%, 60%, 62% and 67% respectively, giving an average rejection rate of 64%. At first glance this may appear disappointing. However if the mechanics of the data rejection process are considered, then the view is more encouraging. To illustrate, consider the situation in which there are six sets of equations - a fairly typical number. This would result in 15 sets of simultaneous equations. If one of these six equations is compromised (due to wind action, operator error, or any of a number of potential problems), then 5 of the 15 possible data pairs (33%) will have to be rejected. If two of the equations are compromised then 9 of the 15 possible data pairs (60%) will be rejected. In other words, a relatively small percentage of problem equations results in a much larger percentage of rejected data pairs meaning that a high data rejection rate is not necessarily a major concern.

It is also interesting to note that airtightness testing standards such as CGSB-149.10 also contain procedures for rejecting individual data points. These will typically result in 10% to 40% of the data being rejected even though the data points can be handled autonomously whereas with the PFAT method, a single bad data point will cause rejection of all data pairs which contain the erroneous measurement.

Overall, if actual field results could be produced which were comparable to those achieved in the laboratory trials, then it is the author's belief (based on having performed several hundred airtightness tests), that such a level of accuracy would be adequate.

6.3 OVERALL COMMENTARY ON THE FIELD TESTING

The primary purpose of the field testing was to evaluate the PFAT technique under real world conditions and to assess its practicality for use in multi-zone buildings. However, it is important to remember that the field tests were not capable of determining the "actual" amount of inter-zone leakage (with "actual" defined as it was for the laboratory tests), only the "measured" leakage. Therefore, no comment can be made on the accuracy of the tests conducted during the field trials.

Qualitatively, the field trials indicated that the PFAT technique was a workable procedure for characterizing the air leakage of the building envelope in a single zone in many multi-zone buildings. Overall, it was found to be well suited to field testing and no major problems were encountered with the procedure (other than those normally associated with testing any large building or zone which has multiple connections to other zones). For example, if we consider the test on Building #1 (since it took longer than any of the other two tests), the most labour intensive part of the work was the preparation (sealing of several heating grilles located in the pool room) - not the test itself.

One concern which arose with Building #3 was possible, unintentional operation of the building's mechanical system during the test. This building contained a number of separate mechanical systems each serving a different part of the structure. Even though that part of the system serving the test zone was successfully disabled, inadvertent operation of the system in other zones may have contributed to the high data rejection rate encountered when the PFAT technique was used.

It is also worth noting that all the trials on all three buildings were conducted at night when the buildings were either totally, or largely, unoccupied and winds were light. This methodology worked well and is recommended for future applications of the procedure.

Data rejection rates in the field tests were found to be slightly higher than in the laboratory rates. Given the additional extraneous variables present in the field tests (winds, failures of temporary heating grilles seals, operator error, exhaustion from having to conduct the test at 3:00 a.m.), this is not very surprising. Rejection rates for Buildings #1 and #2 were both 67% while for Building #3, the rejection rate was 87% when the second blower was used for pressure modification and 90% when the door opening technique was used. In contrast, the average rejection rate for the laboratory trials (when the large blower was used) was 64%.

The remainder of this Chapter discusses some specific technical issues which arose during the laboratory tests and field trials.

6.4 PRESSURE MODIFICATION OF ZONE B

Two methods have previously been identified for pressure modification of the buffer zone in the PFAT method: use of a second masking blower (corresponding to blower F-1 in the laboratory trials) and opening a door or window (corresponding to sealing/unsealing the exhaust duct in the laboratory trials). Summaries of the laboratory results using these two methods are shown in Table 10 and Figs. 7 to 9.

Examining the data, it is apparent that the first method (use of a second blower) significantly improved the accuracy of the procedure. The tests with the blower were further improved when the larger capacity unit was used instead of the original, smaller capacity model. For example, considering all the data in Table 10, the mean errors for the blower method of pressure modification versus the sealing/unsealing method were 18%, 9% and 6%, versus 29%, 19% and 15%, at 10, 50 and 75 Pa respectively. If the data for Tests 1.1 (a) and (b) are excluded (since the small blower was used for F-1), then the mean errors for the blower method results drop to 8%, 2%, and 1%, at 10, 50 and 75 Pa. Overall, these results are very encouraging. However, given the ease with which the sealing/unsealing method of pressure modification could be used on an actual building, it would be desirable to understand why the results were less accurate using this method. At this time, it is not clear why the method of pressure modification had such as pronounced affect on the results.

Otherwise, it appears that: a) use of a second blower is the most accurate means of modifying the pressures in buffer zones, and b) the second blower should have as large a capacity as possible. The latter conclusion may appear to diminish the value of the PFAT technique since one of its advantages is that a smaller blower can be used compared to that needed for the full pressure masking approach (used by NRC). However, it should be remembered that even with this limitation, full and exact equalization of the pressure differential in the buffer zone is still not required (two requirements of the NRC technique which limit its applicability).

6.5 REFERENCE PRESSURE DIFFERENTIAL

For the laboratory tests and field trials, results were calculated at reference pressure differentials of 10, 50 and 75 Pa between Zones A and B. These pressure differentials were chosen because they are standard values referenced in various airtightness testing protocols. For example, CGSB-149.10 references 10 Pa and 50 Pa as suitable indoor-to-outdoor pressure differentials for reporting results. ASTM E 283 and E 783, which describe airtightness test procedures for measuring component leakage under laboratory and field conditions respectively, both use 75 Pa as the reference pressure differential. Further, the 2005 National Building Code of Canada provides requirements for air barrier materials and also makes *recommendations* for the maximum desirable air leakage rates for air barriers and the "air barrier system" of building envelopes at a reference pressure differential of 75 Pa.

As expected, the accuracy of the laboratory results generally improved at higher reference pressure differentials. For example, (the absolute values of) the mean errors for the data in Table 10 were 23%, 13% and 10% at 10, 50 and 75 Pa, respectively. Therefore, we can conclude that airtightness results generated using the PFAT method should be expressed at a reference pressure differential of 75 Pa, although results at other values could also be reported.

6.6 AIR-FLOW AND PRESSURE DIFFERENTIAL STABILITY

One of the key requirements of the new procedure is that flow rate and pressure differential stability has to be maintained during the test. In some of the laboratory tests, this proved to be somewhat of a problem, particularly when relatively small air flow rates were required. In these instances, a small degree of motor/blower fluctuation could be detected which caused slight variations in the air flow rates and pressure differentials. These fluctuations are believed to have been caused by slight voltage variations in the power supply circuit serving the blowers and possibly by other factors. The result was that considerably more time was required to conduct the test to insure that correct readings were being recorded, particularly for the zone pressure differentials. This means that for field measurements using the new procedure, blower stability is essential - perhaps to an even greater extent than with conventional airtightness tests, such as CGSB-149.10.

6.7 PRESSURE MEASUREMENT SENSITIVITY

The laboratory trials clearly showed that the PFAT method requires very accurate measurement of the various pressure differentials - in fact, to an even higher degree than required for CGSB-149.10. Also, we can conclude that the pressure measuring devices should have a high resolution. For example, the digital micromanometers used in the laboratory trials had resolutions ranging from 0.1 Pa to 0.25 Pa. Based on the experiences to date with the new procedure, this should be adequate. Analog micromanometers (such as Magnehelic gauges) are not acceptable.

6.8 ENVIRONMENTAL CONDITIONS

Conventional airtightness tests are normally only conducted under relatively mild wind conditions. For example, CGSB-149.10 requires that the wind speed on site does not exceed 20 km/hr. Based on the laboratory testing and the demonstrated sensitivity of the pressure measurements, it appears that the new procedure may require more stringent limitations on wind conditions - probably a maximum of 10 or 15 km/hr. However, it should be noted that wind data provided by Atmospheric Environment Services is normally reported using measurements made at 10 m above the ground in a relatively unobstructed location (such as an airport). In urban environments (where most large, multi-zone buildings are located) there is usually considerable shielding provided by adjacent buildings and trees. Also, the environmental restrictions for the PFAT method need to be considered in the context of the requirements for alternative test procedures. For example, although the pressure masking approach has never been formalized as a test procedure by any standards writing body, the author's personal experience with the methodology clearly showed that it too is very sensitive to wind action and would likely also benefit from more rigorous environmental restrictions than is specified in CGSB-149.10.

6.9 REQUIRED SKILL LEVEL

A standard, single-zone airtightness test, such as those conducted with CGSB-149.10 or equivalent, is a relatively straightforward procedure which can be learned fairly rapidly. A typical course to train individuals takes about one or two days. The required procedures have been well defined and standardized and, in most cases, little judgment is required. In addition, virtually all blower door manufacturers supply software which handles the data analysis procedures so that the need for labourious calculations is eliminated. As a result, there are presently an estimated two to five hundred individuals in Canada who are trained to perform such tests.

In contrast, the PFAT method requires a higher skill level than a standard airtightness test. More judgment is required, particularly in the planning of the test, its execution, data analysis and in the application of critical review skills to insure that reasonable results have been obtained.

6.10 PRACTICAL ISSUES AFFECTING FIELD TESTING

The field tests revealed some important issues with respect to testing actual buildings. First, to properly execute the test absolute control over the operation of the building must be provided by the owners. Obviously, door and window openings have to be controlled as well as the operation of air-handling equipment, particularly those which move air across either the exterior envelope of the primary zone or the partitions which separate the primary zone from buffer zones. In larger buildings, these devices are often under automatic control so the assistance of building personnel will be required to shut them down during the test and possibly during the preparation phase if grilles or ductwork have to be sealed. Under winter conditions this can result in significant temperature drops in occupied spaces. Although this can be accepted by the test crew it may not be as tolerable to the building's normal occupants. Combustion equipment (such as central boilers, furnaces and hot water tanks) may also have to be disabled since their operation usually results in combustion air being introduced into the building. All of these factors strongly suggest that the test is best performed when the building is unoccupied. Also, if smoke testing is planned (for leakage detection purposes) it may be necessary to disable the smoke alarm system and advise the local fire department.

It is usually desirable to seal any obvious pathways between the test zone and the rest of the building - for example, the grilles encountered in Building #1 during the field trials. Strictly speaking, the only reason to do this is to reduce the amount of inter-zone air movement and thereby make it easier for the masking blower to depressurize the buffer space. If adequate flow capacity were available, it theoretically would not be necessary to seal these pathways since the test measures the leakage of interior partitions which is then used to determine the exterior envelope leakage of the test zone after a normal blower door test has been performed on the test zone. However, this can significantly increase the air flows through the blower doors and may limit the utility of the test procedure; as a result it is normally best to seal such penetrations.

In any event, the key fact to bear in mind if these pathways are planned for sealing is not just that they have to be sealed, but rather that the seals must be stable for the duration of the test (a few hours) since partial opening of a seal could invalidate the entire test and may not become noticeable until the data analysis is being conducted - which, of course, is normally after the test set-up in the building has been dismantled.

As previously mentioned, the test has to be restricted to calm periods. Since these conditions most frequently occur at night, coupled with the need to control the building, it is apparent that the most opportune time to perform the test is at night. It is also important that the owners be appraised of these requirements, as well as whether or not the building's normal maintenance staff may be required and whether the cleaning staff (who normally work at night) may have to be rescheduled. Also, the owners should clearly understand what is going to occur, when the test will be performed, how long it will take, etc. For example, during testing of one of the swimming pools described earlier, the author's attempts to work alone at night in a room containing a swimming pool caused great consternation with the building's safety personnel because of the possibility of an accident occurring when no one else was present while the test was being performed. Apparently, an unguarded indoor swimming pool is now considered to be a major threat to personal safety.

6.11 APPLICATIONS

The laboratory and field experiences demonstrated that the PFAT is not a panacea for the problems of measuring the airtightness of large, multi-zone buildings. Despite the success of the procedure, there are some situations in which it can not be used. For example, consider the case of a single suite within a typical multi-unit residential building (MURB). To use the PFAT method, all of the other spaces surrounding the test zone (A) have to be at the same pressure differential, relative to Zone A. For a MURB, this would mean that (at a minimum) the four suites above, below and on the sides of the test zone, as well as the corridor, would have to be connected together so that they could be simultaneously depressurized. While this could easily be done by opening various interior doors to connect these zones, it is only a practical solution in an unoccupied building. For new construction in which the building is not occupied and which is physically so large (and leaky) that there is not adequate blower capacity to perform a conventional blower door test, the PFAT is a serious alternative. Further, all of the building's exterior doors and windows would have to be kept closed. In such a case, it could be used to measure the leakage characteristics of the building envelope in a single zone and the results either extrapolated to the rest of the structure or used as is.

However, once the building is occupied it becomes much more difficult to open (and keep open) the doors and windows which means it would likely not be possible to use the PFAT technique. For a building with a smaller number of zones, such as the three used for the field trials, this is much less of a problem.

Nonetheless, the results of the laboratory tests and field trials indicates that the PFAT procedure can be used to determine the airtightness of select portions of the building envelope in multi-zone structures provided the buffer zones can be interconnected into a single zone which can then be depressurized using a single blower. Typical applications could include:

- Individual zones within multi-zone buildings
- Individual floors within multi-storey buildings
- Individual units within multi-unit buildings.

Table 10

Summary Of Laboratory Results

Test	Method Of Pressure Adjustment In Zone B	Flow Rate Error		
		At 10 Pa	At 50 Pa	At 75 Pa
1.1 (a)	Blower (small)	-32%	-18%	-14%
1.1 (b)	Blower (small)	-48%	-27%	-21%
1.1 (c)	Sealing/unsealing	5%	7%	7%
1.1 (d)	Blower	-6%	-3%	-1%
2.1 (a)	Sealing/unsealing	14%	7%	5%
2.1 (b)	Blower	6%	1%	0%
2.2 (a)	Sealing/unsealing	-43%	-28%	-23%
2.2 (b)	Blower	-3%	-2%	-2%
2.2 (c)	Sealing/unsealing	-46%	-31%	-26%
3.1 (a)	Sealing/unsealing	-38%	-21%	-16%
3.2 (b)	Blower	16%	4%	1%

Notes:

1. "Error" defined as... $\frac{\text{(actual flow rate) - (PFAT calculated flow rate) x 100}}{\text{(actual flow rate)}}$

Fig. 7
Error At 10 Pa

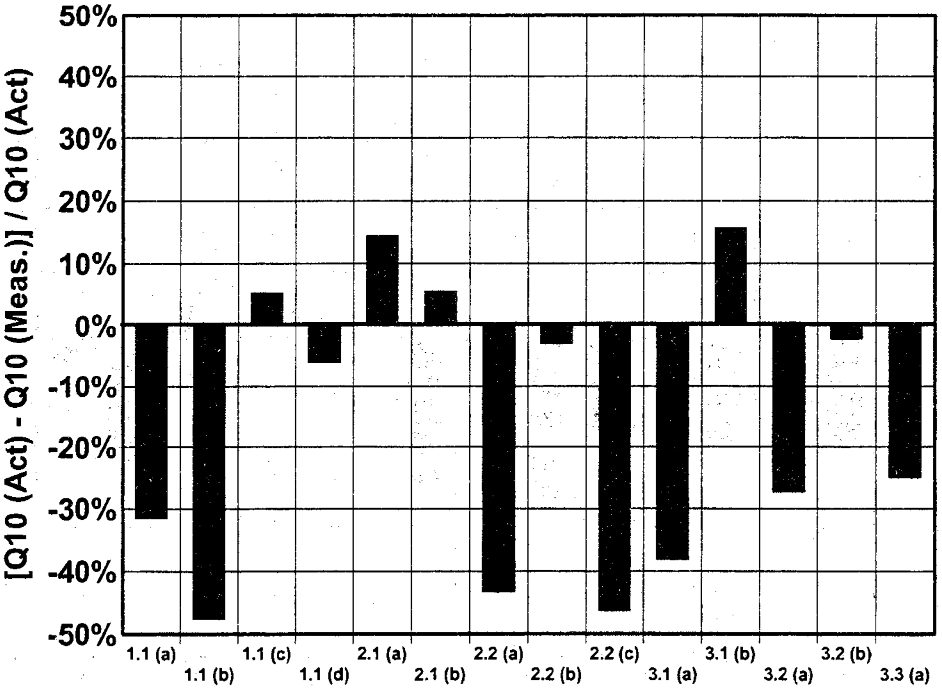


Fig. 8
Error At 50 Pa

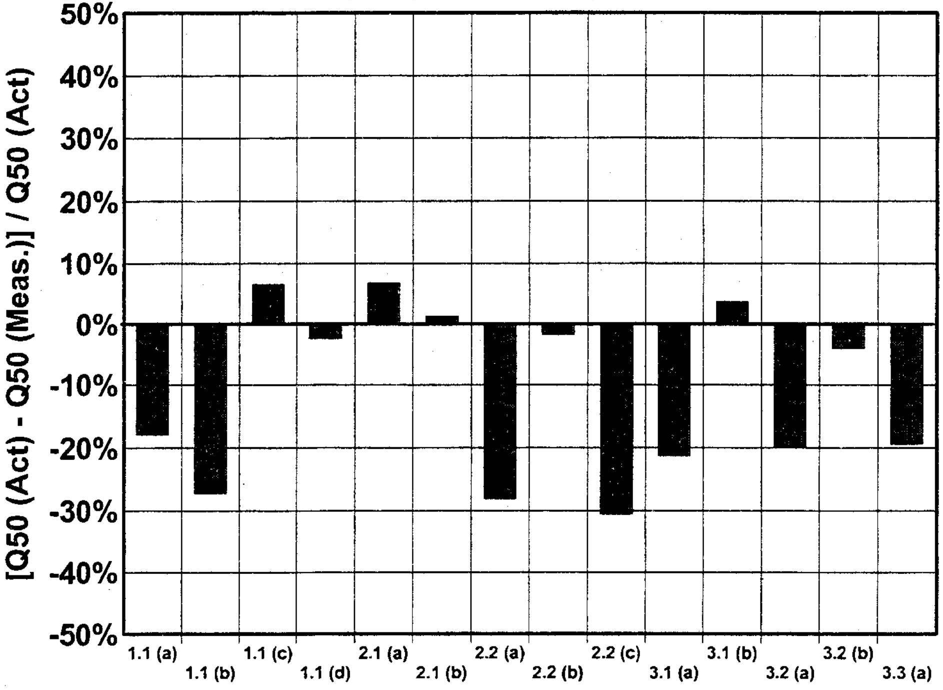
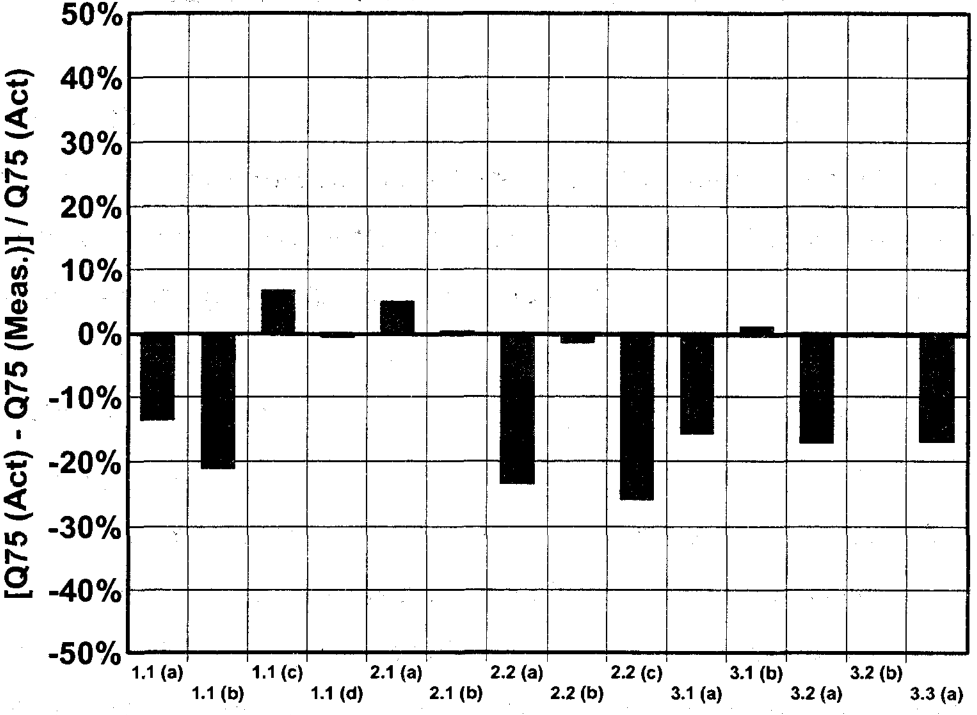


Fig. 9

Error At 75 Pa



CHAPTER 7

DETAILED DESCRIPTION OF THE PFAT METHOD

7.1 INTRODUCTION

Using the lessons learned from the laboratory and field trials, this Chapter describes the test procedures and analysis methods which are recommended performing airtightness tests using the Parallel Flow Airtightness Test procedure.

7.2 PROCEDURE

Step 1, Planning

Airtightness tests performed using the new procedure are more complicated to execute and have a greater vulnerability to outside influences than conventional airtightness tests, so it is important that each test be carefully thought out and thoroughly planned. A site visit should be made to the building prior to the test to assess its suitability and the preparation which will be required. Intentional pathways between the test zone and the rest of the structure (such as ductwork, doors, hallways, etc.) should preferably be sealed since they dramatically increase the air-moving requirements. This may require that some mechanical systems be shut down for several hours which may create a problem, especially during winter. Air-moving devices, whether in the test zone or in the rest of the structure will have to be deactivated since they can alter the pressure regimes and invalidate the test. Open hallways or other passageways can be temporarily sealed using plywood, plastic sheeting and tape. Discussions with building's maintenance personnel and access to the architectural and mechanical drawings would obviously be useful.

Access to the test zone as well as the rest of the structure will have to be controlled during the test - which may mean testing at night or on a weekend. Posting notices of the test and advising occupants that access will be restricted is also beneficial. If smoke testing is also planned (for leakage detection purposes) it may be necessary to disable the smoke alarm system and advise the local fire department.

Step 2, Perform A "Six-Sided" Airtightness Test On The Test Zone

The first step in using the PFAT method is to conduct a standard CGSB-149.10 airtightness test on the test zone to determine its "six-sided" leakage. The blower door can be installed so that it exhausts from the test zone to either the outdoors or to the buffer zone. Unless otherwise desired, the standard sealing schedule for intentional openings within the test zone (as described in CGSB-149.10) shall apply. Zones adjacent to the test zone must be maintained at atmospheric pressure during the "six-sided" airtightness test. This can be achieved by opening doors, windows or ductwork connections to the outdoors. In complex structures with several adjacent zones, care must be taken to insure that each are connected to the outdoors, either directly or by connecting each zone to other zones which are connected to the outdoors. If there is any doubt whether the area of these openings is adequate to maintain the buffer zones at atmospheric pressure, then the pressure differential across the interior partitions, floors and ceilings should be measured to insure it is the same as that measured across the exterior envelope of the test zone during the "six-sided" airtightness test.

Using the results of the CGSB-149.10 airtightness test, the flow coefficient (C) and the flow exponent (n) for the "six-sides" of the test zone can be determined. Dimensional data for calculating volumes and surface areas can be obtained either from the building's drawings or through direct measurements.

Step 3, Perform Parallel Flow Airtightness Test On The Test Zone

Install a blower door assembly (the "primary blower door") to exhaust air from the test zone to either the buffer zone or the outdoors. The former approach is the most effective since it permits greater modification to the pressure differential across the interior surfaces separating the test zone from the buffer zones. Note that the blower door set-up installed for Step 2 can also be used for this purpose.

To perform the parallel flow test, a means of modifying the pressure differential between the buffer zones and the outdoors (and hence the pressure differential between the test zone and the buffer zones) needs to be provided. This can be accomplished using a blower(s), such as standard blower door assembly (referred to as the "masking blower") which exhausts from the buffer zones to the outdoors or by opening doors or windows between the buffer zones and the outdoors. Based on experience to date, the best results are achieved when a blower is used to modify the pressure differential. If there is more than one buffer zone (for example, various rooms or floors), these have to be at the same pressure differential. This can be achieved by opening interior doorways or other openings between the zones. Finally, a micromanometer should be installed to measure the pressure differential between the test zone and the buffer zones.

Once the equipment installation has been completed, carry out the rest of the test using the following procedure:

Step 3.1 Turn on the primary blower door to achieve an initial pressure differential between the test zone and the outdoors. Record: a) the pressure differential between the test zone and the outdoors, b) the pressure differential between the test zone and the buffer zones and c) the air flow rate measured at the primary blower door. The data collection form shown in Fig. 10 can be used.

Step 3.2 Turn on the masking blower or open the designated doors and windows between the buffer zones and the outdoor. It is not necessary to measure the air flow rate through the masking blower.

Step 3.3 Adjust the air flow rate through the primary blower door so that the pressure differential between the test zone and the buffer zones is returned to the value recorded in Step 3.1. Record: a) the pressure differential between the test zone and the outdoors, b) the pressure differential between the test zone and the buffer zones and c) the air flow rate measured at the primary blower door.

Step 3.4 Repeat Steps 3.1 to 3.3 for additional sets of conditions (i.e. pressure differentials between the test zone and outdoors) to generate a series of data pairs. The procedure should be repeated for a minimum of five additional sets of conditions although more are obviously desirable. Zone-to-outdoor pressure differentials should range from 75 Pa to 15 Pa.

Step 4, Calculate The Initial C_p and n_p Values Of The Partition Surfaces

Using the data collected during the test, develop a flow equation of the form shown in Eq. 3 (repeated below) for each data pair. This information will be used to determine the airtightness of the interior partitions, floors and ceilings which separate the test zone from the rest of the building.

$$\Delta Q_T = C_P(\Delta P^{np}_{B\ initial} - \Delta P^{np}_{B\ final}) \qquad (3)$$

where:

ΔQ_t = change in flow rate measured at the blower door between the initial and final conditions (L/s)

C_p = flow coefficient of the partitions (L/s • Pa^n)

n_p = flow exponent of the partitions (dimensionless)

$\Delta P_{B\ initial}$ = initial pressure differential across the partitions (Pa)

$\Delta P_{B\ final}$ = final pressure differential across the partitions (Pa)

Assemble the flow equations generated for each data pair. Note that each pair of equations represents two equations and two unknowns (a solvable situation). Using Table 11, calculate the number of number of possible, unique combinations by which the equations can be combined.

Combine each unique possible combination of equations together and solve for the flow coefficient and flow exponent of the partitions separating the test zone from the buffer zones (C_p and n_p). Solve using an iterative approach in which trial values of C_p or n_p are calculated, the remaining value is computed, and the two estimated values are inserted back into one of the two equations, and its equality assessed. This process can be performed very rapidly using a spreadsheet. Record all calculated values for C_p and n_p.

Step 5, Apply Acceptance/Rejection Criterion To The Initial C_p and n_p Values For The Partitions

Using the iterative approach described in Step 4, tabulate the results for each combination of equations. Reject all solutions in which the flow exponent, n_p, is less than 0.50 or greater than 1.00 (i.e, $0.50 \leq n \leq 1.00$). Based on experience to date, this typically results in half the data being rejected and may, on occasion, result in a rejection rate of up to 75% of the possible solutions.

With the remaining solutions, apply Chauvenet's Criterion for rejecting data points. This is a procedure for discarding questionable data points using an objective, statistically based, methodology (ASHRAE, 1986). According to Chauvenet's Criterion, a data point may be rejected if the probability of obtaining that particular deviation from the mean is less than 0.5n, where "n" is the number of data points. To apply the procedure, an initial mean and initial standard deviation are first computed using all of the available data points (i.e. those whose flow exponents fall within the acceptable range of 0.500 and 1.000). Use the calculated air leakage rates across the partition surfaces at a pressure differential of 75 Pa for this procedure. The deviations of individual data points are then divided by the initial standard deviation and compared to the values shown in Table 15. All data points whose ratio of deviation to initial standard deviation exceed the values shown in Table 12 should be rejected. A new mean and standard deviation are then calculated. In some cases, none of the data points will be rejected using this procedure. Chauvenet's Criterion can only be applied once.

Step 6, Calculate The Airtightness Of The Partitions

Using each of the remaining equations from Step 5, calculate the airtightness of the partitions for pressure differentials (across the partition surfaces) of 10 Pa, 50 Pa, and 75 Pa. Calculate the mean value of the air leakage for each pressure differential.

Step 7, Calculate The Airtightness Of The Exterior Surfaces Of The Test Zone

Using the C and n values from the "six-sided" airtightness test described in Step 2, calculate the "six-sided" air leakage rate, in litres per second, for the test zone at pressure differentials of 10 Pa, 50 Pa and 75 Pa between the test zone and the outdoors. Then, calculate the airtightness of the test zone's exterior surfaces by subtracting the partition leakage from the "six-sided" leakage at pressure differentials of 10 Pa, 50 Pa and 75 Pa, respectively.

$$Q10_{tz} = Q10_{ss} - Q10_{p} \tag{6}$$

$$Q50_{tz} = Q50_{ss} - Q50_{p} \tag{7}$$

$$Q75_{tz} = Q75_{ss} - Q75_{p} \tag{8}$$

where the subscripts are:

tz = test zone leakage

ss = "six-sided" leakage

p = partition leakage

Finally, calculate the Normalized Leakage Rate at 75 Pa (NLR_{75}) of the exterior envelope of the test zone using Eq. (9).

$$NLR_{75} = Q75_{tz} / A_{ex} \tag{9}$$

where:

A_{ex} = Area of the exterior envelope of the test zone (m^2)

Step 8, Reporting

After the analysis is completed, report all relevant information on the test conditions, test procedure and test results. This should include:

- All recorded data

- Openings sealed between the test zone and the outdoors
- Openings sealed between the test zone and buffer zones
- Building characteristics
- Environmental conditions

Table 11

Number Of Possible Combinations Of Equations

Number Of Equations	Number Of Possible Combinations
4	6
5	10
6	15
7	21
8	28

Table 12

Chauvenet's Criterion For Rejecting Data

Number of Readings (N)	Ratio Of Maximum Acceptable Deviation To Standard Deviation (d_{max}/σ)
2	1.15
3	1.38
4	1.54
5	1.65
6	1.73
7	1.80
10	1.96
15	2.13
25	2.33

FIG. 10

PARALLEL FLOW AIRTIGHTNESS TEST DATA FORM

Building:	Project:
	Date:
	Time:
Temp.(inside): °C (°F)	Barometric Pressure: Kpa
Temp. (outside): °C (°F)	Station Pressure: Kpa
Wind Direction:	Wind Speed: km/h
Intentional Openings Sealed:	

Exterior & Interior Pressure Differentials (Pa)			Nozzle*	Nozzle Pressure (Pa)
Exterior Envelope	Interior Partitions			
	Pressurization On	Pressurization Off		
ΔP (start) =	ΔP (start) =			
Δ P (end) =	Δ P (end) =			

*Nozzle Choices: Open/A/B/C

May 1/05 Signature:______________________________

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Based on the laboratory testing conducted to assess the accuracy of the Parallel Flow Airtightness Method (PFAT) and the field testing carried out to assess its practicality under real-world conditions, the following conclusions have been developed:

1. The PFAT method appears to provide a workable method of separating interior partition air leakage from exterior envelope leakage when testing one zone within a multi-zone building. The procedure seems well suited to field work and offers advantages, in terms of time, personnel and equipment, over the conventional pressure-masking technique.
2. The laboratory testing showed that, under ideal conditions (no wind and adequate masking blower capacity), the Parallel Flow Airtightness Test method was capable of measuring the exterior envelope air leakage with a maximum error of about 2% at a reference pressure differential (between the test zone and ambient) of 75 Pa. When the duct sealing/unsealing method was used to modify the pressure differential between zones, the accuracy degraded significantly with maximum errors of up 26%.
3. The accuracy of the results produced by the PFAT method increases at higher reference pressure differentials. A reference pressure differential of 75 Pa is recommended which is also consistent with that used in the 1995 National Building Code as well as ASTM E 283 and ASTM E 783.
4. Greater skill, better planning and more accurate measurement equipment are required to properly conduct an airtightness test using the PFAT method compared to that needed for a conventional CGSB-149.10 airtightness test. Micromanometers should be able to resolve to 0.1 Pa while blower doors and masking blowers should have very stable flow characteristics. Also, tests should

be restricted to relatively low wind conditions - not exceeding about 15 km/hr.

5. While not a panacea to all the problems of testing large, multi-zone buildings, the Parallel Flow Airtightness Test method can be successfully applied in many instances where other testing methods either can not be successfully used or where the cost and practical difficulties would make their use highly problematic.

8.2 RECOMMENDATIONS

1. A better understanding is required to determine why the accuracy of the laboratory tests degraded when the sealing/unsealing method was used to modify the pressure regimes in the buffer zone (which replicates the use of door/window opening and closing).
2. Automation of the data analysis procedures would be highly desirable. Not only would it save time but its use in the field would help to insure that adequate data, of acceptable accuracy, had been obtained before the test set-up was disassembled.

CHAPTER 9

FUTURE WORK

9.1 THE NEED FOR FUTURE WORK

During the course of the laboratory tests and field trials, a small number of technical issues arose which were deemed to be worthy of further investigation for future development of the Parallel Flow Airtightness Test method. This Chapter briefly identifies them and describes the nature of the required study.

9.2 METHODS FOR PRESSURE MODIFICATION OF ZONE B

As previously described, two methods were evaluated during the laboratory trials for modifying the pressures in zone B: use of a second, masking blower (F-1) and sealing/unsealing the exhaust duct (replicating opening a door or window in an actual building). The trials clearly showed that the greatest accuracy and precision were achieved with the first method (the high capacity masking blower). Although these results, in themselves, were very encouraging it would obviously be desirable to understand why the second method (sealing/unsealing of the duct/door) did not achieve comparable behaviour since this method would further simplify the test procedure and potentially eliminate the need for a second blower. At this time, it is not completely clear why the sealing/unsealing method of pressure modification was unable to achieve comparable levels of accuracy and precision. One possibility is that the degree of pressure modification to Zone B has to be fairly pronounced thereby creating enhanced delineation between the flow behaviour for the modified and unmodified cases. If this is correct, then it may be possible to produce guidelines which identify how much modification is required to the pressure in Zone B to achieve a satisfactory level of accuracy. Armed with this information, the practitioner would be able to use whichever of the two techniques was most convenient for a given application.

To explore this issue in more detail, it would be necessary to conduct further laboratory trials since this testing environment offers greater accuracy and repeatability than the field trials. These laboratory trials could either be performed using the test rig described in this thesis or by constructing a new rig with larger flow capacities. At this time, it is suspected that a new rig might be desirable, although the general design features of the existing facility (including methods of controlling extraneous leakage, flow straightening, pressure measurement, etc.) could still be used.

Additional work, using either the existing laboratory equipment or new equipment with larger air flow capacities, is recommended.

9.3 AUTOMATION OF THE DATA ANALYSIS PROCEDURE

Perhaps the greatest single concern with the PFAT procedure is that presently there is no easy means to determine if sufficient data, of acceptable quality, has been collected during the test. Based on the field trials, setting up and breaking down the equipment, along with preparation of the test building (particularly sealing of intentional openings such as heating and ventilation ductwork penetrations through the exterior envelope or interior partitions) consume about 80% of the total time in the field. The test itself is almost an anticlimax (a common situation for many building science test procedures used in the field). Therefore, the possibility exists that one could prepare the building, perform the test, disassemble the equipment, return to the office - and then discover that the data was inadequate for a proper analysis. Although this never occurred during any of the field trials conducted for this project, largely because copious amounts of raw data were collected, such a prospect is obviously an issue and could create major problems. However, it should be possible to eliminate this potential problem by automating the data analysis procedures. Using a laptop computer, coupled with a spreadsheet (or equivalent), and a screen-guided analysis procedure, the analysis could be completed in the field or at least to a sufficient stage to verify that adequate data had been collected. Once it could be verified that a solution to the flow equations had been obtained, the test set-up could be disassembled without fear.

It is interesting to note virtually all manufacturers of commercial blower doors include data analysis software as part of the overall test kit. Early versions of this software were intended for use with various types of printing calculators but in recent years all of these have been updated for use with laptop computers. Although the analysis procedures for the PFAT method are somewhat more complex than those for a standard blower door test, they are nonetheless well within the capabilities of a laptop.

Therefore, future work should include automation of the data analysis procedures for the PFAT method.

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APPENDIX A
AIR LEAKAGE IN BUILDINGS

APPENDIX A

CHAPTER A-1

BASIC PRINCIPLES OF AIR LEAKAGE IN BUILDINGS

A-1.1 INTRODUCTION

This Appendix discusses the basic principles of air leakage in buildings including: the mechanisms (or driving forces) which produce it, the affects of uncontrolled air leakage, how leakage rates are measured and how they are reported in the literature.

A-1.2 DRIVING FORCES

Air leakage can be defined as the uncontrolled, and often unintentional, movement of air through the building envelope. As such, it includes air movement across opaque and transparent portions of the envelope as well as above-grade and below-grade components. It includes air movement which results from natural forces and mechanically induced pressure differentials, such as exhaust or supply fans. However, air leakage is not normally considered to include air movement which occurs through mechanical ducts or other penetrations in the envelope which are intentionally placed there to provide a pathway for air. Two requirements must be satisfied for air leakage to occur: a physical opening in the envelope and a pressure differential across the opening. Unintentional cracks, openings and other discontinuities exist in the envelope of virtually all buildings, although their collective size can vary dramatically between structures. These openings are the inevitable consequence of the fact that most construction materials (and the aggregate systems created from them) are permeable to air flow. The only exceptions commonly encountered are materials such as glass, metal and some plastics. There are three driving forces which can generate pressure differentials across the building envelope: wind action, stack effect and the building's mechanical systems.

A-1.2.1 Wind Action

In the simplest terms, the wind generates positive pressure differentials (relative to the interior of the structure) on the windward side of the building and negative pressure differentials on the leeward side. The wind-induced pressure differential can be described by Eq. (6), which is derived from Bernoulli's equation. Note that the pressure differential is proportional to the square of the velocity so that doubling of the wind velocity increases the wind-induced pressure differential by a factor of four.

$$\Delta P_w = (1/2)\, C_p\, \rho\, V^2 \tag{6}$$

where:

ΔP_w = pressure differential due to wind action (Pa)

C_p = pressure coefficient (dimensionless)

ρ = outside air density, about 1.2 (kg/m^3)

V = wind velocity (m/s)

The most difficult term to predict in Eq. (6) is C_p, the pressure coefficient (Dalgliesh and Schriever, 1962). Wind-tunnel and flow visualization investigations have shown that the effects of the wind become more complex and difficult to estimate near corners and around complex geometries on the structure. The presence of adjacent structures or vegetation also distorts the flow regime and may produce unexpected wind forces on the subject building. Wind strength is also affected by the building's height since the presence of the ground, other structures, natural vegetation, etc. all combine to create a boundary layer effect which significantly reduces the wind velocity close to the ground. This effect is typically felt in the lower 100 m to 500 m of the atmosphere and, therefore, has the most pronounced effect on very tall structures.

Since the wind velocity is very difficult to predict at a specific location on the building envelope, wind-induced pressure differentials are also difficult to estimate. However, wind pressures vary greatly depending on the wind velocity, building height and local shielding effects. Pressures on exposed faces can exceed 1000 Pascals (Pa) for extended periods of time and rise to perhaps 2500 Pa for a few seconds during extreme gust conditions. And, of course, wind action is uncontrolled in its magnitude, duration and direction (Proskiw, 2001).

A-1.2.2 Stack Effect

Temperature differentials between the indoors and the outdoors create differences in the air density which generate pressure differentials across the building envelope. Under winter conditions a heated building acts like a chimney: warmer air rises vertically through the structure and exfiltrates across the upper portions of the building. It is replaced by cold, outside air which enters through the lower portions of the structure. This is known as the "stack effect" and its magnitude depends on the vertical location on the building face relative to the Neutral Pressure Plane (NPP). The NPP is the locus of points on the exterior envelope at which the pressure differential is equal to zero. Assuming an equal and uniform distribution of leakage pathways over the envelope, the NPP (due to the stack effect) would be located at the mid-height elevation. The magnitude of the stack effect can be described by Eq. (7):

$$\Delta P_s = \rho_i\, g\, (H - H_{np})(T_i - T_o)/T_o \tag{7}$$

where:

ΔP_s = pressure differential due to stack effect (Pa)

ρ_i = air density (kg/m^3)

g = gravitational constant, 9.81 m/s^2

H = height of observation (m)

H_{np} = height of the neutral pressure plane (m)

T_i = indoor temperature (K)

T_o = outdoor temperature (K)

Under cooling conditions when the inside air temperature is less than the ambient air temperature, the driving force and hence the pressure differentials are reversed. Warmer, outdoor air infiltrates over the upper portions of the building and exfiltrates across the lower parts. However, since the summer indoor-to-outdoor temperature differentials are usually much smaller than those produced in the winter, the magnitude of the summer stack effect is relatively weak compared to those produced under winter conditions.

Figure A-1 illustrates the magnitude and direction of the stack effect for a simple, single-zone structure (such as a house) in which there is no appreciable restriction to air flow due to interior partitions, floors, etc. In multi-zone structures with significant interior partitioning, the resistance to air flow created by interior obstructions can be very significant. Figure A-2a) illustrates the stack effect for a five storey building with no internal partitions, i.e. it is equivalent to a tall house - the only difference being that the magnitude of the pressure differentials is larger. If perfectly airtight floors are added, then no internal air flows can take place across the floors. In other words, the pressure differentials created by the difference in air densities between the indoors and outdoors can not be transmitted beyond the floor levels. Hence, the magnitude of the pressure differentials across the building envelope are significantly reduced. In essence, the structure acts as if it were five, single-storey buildings stacked one on top of each other. Of course, the idealized situation shown in Fig. A-2a) is never achieved since the floor systems and other interior partitions always permit some amount of air leakage. The resultant effect is shown in Fig. A-2b) in which part of the overall pressure differential created by the stack effect occurs across the exterior envelope and part across the various interior surfaces. Notice that as the interior surfaces become more airtight, the pressure differential across the exterior envelope decreases. In fact, this concept has been investigated as a method of reducing stack effect in tall buildings, i.e. compartmentalization of the structure by making interior floors, walls, elevator shafts, etc. as airtight as possible. A more typical situation is shown in Fig. A-2c) in which the interior surfaces display some, but not absolute, resistance to air leakage. Part of the overall stack effect occurs across the building envelope and the remainder takes place across the interior surfaces, with the distribution of pressure differentials depending on the relative overall leakage characteristics of the two sets of surfaces.

In low-rise, residential construction and other types of small buildings, the pressure differentials created by the stack effect seldom exceed 10 to 20 Pa, whereas in taller buildings the stack effect can reach 50 to 100 Pa or more. Like wind action, the stack effect is largely uncontrolled, other than as described above.

A-1.2.3 Mechanical Systems

The building's mechanical systems, specifically its air-moving components, can induce significant positive or negative pressure differentials across the envelope whenever air is exhausted from, or supplied to, the building. The mechanical system can also create pressure differentials between zones within a multi-zone building which can affect envelope performance as well as inter-zone air movement and the operation of various building systems. Historically, mechanically induced pressure differentials in many buildings were relatively small (a few Pascals). However, with the advent of tighter envelope construction and more powerful air-moving equipment (including those devices not normally associated with the "mechanical" system - such as indoor barbeques and clothes dryers), mechanically induced pressure differentials of 10 Pa to 30 Pa are now encountered on a regular basis in some buildings, such as houses.

Larger buildings usually have much more powerful air-moving equipment. Despite the greater surface area, and the fact that their envelopes are generally less airtight than those in residential construction, the mechanical systems can still impose significant pressure differentials. Since larger buildings are often served by several fan systems and contain significant internal restrictions to air flow (thereby creating a number of internal zones) the mechanically induced envelope pressure differentials may vary significantly with time and with location on the envelope.

Unlike wind action, and (to a lesser extent) stack effect, mechanically induced pressure differentials are often fairly constant for extended periods of time, rather than transient in nature. However, some types of HVAC (heating, ventilating and air-conditioning) systems vary the amount of air which they move into or out of the building, or to specific zones within the building, depending on the heating and cooling requirements. This creates a time-dependent, dynamic component to the envelope pressure fields. The effects of the building's occupants also have to be considered since their usage of exhaust and supply devices (e.g. indoor barbeques) can have a huge impact on the overall air leakage rate. Generally, the effects of occupant behaviour is more pronounced in residential construction since larger buildings use automated control systems for the mechanical systems thereby affording less authority to the occupant.

A-1.2.4 Combining Driving Forces

The net pressure differential which each location on the building envelope experiences is the algebraic summation of the individual pressure differentials created by each of the three forces acting independently (Hutcheon and Handegord, 1983). The corresponding, net air leakage rate at any given point on the envelope is a function of the net pressure differential at that point. However, the leakage is not a linear summation of the leakage which would be produced by each of the driving forces acting independently.

The net pressure differential varies significantly at different locations on the envelope since the strength and direction of the three driving forces is usually location-dependent. Further, these forces (particularly wind action) tend to be fairly dynamic and time-dependent with the result that the "pressure differential across the building envelope" is both location-and-time-dependent. That is why estimating the air leakage rate in building energy simulation models is one of the most difficult variables to evaluate.

A-1.3 EFFECTS OF AIR LEAKAGE ON BUILDING PERFORMANCE

There are at least a half dozen different effects which uncontrolled air leakage can have on a building - and none of them are beneficial from either the building's perspective or that of the occupants (Garden, 1965).

A-1.3.1 Moisture Transport Into The Envelope

Perhaps the most significant consequence of air leakage is the transport of water vapour from the building interior, through the envelope, to the outdoors (in a heating climate; in a cooling climate, the flow directions are reversed). If the outdoor temperature is lower than that indoors, a temperature differential will exist across the envelope. As exfiltrating air passes through the porous, insulated matrix of the envelope, it will therefore be cooled.

When this occurs, the air's relative humidity (R/H) will increase. If the temperature differential is sufficiently large, the exfiltrating air will be cooled until it is fully saturated (i.e. the relative humidity will equal 100%). If it is cooled even further, water vapour will begin to condense out of the air stream and be deposited on a suitable solid surface within the matrix of the building envelope. This phenomenon is known as "interstitial condensation" and can result in the deposition of significant quantities of water inside the structure of the envelope. In fact, not only does water deposition occur, but it is concentrated at those locations through which the air leakage takes place, rather than uniformly over the envelope (such as occurs with water vapour transport due to vapour diffusion). Depending on the temperature, this condensed water may exist in either a liquid or solid state. In heating climates, such as those found in Canada, this process can continue for several months every year.

From a building science perspective, this is obviously an undesirable situation. Most materials used in the construction of building envelopes are vulnerable to moisture damage. For example, wood is subject to fungal attack (wood rot) if its moisture content exceeds about 22% and the temperature is above approximately 4 °C. That is the reason wood used in construction is required to have a moisture content not exceeding 19% (NBC, 1995). Metal which is exposed to moisture becomes vulnerable to corrosion. Masonry materials can be damaged by liquid water and can also suffer structural degradation when water entrained within its structure freezes and the water expands during solidification. Most types of interior drywall can also be damaged if exposed to liquid water. Many types of insulation will have their insulating properties severely reduced, often irreversibly, if they become wet. Some calculations have suggested that the damage to Canadian buildings due to moisture damage resulting from air exfiltration/moisture deposition (in whole or in part) is in the order of hundreds of millions per year.

During the heating season, this process can result in large quantities of water accumulating within the envelope in the form of ice. When the outdoor temperature rises in the spring, the ice will melt resulting in the release of a large quantity of water in the envelope over a very short period of time. This phenomenon can often be observed on the first warm day of spring when many buildings literally have water pouring out of their walls. Overall, this problem is perhaps the most significant in attics and ceilings since these are usually horizontal surfaces and there is little opportunity for gravity-induced drainage to occur. The only moisture removal mechanisms available are evaporation (which is comparatively weak) and by drainage back into the building (which is undesirable).

The reverse situation can take place in a cooling climate if the building is air-conditioned. The temperature gradient across the envelope is reversed and outdoor air infiltrating into the structure can be cooled sufficiently that condensation can take place within the envelope. However, since the temperature differentials are relatively modest, the pressure differentials are also weak, relative to those which occur in winter.

Air exfiltration/moisture deposition within the building envelope is arguably the most important consequence of air leakage because of the significant harm which interstitial condensation can cause - particularly in buildings constructed with moisture-sensitive materials, such as wood-frame houses. In fact, the author has long believed that one of the most fundamental principles of building science is that "Except for structural errors, about 90% of all building problems are associated with water in some way" (ASTM, 1980).

A-1.3.2 Increased Energy Use

Air leaking across the building envelope can increase heating costs in winter and cooling costs in summer. While, some leakage provides beneficial ventilation for the occupants, in all but the newest structures the amount of wintertime air leakage which occurs far exceeds that required to maintain acceptable indoor air quality. Air leakage into the building has to be heated if cold drafts are to be avoided, thereby creating a sensible energy load. A latent load may also be produced if the outdoor air is at a much lower temperature and the indoor space has to be humidified to maintain a comfortable and healthy environment. The magnitude of this increased energy load is difficult to generalize. Air leakage across the building envelope can vary dramatically depending on the airtightness of the structure. In many older Canadian houses, air leakage constitutes about one-third of the total space heating load, although individual houses may behave very differently.

A-1.3.3 Degradation of Comfort

Cold, outdoor air leaking into the structure can have a negative impact upon comfort levels in the occupied space. If the air leakage pathway through the envelope is relatively long, or sufficiently small that minimal amounts of leakage occur, this impact may be minor, particularly since some preheating of the outdoor air can take place via the "dynamic wall effect". Conversely, if the pathway is short and large, the impact on comfort can be significant. A prime example is window leakage. Since most older windows tend to be very leaky, and there is little opportunity for preheating, jets of outdoor air are free to intrude directly into the living space. Since windows are meant for viewing, people like to be near them and position furniture in close proximity - which accentuates discomfort problems.

A-1.3.4 Degradation of Indoor Air Quality

Contrary to popular belief, outdoor air leaking into a building may contain significant, even toxic, levels of pollutants. Infiltration of soil gas into basements and crawl spaces is perhaps the most obvious example. Most soil in the upper portions of the earth is quite porous such that air is able to migrate through it given a suitable pressure differential. Even during winter conditions, when the upper one to two meters of the soil may be frozen (under Canadian conditions), the underlying soil is usually still porous. Unfortunately, during its residency in the soil, air can become contaminated by a variety of soil-based, naturally occurring pollutants including radon, water vapour and methane, as well as man-made chemicals such as pesticides or hydrocarbons, which are often present in the soil. The latter is a particular problem in locations which were originally developed as “brownfield” sites, i.e. where some other building was originally located on the site or it was used for some other type of use - such as an agricultural, commercial or industrial application.

Degradation of the indoor air can also occur if the air leakage occurs through attached spaces such as garages which contain operating motor vehicles or other sources of pollution.

For example in the case of a garage, even if the vehicle door is open carbon monoxide from the engine exhaust can be trapped against the house wall (given proper wind conditions), and infiltrate into the house. In fact, this results in a small number of fatalities each winter in North America.

A-1.3.5 Smoke Control

Smoke control is an important life safety issue, particularly in larger buildings in which egress through a window may not be an option. Automated control systems in larger buildings are typically designed to shut off the supply of outdoor air to the structure upon activation of the fire alarm, while pressurizing stairways to provide a safe escape route for the occupants. The degree of pressurization which can be developed obviously depends on the airtightness of the enclosure.

Curiously, there appears to be little communication between the air leakage and smoke control "communities" such that valuable information often has to be learned separately even though the other group may have already developed the knowledge base.

A-1.3.6 Life Safety

Envelope air leakage can also be a significant issue for structures which harbour potentially dangerous substances - such as laboratories or hospitals. In such cases, the building envelope is the last line of defence against the accidental release of airborne chemicals or biological agents. For example, it is now common practice in hospitals to maintain isolation rooms under a slight negative pressure differential (about 10 to 20 Pa) relative to the other parts of the building to mitigate against the transmission of airborne contaminants. Conversely, operating rooms are normally maintained under a slight positive pressure differential such that the only air which enters the zone is that provided by the building's ventilation system thereby permiting it to be properly filtered and treated.

A-1.4 NEUTRAL PRESSURE PLANE

Since the Continuity Equation dictates that the mass flow rate of air leaking into the building must equal the mass flow rate which is leaking out, it follows that in most circumstances some portion of the building envelope will be subject to air infiltration while the remaining portions experience air exfiltration. This is graphically illustrated in Fig. A-1 which shows the variation in the envelope pressure differentials over the envelope due to the stack effect. As previously mentioned, the locus of points on the building envelope at which the pressure differential is zero is defined as the Neutral Pressure Plane (NPP), or neutral plane. In Fig. A-1, the NPP is shown as a horizontal line since the only driving force is assumed to be the stack effect, i.e. there is no wind or mechanically driven air movement. In practice, the NPP is not necessarily horizontal, nor is it a straight, since the other driving forces can alter its shape. Also, the location and shape of the NPP is usually very dynamic due to the normal fluctuations in wind speed and direction, operation of the various mechanical system components, etc.. It is also possible that there will not be any physical locations on the envelope which are occupied by the NPP. Such a situation would occur if the building were (positively or negatively) pressurized such that the entire envelope were exposed to only positive or negative pressure differentials.

Even if the driving forces remain constant, the location and shape of the NPP can be radically altered if the airtightness of the envelope is changed (intentionally or otherwise). For example, if a window (which has a relatively large leakage area) is opened, the effect will be to move the NPP towards the open window - a fact which helps to mitigate the impact of large holes since this reduces the pressure differential across the opening.

A-1.5 THERMAL DRAFT COEFFICIENT

One of the major differences between smaller structures (such as houses and smaller commercial buildings) and larger, often high-rise buildings is that the former can usually be treated as single-zone structures (acknowledging that interior doors may be closed), while the latter generally have to be treated as multi-zone structures with interior partitions, floors, etc.

that create significant resistance to air flow relative to the building envelope. For this reason, the concept of the Thermal Draft Coefficient (TDC) has been developed. The ASHRAE Handbook of Fundamentals (ASHRAE, 2001) defines the TDC as the actual pressure differential across the envelope divided by the theoretical pressure differential which would occur if there were no internal floors, partitions, etc. - in other words, if the structure were a single-zone building. The difference between the theoretical and actual pressure differentials is a measure of the internal flow resistance created by the floors, partitions, etc. Although data is limited, some measurements by Tamura and Wilson of the National Research Council of Canada (NRC) found TDC values ranging from 0.8 to 0.9 for a three storey building (1967). Given that the TDC is relatively easy to measure under field conditions, it can represent a very useful, and easily obtained, variable for better understanding the leakage characteristics of larger buildings.

As a building becomes more compartmentalized (i.e. sub-divided into separate physical zones which have appreciable levels of airtightness between each other), the value of the TDC decreases. Increasing levels of compartmentalization reduce the pressure differential across the building envelope since a greater portion of the driving force (which causes air leakage) is assumed by the interior partitions, floors, etc. For this reason, compartmentalization is now being suggested, and occasionally used, as a means of reducing air leakage since it moderates the envelope pressure differentials.

A-1.6 CHARACTERIZING AIRTIGHTNESS RESULTS

A-1.6.1 Basic Flow Equation

Any meaningful discussion about air leakage requires a quantitative understanding of building leakage rates, which in turn dictates an understanding about the relationship between the driving force (the pressure differential across the envelope) and the resultant leakage rate. Air flow through a porous structure, such as a building envelope or components making up the building envelope, follows a mathematical relationship which can be described using a power equation of the form shown in Eq. (1).

$$Q = C\,\Delta P^{n} \qquad (1)$$

where:

Q = air flow rate (L/s)

C = flow coefficient ($L/s \bullet Pa^{n}$)

ΔP = indoor-to-outdoor pressure differential (Pa)

n = flow exponent (dimensionless)

A-1.6.2 Laminar Flow

While Eq. (1) has been found to work remarkably well, it is not derived from first principles, such as the Continuity equation or Bernoulli's theory. However, we know that the behaviour of a fluid flowing through a hole is strongly affected by the geometry of that hole. For example, if we apply Bernoulli's equation for frictionless flow to air flow through a circular pipe...

$$\frac{f\,L\,V^2}{D\,2g} + \frac{(p_2 - p_1)g_c}{\rho \quad g} + (H_2 - H_1) + (V_2^2 - V_1^2)/2g = 0 \qquad (8)$$

where:

f = friction factor (dimensionless)

L = length (m)

V = velocity (m/s)

D = pipe diameter (m)

g = acceleration due to gravity (m/s^2)

g_c = conversion factor ($kg\ m/m^2$)

p = pressure (kg/m^2)

ρ = density (kg/m^3)

H = height (m)

First, let us assume there is no change in elevation, then $H_1 = H_2$. Also, we know that for laminar flow the friction factor can be expressed in terms of the Reynolds number (John and Haberman, 1971)...

$$f = 64/R_e = (64\ v) / V\ D \tag{9}$$

where:

R_e = Reynold's number (dimensionless)

v = kinematic viscosity (m^2/s)

Substituting into Eq. (12), we get...

$$\{(64\ v) / V\ D\}\ (L/D)\ V^2/2g\ + (p_2 - p_1)/\rho(g_c/g) + (V_2^2 - V_1^2)/2g\ = 0$$

$$\{(32\ v) / D^2\}\ (L/g)\ V\ + (p_2 - p_1)/\rho(g_c/g) + (V_2^2 - V_1^2)/2g\ = 0$$

If we assume a constant cross-section through the pipe, then the velocity will remain constant at all sections through the pipe, $V_1 = V_2$, and...

$$\{(32\ v) / D^2\}\ (L/g)\ V\ + (p_2 - p_1) / (\rho g_c/g)\ = 0$$

$$\{(32\ v)\ (L/g) / D^2\}\ V = -\ (p_2 - p_1) / (\rho g_c/g)$$

But, we know that the flow rate through the pipe, Q, is equal to the velocity times the cross-sectional area, A, so...

$$\{(32\ v\ L) / g\ D^2 A\}\ Q = -\ (p_2 - p_1) / (\rho g_c/g)$$

$$Q = -\ \{g_c D^2 A\}/\{(32\ v)\ L\ \rho\}\ \Delta p \text{ or}$$

$$Q = (\text{constant})\ \Delta p \tag{10}$$

If we recall the classic flow equation for air leakage in buildings, $Q = C\ \Delta p^n$, it is obvious that Eq. (10) simply demonstrates that for laminar flow, $n = 1$.

A-1.6.3 Turbulent Flow

Now, let us consider the situation for fully developed turbulent flow. In this case, the friction factor is independent of the Reynolds number and hence independent of velocity. If we also assume there is no change in elevation and the flow cross-section is constant, then...

$$\frac{f\,L\,V^2}{D\,2\,g} + \frac{(p_2 - p_1)g_c}{\rho \quad g} + (H_2 - H_1) + (V_2^{\,2} - V_1^{\,2})/2g = 0$$

If $H_1 = H_2$ and $V_1 = V_2$, then...

$$\frac{f\,L\,V^2}{D\,2\,g} + \frac{(p_2 - p_1)g_c}{\rho \quad g} = 0$$

$$\frac{f\,L\,V^2}{2\,D\,g} = -\Delta p\,(g_c/g\,\rho)$$

But $Q = VA$, or $V = Q/A$

$$\frac{f\,L\,(Q/A)^2}{2\,D\,g} = -\Delta p\,(g_c/g\,\rho)$$

$$Q^2 = -\{(2\,D\,g_c A^2)/(\rho\,f\,L)\}\,\Delta p$$

$$Q = \{(2\,D\,g_c A^2)/(\rho\,f\,L)\}^{0.5}\,\Delta p^{0.5}$$

$$Q = (\text{constant})\,\Delta p^{0.5} \qquad (11)$$

Once again, if we compare this to the classic flow equation for buildings, $Q = C\,\Delta p^n$, we see that Eq. (11) is simply the case for $n = 0.5$. Since we know that air flow through a porous structure (e.g. a building envelope) is neither pure laminar flow nor pure turbulent flow, we can make the argument that Eq. (1) represents a valid representation of measured airtightness data. Further, the flow exponent, n, must have a value between 0.5 and 1.0. This belief has been supported by voluminous test data which shows the consistent and surprisingly uniform fashion in which Eq. (1) can be used to represent measured test data.

A-1.6.4 Methods Of Reporting Airtightness Data

The resistance to air flow created by the porous structure of the building envelope is a function of the flow geometry, crack length, and the entrance and exit effects. As will be discussed in more detail later, building airtightness is measured by mechanically pressurizing or depressurizing the structure and recording both the air flow rate and the corresponding indoor-to-outdoor pressure differentials. Mathematically, the relationship between air leakage and the pressure differential can be represented by the empirical power law function shown in Eq. (1). However, a common problem encountered in the literature is that researchers use a variety of methods to express their results and to report other relevant data. The vast majority of airtightness test results are expressed using one of two types of parameters: those based on the volume of the building and those based on the equivalent hole area of all the randomly distributed holes in the envelope.

A-1.6.4.1 Air Change Rate Per Hour

This is a volumetric-based parameter and is commonly used for reporting results for residential construction and occasionally for individual zones within buildings.

Air Change Rate at 50 Pa

$$AC/HR_{50} = \frac{\text{(Total leakage at 50 Pa, expressed in building or zone volumes)}}{\text{Volume of the building or zone}} \tag{12}$$

Air Change Rate at 75 Pa

$$AC/HR_{75} = \frac{\text{(Total leakage at 75 Pa, expressed in building or zone volumes)}}{\text{Volume of the building or zone}} \tag{13}$$

The units used in Eqs. (12) and (13) to express results are "air changes per hour" at a pressure differential of 50 Pa or 75 Pa, respectively. In Canada, the ac/hr_{50} parameter is the most commonly used metric, while the ac/hr_{75} is occasionally used in other countries.

A-1.6.4.2. Equivalent Leakage Area

The Equivalent Leakage Area (ELA) is an area-based parameter which is based on the assumption that all of the openings in the building envelope can be combined and represented by a single, sharp-edged orfice. As such, it represents the size of a single, equivalent hole. One limitation of this parameter is that it does not reflect the size of the building, i.e. an Equivalent Leakage Area of 1000 cm^2 in a house would indicate a very loose structure whereas the same hole in a large, multi-storey commercial building would represent an extremely airtight structure. The Equivalent Leakage Area is referenced in the primary Canadian airtightness test standard, CGSB-149.10, and is normally expressed at a pressure differential of 10 Pa and thus has the symbol "ELA_{10}" (CGSB, 1986). It is calculated according to Eq. (14)...

$$ELA_{10} = 0.001157 \times (\rho_r)^{0.5} \times C_R \times 10^{n-0.5} \qquad (14)$$

where:

ELA_{10} = Equivalent Leakage Area at 10 Pa (m^2)

ρ_r = air density at reference conditions, defined as the temperature equal to 20 °C and the atmospheric pressure equal to 101.325 kPa

C_R = flow coefficient under reference conditions ($L/s \bullet Pa^n$)

n_r = flow exponent under reference conditions (dimensionless)

A-1.6.4.3 Normalized Leakage Area

The Normalized Leakage Area (NLA) is based on the ELA except that it is normalized to reflect the size of the building by dividing the ELA by the envelope area. It is also referenced in CGSB-149.10 and is reported at a pressure differential of 10 Pa.

$$NLA_{10} = (ELA_{10} \times 10{,}000) / (\text{area of the building envelope}) \qquad (15)$$

where:

NLA_{10} = Normalized Leakage Area at 10 Pa (cm^2/m^2)

ELA_{10} = ELA at 10 Pa

Area of the building envelope in units of m^2

A-1.6.4.4 Normalized Leakage Rate

The Normalized Leakage Rate (NLR) is another area-based parameter and is referenced in the 1995 National Building Code of Canada for expressing material and component leakage rates. In Canada it is normally referenced at a pressure differential of 75 Pa although other values are occasionally used in the literature, particularly those originating in Europe. Its units are (L/s•m^2).

Normalized Leakage Rate at 25 Pa

$$NLR_{25} = \frac{\text{(Total leakage at a pressure differential of 25 Pa)}}{\text{Envelope area}} \tag{16}$$

Normalized Leakage Rate at 50 Pa

$$NLR_{50} = \frac{\text{(Total leakage at a pressure differential of 50 Pa)}}{\text{Envelope area}} \tag{17}$$

Normalized Leakage Rate at 75 Pa

$$NLR_{75} = \frac{\text{(Total leakage at a pressure differential of 75 Pa)}}{\text{Envelope area}} \tag{18}$$

A-1.6.4.5 Envelope Area

The definition of "envelope area" in Eqs. (16) to (18) may also vary among researchers. Some of the earliest airtightness data was reported using the area of only the exterior walls (including doors and windows) without any consideration of the foundation or roof - presumably because of the belief that leakage through these two components was sufficiently small that it could be ignored (a belief which is untrue). Other researchers, particularly those in Great Britain and a few in the United States, have reported airtightness data on the basis of only the above-grade portions of the envelope, i.e., walls, windows, doors and the roof. British data is generally reported using Eq. (17) with the "envelope area" consisting of the above-grade area; the resulting value is referred to as the "Air Leakage Index". Occasionally the total envelope area is used, in which case the resultant value is referred to as the "Air Permeability" (CIBSE, 2000).

A-1.6.4.6 Selecting The Correct Airtightness Parameter

On the surface, Eqs. 16 to 22 are all attempting to describe the same phenomenon. However, due to the non-linearity of air flow versus pressure differential, coupled with the different reference pressure differentials used in these equations, direct comparisons between airtightness results expressed using different parameters can be quite confusing. For example, say a building is retrofitted to reduce air leakage and the measured ac/hr_{50} decreases by 25% while, the NLA_{10} is reduced by 18%. How much has the leakage been reduced - 18% or 25%? In fact, this is not an unusual situation, but one which is very common. This can be particularly confusing for laymen not conversant with the subtleties of air leakage behaviour - a group which includes most builders, architects and building code officials. Recognizing that “airtightness”, “air leakage rate”, etc. are terms which can not be represented by a single number, but rather an equation or curve, it becomes apparent that the purpose of an airtightness test is actually to “characterize”, rather than to quantify the leakage characteristics of the building. Therefore, it is worthwhile to explore the behaviour of these different leakage parameters to develop an understanding of which applications they are best suited for.

For this analysis, we will use the airtightness requirements defined in the R-2000 Standard since more buildings in Canada have been constructed to this requirement than any other. The R-2000 Standard (Natural Resources Canada, 2000) states...

> “The building envelope shall be constructed sufficiently airtight such that either the air change rate at 50 pascals is no greater than 1.5 air changes per hour, or the Normalized Leakage Area at 10 pascals does not exceed 0.7 cm^2/m^2 (1.0 $in^2/100ft^2$, when measured in accordance with CAN/CGSB-149.10-M86 *(Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method)*.”

Consider three simple cubes (A, B and C) which will be used to represent houses of different sizes, as shown in Fig. A-3 (Proskiw, 2004). We can define Cube A as being a small structure with an edge length of 1 unit while Cube B is a larger building with an edge length of 2 units. Now, we can perform some simple geometric calculations on the two cubes...

Cube A

Surface area (S) = 6 units^2

Volume (V) = 1 unit^3

Surface/volume ratio (S/V) = 6/1 = 6

Cube B

Surface area (S) = 24 units^2

Volume (V) = 8 unit^3

S/V = 24/8 = 3

Next, imagine that the air "leakiness" of each cube can be represented by one equivalent hole per unit of surface area, such that the leakage through each hole is the same. Further, imagine that each cube has to meet the R-2000 Standard's airtightness requirements. To satisfy the (volumetric-based) ac/hr$_{50}$ requirement, Cube A's maximum leakage at 50 Pa cannot exceed 1.50 x its volume, i.e....

= 1.50 x 1

= 1.50 cube^3/hour

Since there are six "holes" through which air leakage can occur in Cube A (i.e. one per unit area), the maximum leakage which each of the six "holes" can exhibit is...

1.50/6 = 0.25 cube^3/hour

Now consider Cube B, which also has to meet the 1.50 ac/hr$_{50}$ requirement. Its maximum permitted air leakage would be...

= 1.50 x 8
= 12 cube^3/hour

Since there are 24 "holes" through which air leakage can occur in Cube B, the maximum permitted leakage through each of the 24 "holes" would be...

12/24 = 0.50 cube^3/hour

In other words, the maximum air leakage which can occur through each hole in Cube B, while still meeting the R-2000 requirements, is exactly twice that of Cube A.

This analogy can be then be extended to a more extreme situation, Cube C, which has an edge length of 100 units...

<u>Cube C</u>
Surface area (S) = 6 sides x (100 x 100) = 60,000 units^2
Volume (V) = 100 x 100 x 100 = 1,000,000 unit^3
S/V = (60,000)/(1,000,000) = 0.060

To meet the same R-2000 ac/hr$_{50}$ requirement, the maximum permitted air leakage would be...

= 1.50 x (100 x 100 x 100)
= 1,500,000 cube^3/hour at 50 Pa.

Since there are now 60,000 "holes" through which air leakage can occur, the maximum permitted leakage through each "hole" would be...

$(1,500,000)/(60,000) = 25$ cube^3/hour

This is 100 times the air leakage (per unit of surface area) which Cube A was allowed to exhibit. However, Cube C's S/V ratio is also 100 times that of Cube A, (i.e. $6/(0.06) = 100$). Therefore, it appears that the maximum amount of air leakage per unit of surface area, for a fixed ac/hr$_{50}$ value, varies in direct relation to the surface area/volume ratio (S/V). In other words, if a builder is attempting to meet the ac/hr$_{50}$ requirement in progressively larger buildings, the amount of air leakage which can take place per square metre of envelope area can actually increase. Therefore, each square metre of envelope area requires less additional care and effort to achieve the R-2000 airtightness requirements.

Of course, the air leakage which occurs through each hole in our conceptual model is analogous to the NLA$_{10}$ since the NLA$_{10}$ is based on air leakage per unit of building surface area. In fact, if we think about what the air leakage per unit area of envelope surface area physically represents, it is apparent that it is a measure of the "quality" of construction from an airtightness perspective. It describes how much care, and money, has to be devoted to each square metre of envelope area at the design, construction and commissioning phases.

The relationship between the ac/hr$_{50}$ and NLA$_{10}$ can be explored in more general terms by reviewing the basic equations which define these terms.

ac/hr$_{50}$ = Q_{50}/V, and

NLA$_{10}$ = Q_{10}/A

where:

ac/hr$_{50}$ = air changes per hour at 50 Pa

NLA$_{10}$ = Normalized Leakage Area at 10 Pa (L/s•m^2)

V = house volume (m^3)

A = building envelope surface area (m^2)

Q_{10} = air leakage at 10 Pa (m^3/s)

Q_{50} = air leakage at 50 Pa (m^3/s)

Also, recall that...

$Q = C\Delta P^n$,

Therefore...

$Q_{50}/Q_{10} = C(50^n) / C(10^n)$, so

$Q_{50}/Q_{10} = 5^n$

The flow exponent (n) has a minimum possible value of 0.50 and a maximum value of 1.00. It is generally accepted that a typical value is about 0.65. If we use n = 0.65, then...

$Q_{50}/Q_{10} = 5^{0.65} = 2.8466$, therefore

$Q10 = Q_{50} / (2.8466)$ and

$Q_{50} = Q_{10} (2.8466)$

Next, to simplify the analysis, assume the house is a simple box of dimensions x, y and z. Then, the volume (V) and surface area (A) of the house can be represented by...

$V = x\,y\,z$

$A = (2xy) + (2xz) + (2yz)$

We can now use the ac/hr_{50} and NLA_{10} to describe the airtightness characteristics of this simple house...

$Q_{50} = (ac/hr50)\,(V)$

$Q_{10} = (NLA_{10})\,(A)$, but

$Q_{50} = Q_{10}\,(2.8466)$, so

$Q_{10}\,(2.8466) = (ac/hr_{50})\,(V)$ and

$(NLA_{10})\,(A)\,(2.8466) = (ac/hr_{50})\,(V)$, or

$$NLA_{10} = [(ac/hr_{50})\,(V)] \,/\, [(2.8466)\,(A)] \text{ and} \tag{19}$$

$$ac/hr_{50} = [(2.8466)\,(NLA_{10})\,(A)] \,/\, V \tag{20}$$

Equation (19) can be used to explore the variation in the NLA_{10} for various sized houses, as the ac/hr_{50} is held constant, while Eq. (20) can be used to show the behaviour of the ac/hr_{50} as the NLA_{10} is held constant. These relationships are shown in Figs. A-4 and A-5 which plot the air leakage characteristics using an assumed value of n = 0.65, for a simple house design of the following dimensions...

$x = 4$ to 15 m

$y = 8$ m

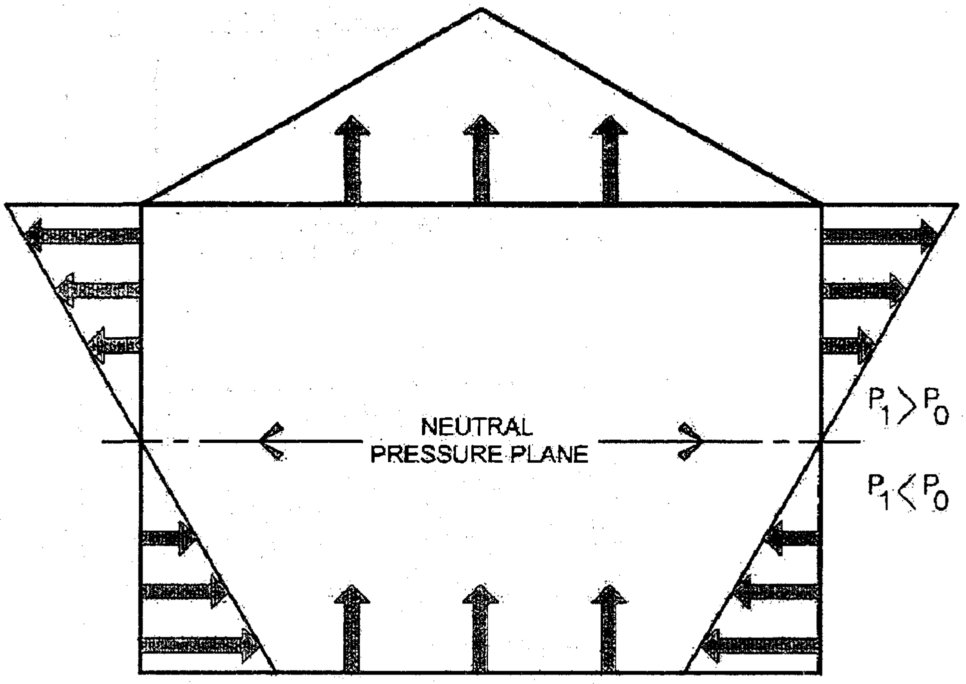
$z = 8$ m

To further expand the results, Figs. A-6 and A-7 shows the relationship between the ac/hr_{50} and the NLA_{10} over the maximum possible range of flow exponents, between 0.50 and 1.00. Thus, for the house dimensions described above, the correct relationship between ac/hr_{50} and NLA_{10} has to lie on, or between, the area bordered by the two lines shown in Fig. A-6 and A-7.

What can be concluded from this analysis? First, the popularly held belief that it is easier to meet the volumetric-based ac/hr_{50} requirement in a larger (e.g. Canadian) house than in a smaller house is correct. But that does not give larger houses an advantage since the R-2000 Standard nullifies the size dependence through use of the NLA_{10}. Since the NLA_{10} is area, rather than volume dependent, the maximum permitted air leakage per "hole" (in the conceptual model) remains constant. Therefore, is it valid to state that larger houses can meet the R-2000 airtightness requirements with greater ease than smaller houses? The answer is no. While builders of large houses will find it easier to meet the ac/hr_{50} requirements than those who build small houses, it must be remembered that they still have the option of meeting the NLA_{10} requirement - and the NLA_{10} is independent of house size.

For example, the 2005 National Building Code (NBC) of Canada specifies maximum air leakage rates for large (i.e. non-Part 9) buildings using the Normalized Leakage Rate at a pressure differential of 75 Pa (NLR_{75}) (NBC, 2005). Its units are litres/second of air leakage per square metre of envelope area at 75 Pa, i.e. $l/(s \bullet m^2)$ (the NBC defines "envelope area" in a slightly different manner than the R-2000 Standard but that has no bearing on the current discussion). Obviously, the NLR_{75} is analogous to the NLA_{10} since they both define leakiness as air leakage per unit of envelope area, with slight variations in the definitional details and pressure differentials.

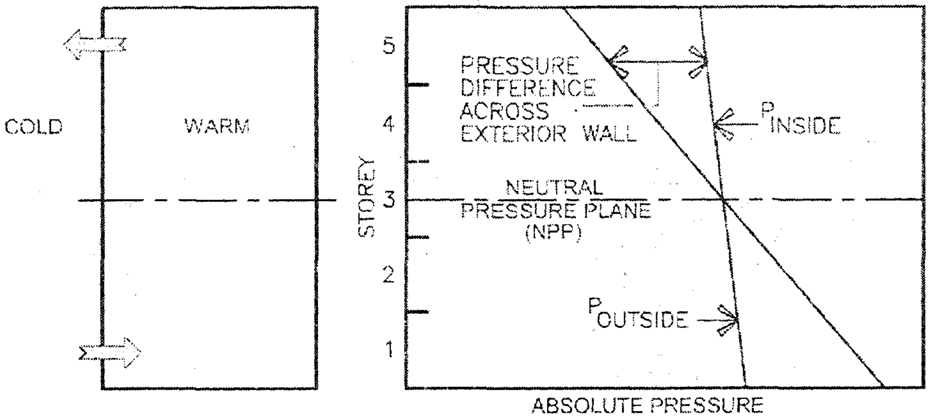
This brings us to a very important point regarding the various air leakage parameters. From the preceding analysis, it is apparent that volumetric-based air leakage parameters, such as the ac/hr_{50} are not good indicators of moisture transport capability whereas area-based parameters, such as the NLA_{10} are more appropriate for this purpose. The value of volumetric air leakage parameters is that they are good indicators of the total energy liability which air leakage creates in a building since the energy load is directly related to the total volume of air which has to be conditioned (per unit time).



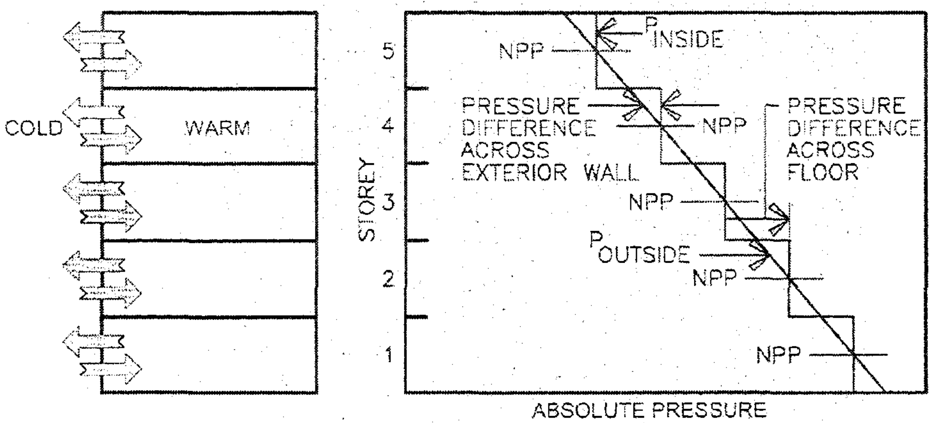
NO WIND

NOTE: ARROWS INDICATE MAGNITUDE AND DIRECTION
OF PRESSURE DIFFERENTIAL.

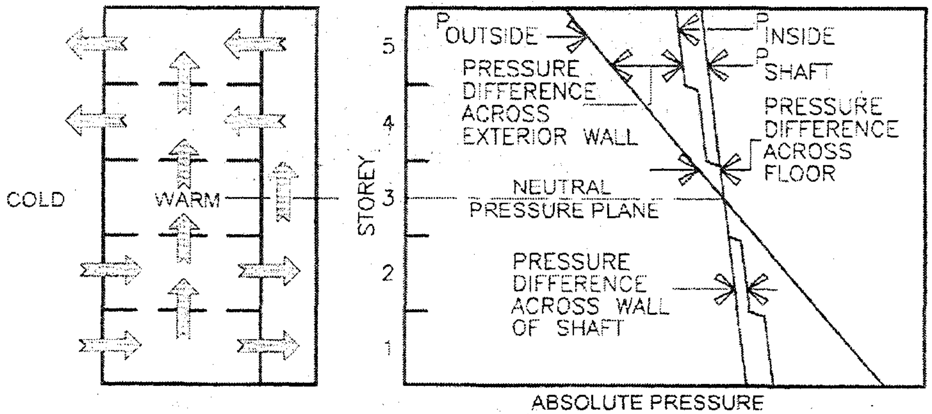
Fig. A-1 Stack Effect



A. BUILDING WITH NO INTERNAL PARTITION



B. BUILDING WITH AIRTIGHT SEPARATION OF
EACH STORY



C. REAL BUILDING WITH OPEN SHAFT

Fig. A-2 Compartmentalization In Buildings (ASHRAE, 2005)

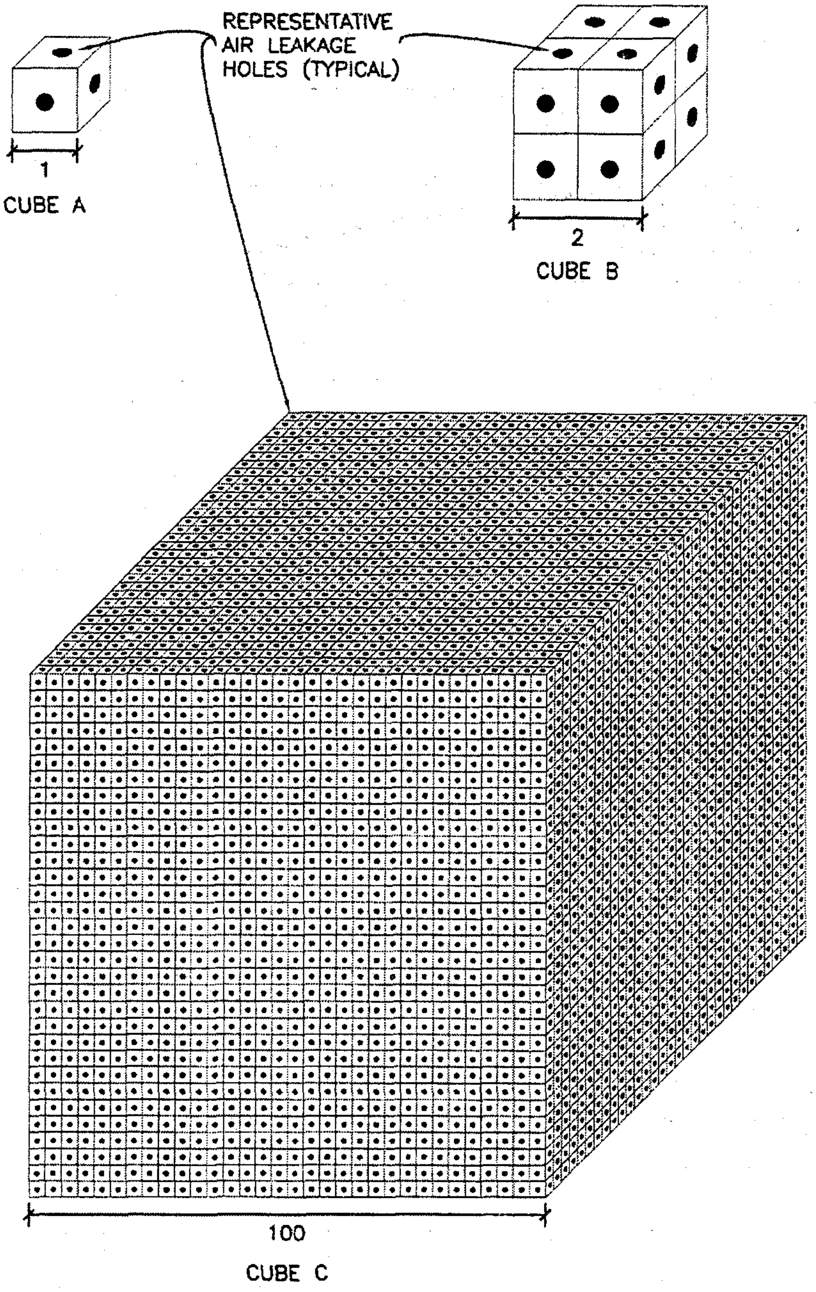


Fig. A-3 Geometric Relationship Between Building Size And Air Leakage Characteristics (Proskiw, 2004)

NTS

Fig. A-4: NLA10 vs. Volume
With ac/hr50 = 1.50 (Proskiw, 2000)

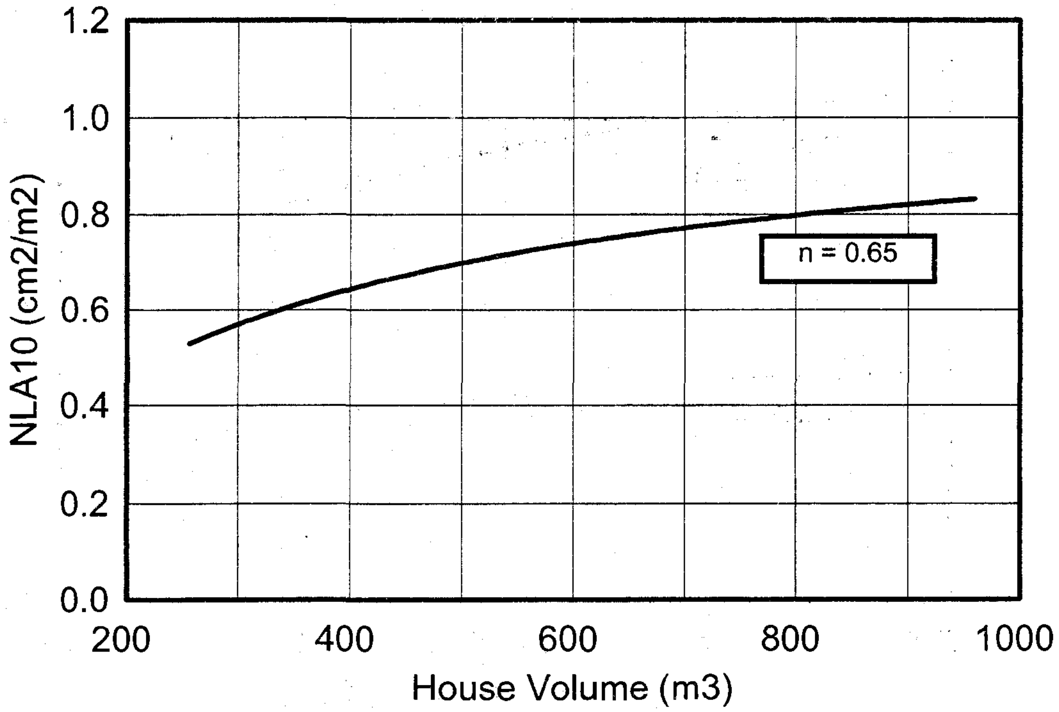


Fig. A-5: ac/hr50 vs. Volume
With NLA10 = 0.70 (Proskiw, 2000)

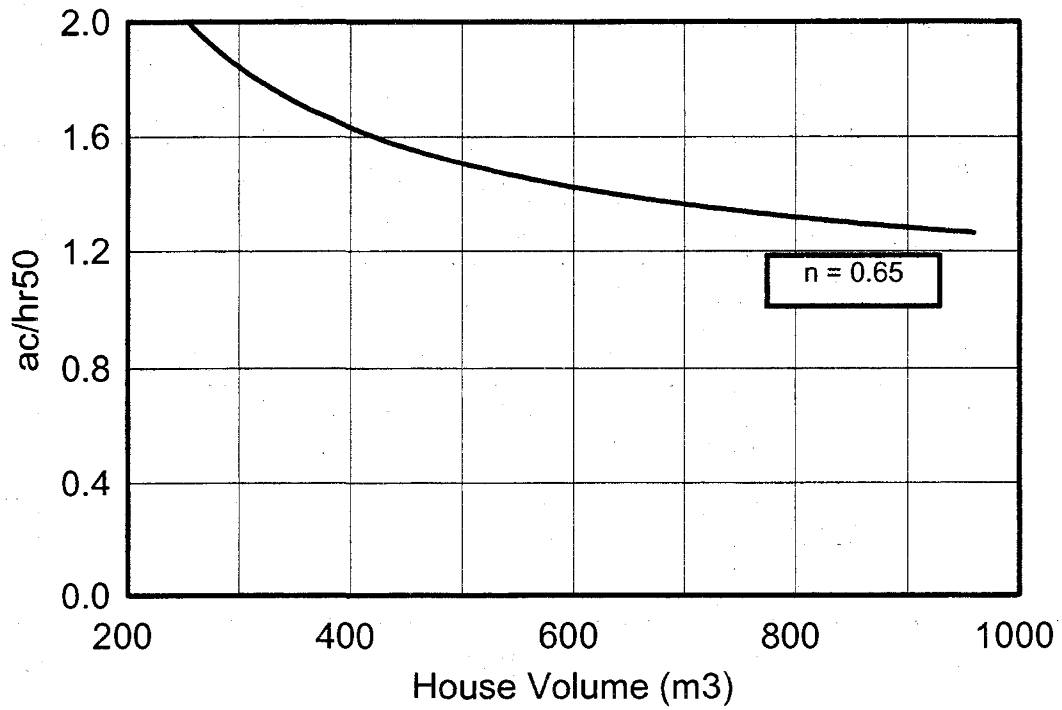


Fig. A-6: NLA10 vs. Volume
With ac/hr50 = 1.50 (Proskiw, 2000)

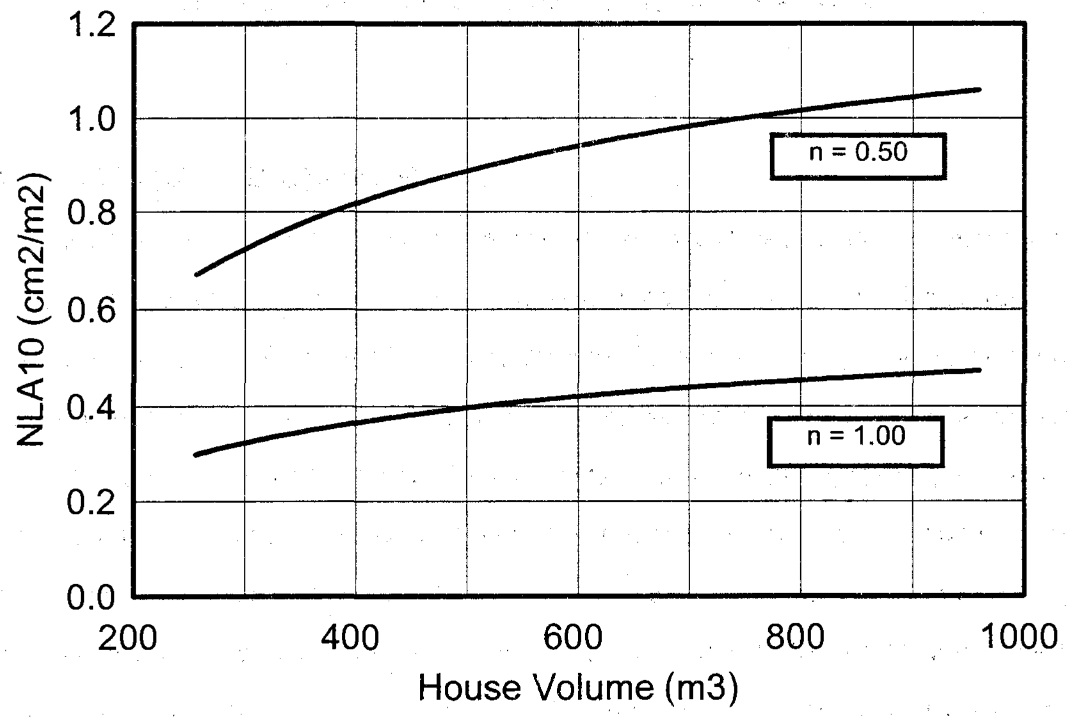
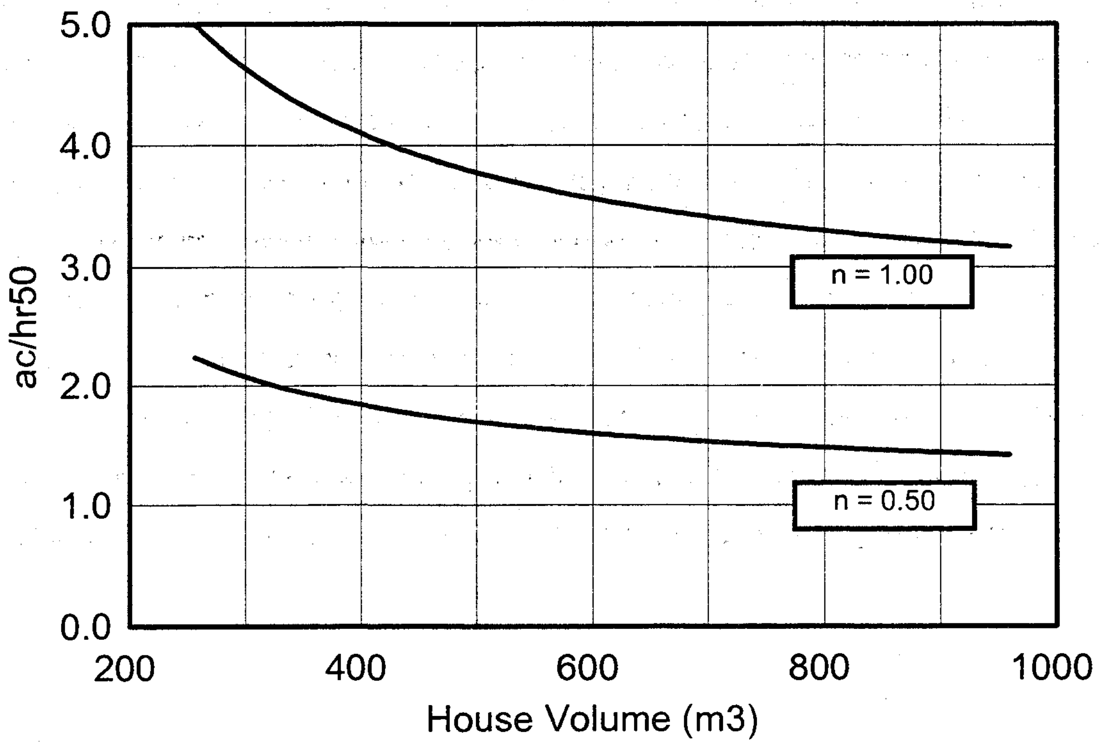


Fig. A-7: ac/hr50 vs. Volume
With NLA10 = 0.70 (Proskiw, 2000)



CHAPTER A-2

AIR LEAKAGE CHARACTERISTICS OF RESIDENTIAL AND COMMERCIAL BUILDINGS

A-2.1 RESIDENTIAL CONSTRUCTION

The concept of testing buildings to measure their airtightness was first developed in Scandinavia and eventually found its way to Canada in the 1970's where the initial work was carried out by the National Research Council of Canada. Testing protocols and equipment were originally developed for residential applications, not because that was where the greatest need for information existed - but rather because the equipment requirements were relatively modest. NRC and a small number of research and consulting engineering firms constructed their own test rigs and began using them for research and demonstration purposes. The first test rigs, now commonly known as "blower doors" became available in the 1980's, which was about the time that the R-2000 Standard was introduced by Energy, Mines and Resources Canada (now Natural Resources Canada). Since then, hundreds of thousands of tests have been performed on houses - largely for quality control, rather than research, purposes. For example, the R-2000 Program has always required that every house enrolled in the program must receive an airtightness test conducted according to a prescribed standard and that the measured leakage not exceed a specified amount. Approximately 10,000 new houses have been tested under the auspices of the R-2000 Program. In addition, airtightness testing is now used routinely for energy retrofit programs such as the EnerGuide for Houses Program (EGH) operated by Natural Resources Canada in association with various, local delivery agents. It has been calculated that in excess of 142,000 houses have been tested since 1998 for EGH purposes (Parekh, 2005). Similar, although generally more modest efforts are underway in other countries. Interestingly, Canada is now regarded as a world leader in airtight construction practices - a fact which has led to the development of intriguing export opportunities for Canadian house builders.

Overall the last 25 to 30 years, these efforts have created a huge body of knowledge on residential airtightness characteristics covering a variety of topics including:

- Leakage characteristics of new houses
- Leakage characteristics of older houses
- Effect of different styles of construction (types of air barriers, construction details, house age, builder, etc.) on airtightness
- Impact (effectiveness) of air leakage sealing
- Long-term performance of airtightness (i.e. durability)

As previously mentioned, most residential airtightness data is reported using one (or more) of three leakage parameters:

- Air Change Rate at 50 Pa (ac/hr_{50}), Eq. (16)
- Equivalent Leakage Area (ELA_{10}), Eq. (18)
- Normalized Leakage Area at 10 Pa (NLA_{10}), Eq. (19)

Figure A-8 summarizes the results of 583 airtightness tests performed on detached houses, located across Canada, over a multi-year period (Gusdorf, 1997) with the results reported using ac/hr_{50} data. All of the houses shown were newly constructed at the time of the tests and were selected on a quasi-random basis; none were designated as R-2000 houses.

Reviewing Fig. A-8, several important observations can be made. First, over all three testing periods there has been a significant difference in the measured airtightness of new houses among various regions of the country. This is largely due to the inherent differences in construction practices among the various regions as well as the care with which builders in different regions exercise on air leakage details. With respect to the former, wood-frame houses are not constructed the same in all regions. For example, the major source of air leakage in detached houses is generally the basement/floor/main wall intersection since it represents a "three-sided intersection" and can be particularly difficult to seal if the detail has not been properly designed. In many parts of the prairies, common practice (until the advent of truss joists) was to embed the floor system into the cast concrete of the basement wall which tended to dramatically reduce air leakage through this critical location relative to that which would be achieved with the more common sill-plate method of construction. Another example of regional differences is the exterior cladding system used on new houses. Once again, on the prairies stucco is by far the dominant system employed whereas brick veneer is the norm in much of eastern Canada while wood siding is prevalent in British Columbia. Since both brick and wood are designed to be highly air permeable (to provide proper venting and drying), they provide little effective resistance to air leakage. In contrast, stucco is actually a reasonably effective barrier to air leakage when properly applied.

Second, Fig. A-8 clearly shows that there has also been a significant improvement over time in the airtightness of new houses in all regions of the country with the most dramatic reductions (in absolute terms) occurring in those areas which initially had the leakiest houses (British Columbia).

Similar trends illustrating improvements in airtightness in new houses have been reported elsewhere. For example, Fig. A-9 shows the results of airtightness tests conducted on a quasi-random sample of 32 new, Manitoba houses constructed in 1998 and 1999; no R-2000 houses were included in the sample (Proskiw, 2002). Airtightness rates ranged from 0.40 to 3.13 ac/hr$_{50}$, with a median value of 1.60 ac/hr$_{50}$. If we accept the argument that the R-2000 airtightness requirement of 1.50 ac/hr$_{50}$ represents an unofficial boundary between "tight" and "loose" construction, then 44% of the houses shown in Fig. A-9 could be categorized as tight

Figure A-10 is taken from the 2001 ASHRAE Handbook of Fundamentals and shows a typical, atypical distribution of airtightness data for a large group of buildings. This is typical of airtightness data since there is a lower limit (zero) but no upper limit. Dumont (2002) has suggested that airtightness data can be best represented as a log-normal distribution.

A-2.2 COMMERCIAL CONSTRUCTION

While tens of thousands of houses (and other small structures) have had their airtightness measured, the same can not be said for commercial buildings; "commercial" in this discussion is considered to be any building significantly larger than a house, and would include apartment buildings and other multi-unit residential buildings (MURB's) normally used for residential applications. In theory, the test procedures used on houses can also be applied to commercial construction. In practice, a variety of technical problems exist which often require additional care to be taken and specialized equipment to be employed. For example, obtaining equipment with the air-moving capability to sufficiently depressurize the building usually requires a large, expensive fan system, possibly with its own power supply since on-site power may be unavailable or of insufficient capacity. Environmental factors, such as the wind and the indoor-to-outdoor temperature differential often have a more significant influence on large buildings than they do on houses. Obtaining access to all areas in a large building may be difficult, particularly in older buildings. If the test structure is physically attached to adjacent buildings (as is often the case), then alternate procedures (such as the one described in this thesis) may need to be employed.

Nonetheless, a small but significant body of knowledge exists on the leakage characteristics of commercial buildings. The largest known study on the subject was completed by Proskiw and Phillips (2001) who reviewed the literature and developed a data base of airtightness results for 192 MURB's, offices, schools, as well as other types of commercial, industrial and institutional buildings in Canada, the United States, Great Britain and Sweden. Their results showed that virtually all large buildings, including those built within the last few years, are quite leaky. For example, the vast majority would not meet the current recommendations contained in the Appendices of the 2005 National Building Code of Canada. Typical leakage rates were found to be 10 to 50 times those referenced in the NBC. Proskiw and Phillips identified three distinct classes of data. Type 1 data was defined as those results obtained when the airtightness test was performed on the entire building and the total envelope area was used to calculate the results (the same procedure used in Canada for testing houses). Type 2 data was defined as those results obtained when the test was performed on the whole building but some other area was used to calculate the NLR_{75}, such as only the above-grade area of the envelope rather than the above-grade and below-grade area. Type 3 data defined results in which the test was performed on individual floors or suites and the exterior wall area of the floors or suites was used to calculate the NLR_{75}. Fortunately, the majority of the data was classified as Type 1 - since it compares the most directly to results obtained for residential construction. When data was encountered in one of the alternate formats, corrections were applied wherever possible to convert it to the format used in this document (i.e., total envelope area). Incomplete and ambiguous data was also a common problem. For example, construction details and dimensions were often very sketchy or non-existent. Occasionally, area-normalized data was reported without a clear definition of "area" being provided.

The results showed that there was little correlation between airtightness and building type; in fact, in almost all cases, significant variations appeared among buildings within a given type. The only exception occurred with institutional buildings, but for this category the sample size was only two buildings.

A-2.2.1 Impact Of Wall Type

The airtightness data for Type 1 buildings was compared on the basis of the dominant wall type used in the structure as described in the literature. This comparison, which is summarized in Fig. A-11, showed a wide variation in NLR_{75} values among the different wall systems reported. The three leakiest wall types were those reported as: brick veneer/steel stud, curtain walls and wood frame construction, however it should be remembered that the wall descriptions provided in the literature were occasionally not very descriptive.

A-2.2.2 Impact Of Building Age

The Type 1 data was also categorized on the basis of building age, as summarized in Fig. A-12 Surprisingly, some structures with very low leakage rates were several decades old, challenging the notion that tight construction is the sole domain of newer structures. Conversely, many buildings constructed with the last five to ten years displayed very high leakage rates. This data nicely displayed the absence of any correlation between airtightness and the age of the building.

A-2.2.3 Impact Of Year Of Construction

"Year of construction" is different from "building age" in that the former reflects the construction standards which were in effect when the structure was built. Fig. A-13 shows the impact on airtightness of the year in which the building was constructed, which shows that year of construction had no significant influence on airtightness. One might expect to see lower NLR_{75} values commencing in the 1980's as the effects of rising energy costs began to be felt. However, this does not appear to be the case as leakage rates for buildings constructed in the 1980's and 1990's were indistinguishable from the rest of the sample. However, the three buildings in the sample which were constructed just prior to 2000 showed relatively low air leakage rates compared to the rest of the database. All three were constructed in Canada after release of the 1995 NBC, and all three were designed with air leakage control as an explicit design objective. Although the sample size is small, they do demonstrate the beneficial impact of adopting and implementing measures to control air leakage.

A-2.2.4 Impact Of Number Of Stories

Figure A-14 shows the variation in airtightness as a function of the number of storeys. There appears to be a trend toward lower air leakage rates for taller buildings, which is somewhat surprising given that similar construction practices are typically used for buildings with more moderate height. However the sample size for multi-storey buildings was somewhat limited so it is difficult to draw firm conclusions.

A-2.2.5 Impact Of Country Of Origin

The country of origin illustrates local construction practices as well as the influence of building codes which might have some influence on airtightness. Figure A-15 compares the NLR_{75} data for the Type 1 buildings for which information was available. The Canadian buildings had the lowest mean NLR_{75} value along with the smallest standard deviation. The American structures, which were predominately low-rise commercial structures in Florida, were roughly three times as leaky as those in Canada and also had a very large standard deviation.

The British buildings were slightly more leaky, on average, than the American structures, although with less variation.

A-2.2.6 Impact Of Air Leakage Sealing

Sixteen of the buildings identified in the literature survey received some form of retrofit intended to reduce the structure's air leakage, although in most cases the descriptions provided of the retrofits were rather vague. All the structures were Type 1 buildings and consisted of MURB's, office buildings, schools, industrial and institutional buildings. Reductions in the NLR_{75} ranged from 3% to 92% (although the latter retrofit consisted of virtually rebuilding the entire exterior wall assembly), with an average reduction of 22%.

Fig. A-8 Airtightness Of New Canadian Houses (Gusdorf, 1997)

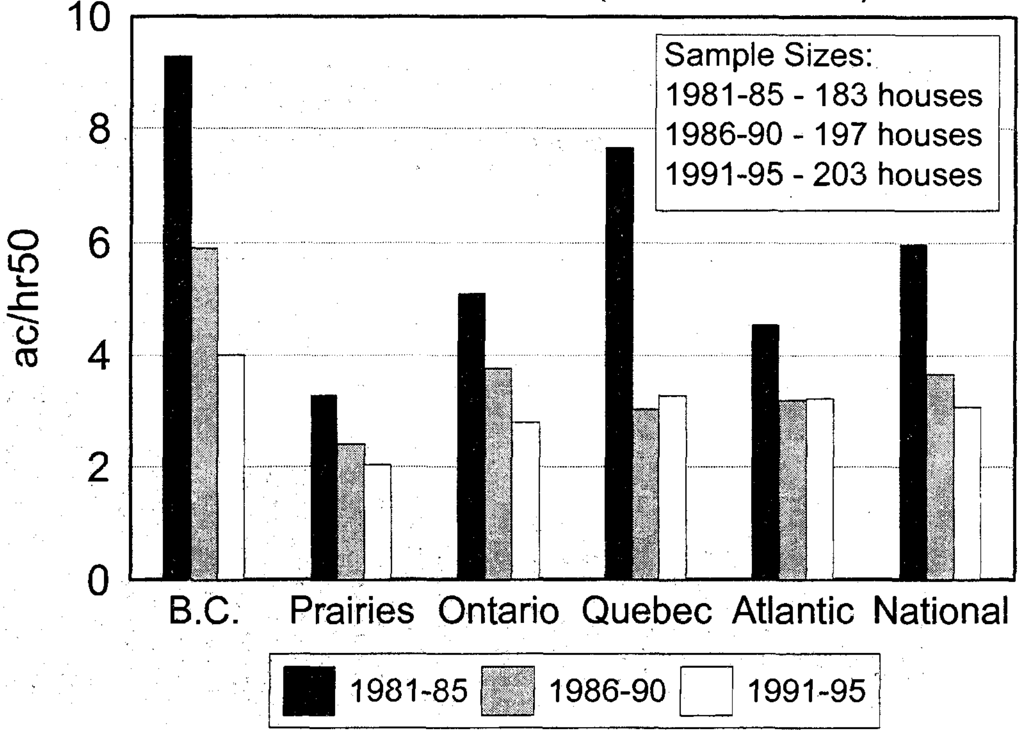
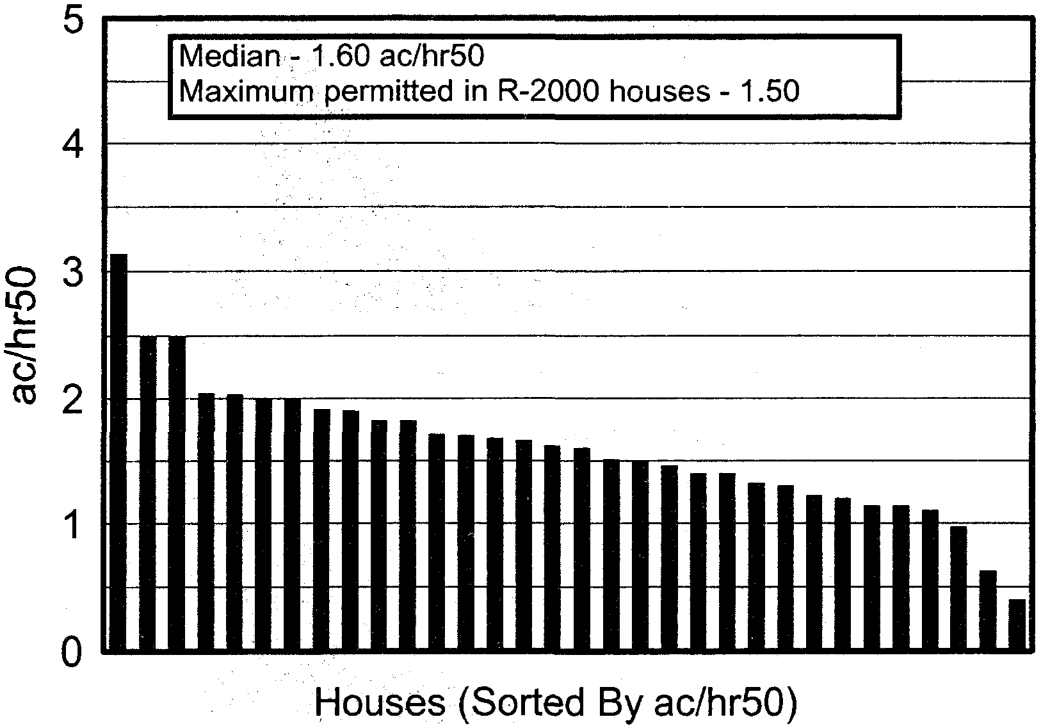


Fig. A-9

Airtightness Of New Manitoba Houses

(Proskiw, 2002)



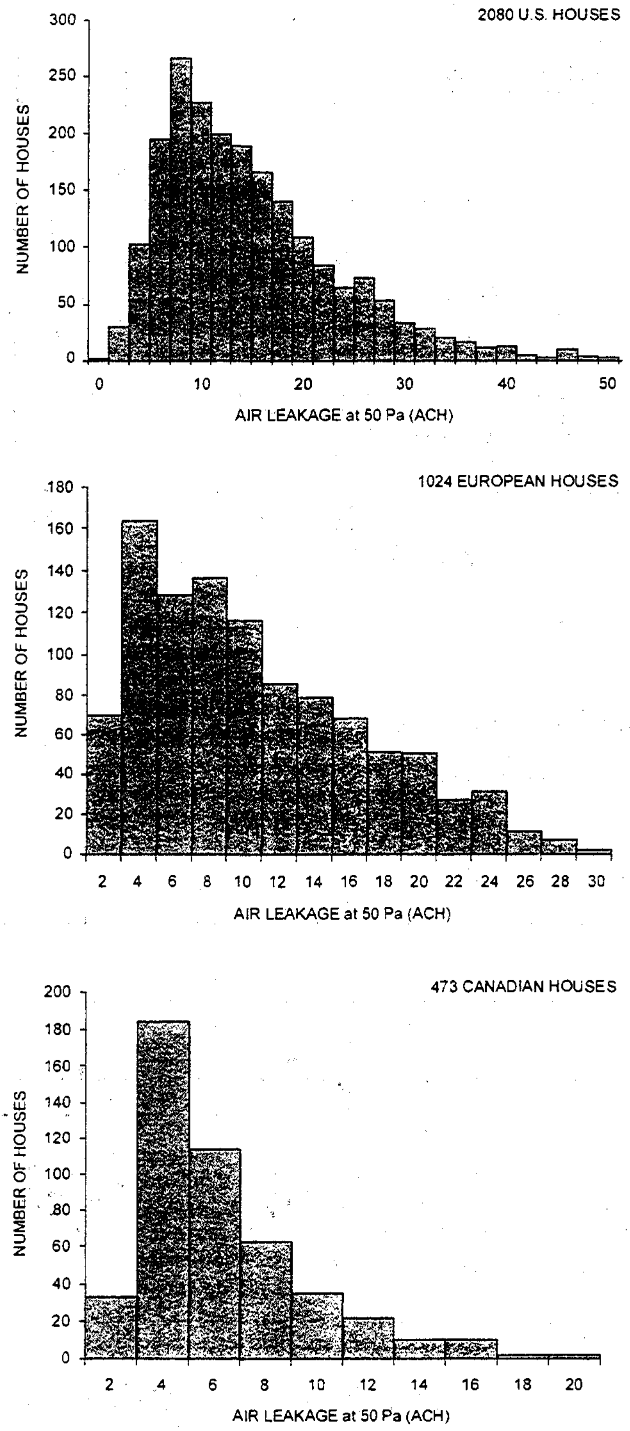


Fig. A-10 Envelope Leakage Measurements (ASHRAE, 2001)

Fig. A-11 Impact Of Wall Type
(Proskiw and Phillips, 2001)

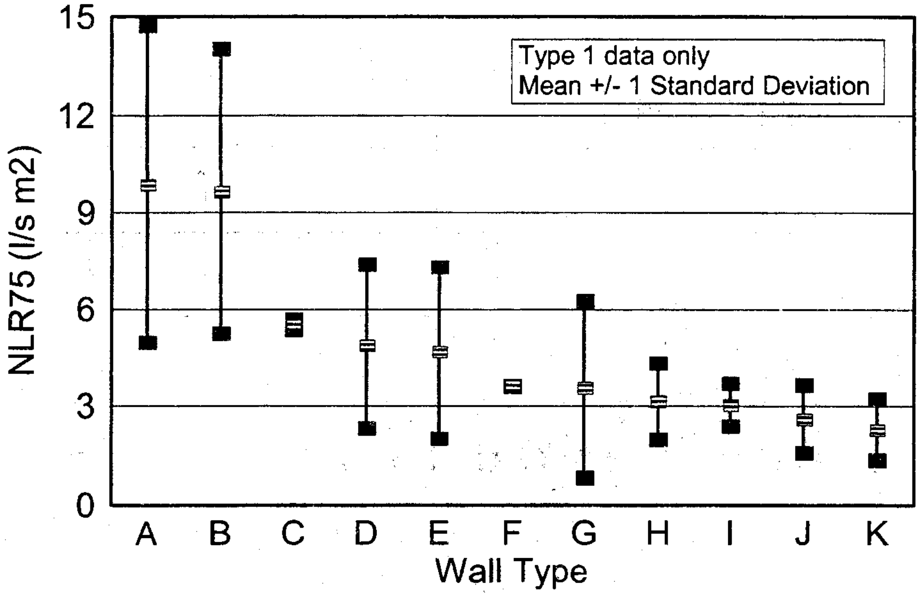


Fig. A-12 Impact Of Building Age
(Proskiw and Phillips, 2001)

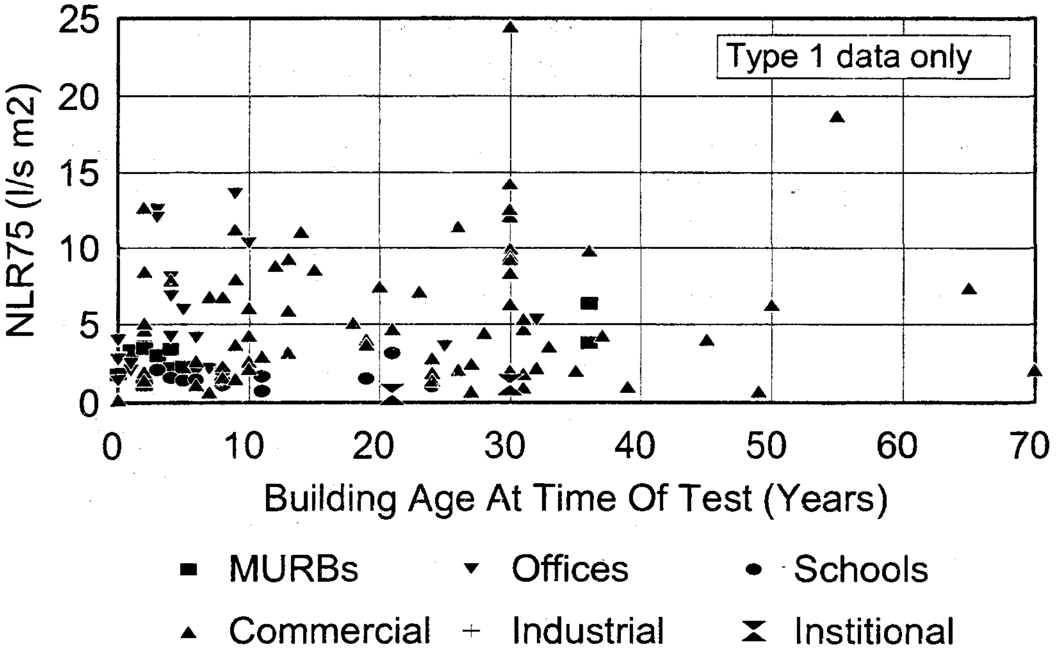


Fig. A-13 Impact Of Year Of Construction (Proskiw and Phillips, 2001)

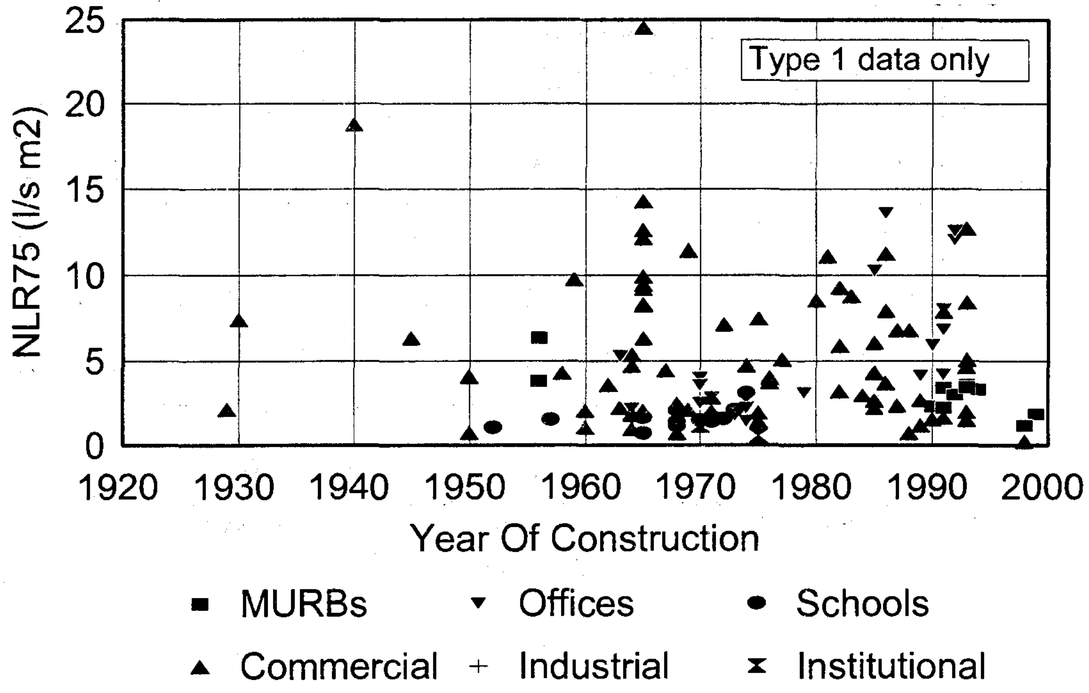


Fig. A-14 Impact Of Building Height (Proskiw and Phillips, 2001)

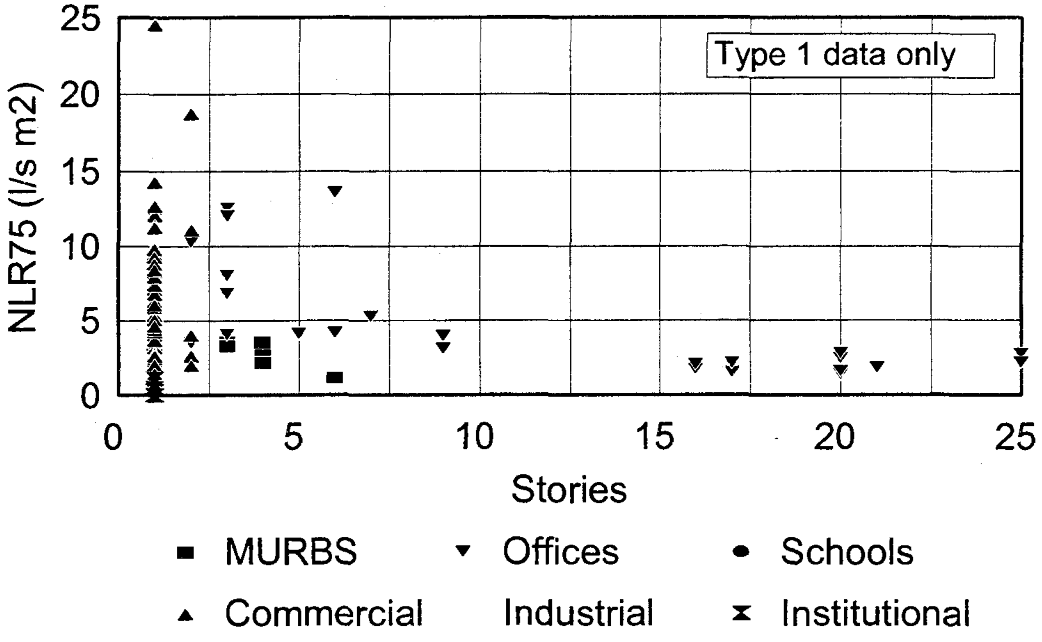
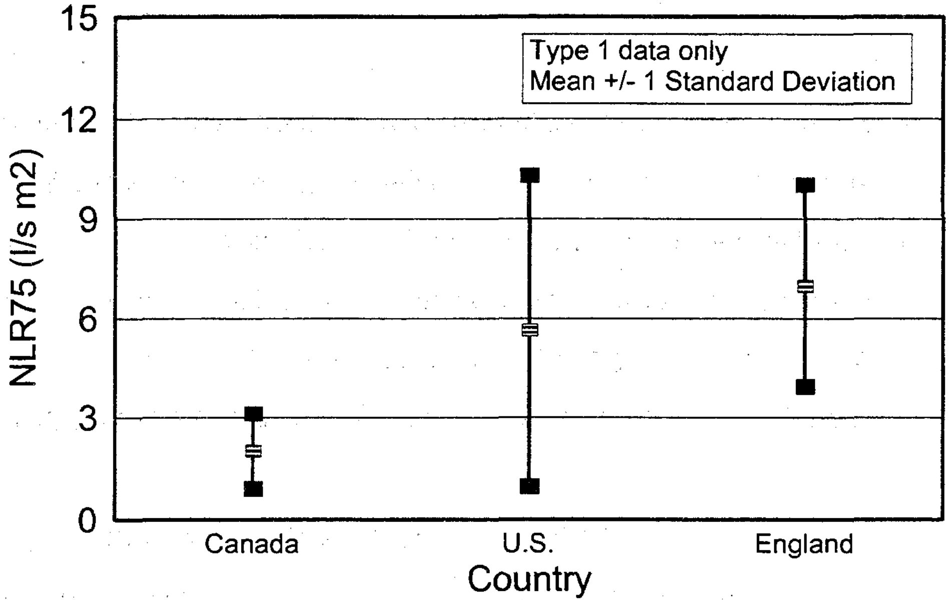


Fig. A-15 Impact Of Country
(Proskiw and Phillips, 2001)



CHAPTER A-3

AIRTIGHTNESS TEST METHODS, EQUIPMENT AND PERFORMANCE STANDARDS

A-3.1 INTRODUCTION

This Chapter provides a backdrop for the project described in this thesis, namely the development of the innovative testing procedure. It describes existing and proposed test methods which have been developed for conducting quantitative and qualitative airtightness tests on complete buildings as well as building components. It also considers the equipment used for these tests as well as the associated costs. Finally, the various Canadian and international airtightness performance standards and specifications are reviewed.

A-3.2 WHOLE-BUILDING AIRTIGHTNESS TEST METHODS

A-3.2.1 CGSB-149.10, *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method*

Published by the Canadian General Standards Board in 1986, this is the most common test method used in Canada for determining the airtightness of building envelopes (CGSB, 1986). The procedure was developed for houses and other small buildings, however, it can be used on larger structures provided sufficient air-flow moving capacity is available. As shown in Fig. A-16, the test equipment consists of an exhaust blower or blowers, usually with an integral flow-measuring device (referred to as a blower door) and a pressure gauge for measuring the indoor-to-outdoor pressure differential. When used on small buildings, a single blower is usually sufficient. On large buildings, multiple blowers, or a single high-capacity unit, may be required. However, the use of multiple blowers degrades the test accuracy while large capacity blowers may require their own power supplies (although the British Research Establishment's BREFAN system is able to use the building's existing 220 V power supply). The test procedure consists of depressurizing the building to eight different indoor-to-outdoor pressure differentials between 15 Pa and 50 Pa (i.e., in increments of 5 Pa) while measuring the exhaust flow rate required to sustain each pressure differential. The standard includes a detailed sealing schedule for the preparation of intentional openings in the envelope (such as ventilation air intakes, exhaust ducts, combustion vents, etc.) as well as prescribed analysis procedures and acceptance/rejection criterion for the data. The analysis method calculates the flow coefficient and flow exponent, C and n in Eq. (1), thereby permitting the results to be expressed in any desired format. However, they are normally reported at a pressure differential of 10 Pa and/or 50 Pa. CGSB-149.10 (and other quantitative test procedures) can also be used for quality control purposes, particularly if used in conjunction with smoke wands to highlight leakage locations. This requires the building (or zone) to be largely complete before it can be tested. CGSB-149.10 is currently being revised. Possible changes being considered include the addition of both single- and two-point test methods as alternatives to the current multi-point procedure.

Thousands of buildings have been tested using CGSB-149.10 although the vast majority of these have been houses rather than large buildings. However, it is worth noting that if the building envelope is constructed to a very airtight level, such as those recommended by the 1995 NBC Appendices, then theoretically many large buildings could be tested using CGSB-149.10 and commercially available test equipment. For example, consider a building, in the shape of a cube, with an airtightness equal to 0.1 L/s•m^2 @ 75 Pa (the NBC-recommended Normalized Leakage Rate for most commercial buildings). Using a typical commercial blower door with the capacity to move 2,000 L/s against a pressure differential of 50 Pa, the maximum sized building which the blower door could test would have a side dimension of 66 m (216'). In other words, a standard *residential* blower door could successfully test a 21 storey building with a plan area of 4,356 m^2 (47,000 ft^2) and a total floor area of about 91,500 m^2 (1,000,000 ft^2)! Obviously, as large buildings become tighter, it becomes progressively easier to test them.

A-3.2.2 CGSB-149.15, *Determination of the Overall Envelope Airtightness of Office Buildings by the Fan Depressurization Method Using the Building's Air Handling System*

Published in 1996 by the Canadian General Standards Board, this standard describes a test method for determining the airtightness of the building envelope using the building's existing mechanical system to provide the required depressurization (CGSB, 1996). It was written specifically for larger buildings which cannot be tested using CGSB-149.10 given the limited flow capacity of most portable equipment.

As shown in Fig. A-17, CGSB-149.15 uses the building's air-handling system to pressurize or depressurize the building such that the total inward or outward flow can be measured. Air flow rates are varied in increments to create at least four different pressure differentials across the building envelope. The standard also includes a detailed sealing schedule for the treatment of intentional openings and prescribed data analysis procedures. Aside from using the building's own mechanical system, the major differences between CGSB-149.15 and CGSB-149.10 are that the former: permits either positive or negative pressurization of the envelope (rather than negative only), fewer data points are required (four versus eight), indoor-to-outdoor pressure differentials are measured at the top and bottom of the building (instead of at just one elevation) and there are restrictions on the minimum outdoor temperature under which the test can be conducted (to limit the variation of envelope pressure differentials caused by stack effect). The standard describes how the flow coefficient and flow exponent (C and n) are to be calculated. Results are normally expressed at pressure differentials of 10 Pa, 50 Pa and 75 Pa. Bahnfleth et al (1999) investigated the uncertainty associated with this test method and proposed guidelines for improving the precision of the test. These included: establishing the minimum and maximum pressure differentials used in the test to be12.5 Pa and 75 Pa; restricting the test to periods when the wind speed was less than 14 km/hr and the outdoor temperature was between 5°C and 35°C.

It should also be noted that not all large buildings have sufficiently flexible mechanical systems to permit them to be used for this procedure. Because of the extra manpower and equipment requirements plus the time required to establish satisfactory test conditions, the cost of performing a test can be much greater than one performed using CGSB-149.10. In contrast to the thousands of successful applications of CGSB-149.10, CGSB-149.15 has only been used on a handful of occasions - mainly for research purposes.

A-3.2.3 ASTM E 779, *Determining Air Leakage Rate by Fan Pressurization*

First published in 1987, and then re-approved in 1992 by the American Society for Testing and Materials, ASTM 779 is very similar to CGSB-149.10, and is commonly used in the United States (ASTM, 1992). The major differences are that ASTM 779: permits either a pressurization or depressurization test to be performed (which produces slightly different results), uses a test pressure range between 12.5 Pa and 75 Pa in increments of 12.5 Pa, and employs a slightly different analysis procedure. The standard describes how the flow coefficient and flow exponent are calculated. However, it recommends a reference pressure differential of 4 Pa to express the results since this is considered to be closer to the typical pressure differentials experienced by most low-rise buildings.

A-3.2.4 ASTM E 1827, *Determining Airtightness of Buildings Using an Orifice Blower Door*

Published in 1996, this standard is an adaptation of ASTM E 779 for orifice blower doors (ASTM, 1996) and describes two alternative measuring and analysis procedures. The first is a single-point method in which multiple flow measurements are made at a pressure differential near 50 Pa and a flow exponent (n) of 0.65 is assumed. The second procedure is a two-point method in which multiple flow measurements are made near each of two pressure differentials, 12.5 Pa and 50 Pa, thereby permitting both the flow coefficient and flow exponent to be estimated. Either depressurization or pressurization is permitted. Results can be reported at a variety of pressure differentials including 4 Pa, 10 Pa, 30 Pa or 50 Pa. It includes much more detailed analysis protocols than E 779 and also contains a recommended sealing schedule for the treatment of intentional openings.

A-3.2.5 ISO 9972, *Thermal Insulation - Determination of Building Airtightness - Fan Pressurization Method*

Published by the International Standards Organization in 1996, this test method is primarily used in Europe and other parts of the world (ISO, 1996). It is similar to both CGSB-149.10 and ASTM E 779 except that it permits the building to be pressurized or depressurized, using a conventional blower door, the building's mechanical system (like CGSB-149.15) or a separate fan and duct system (presumably for situations in which the blower door has inadequate capacity). The test pressure range is from 10 Pa to 60 Pa in increments of no more than 10 Pa, with a minimum of five data points. The standard reference pressure for expressing results is 4 Pa, although other values can be used. It also explicitly describes how component leakage rates can be determined by sequential masking (although this technique can also be used with the other whole-building test procedures).

A-3.2.6 Balanced Fan Depressurization Technique

A common situation which arises with large buildings is that the building envelope in only one zone is of interest for the airtightness test. This might be a single floor, or merely a portion of one floor. If one of the preceding methods were used with the blower door located in the test zone, then both interior and exterior air would be measured at the blower door since partition air leakage is usually quite significant and certainly cannot be assumed to be zero. Conversely, several zones may be connected or otherwise joined together thereby making determination of the airtightness of one building within the group very difficult since it is often hard, or impossible, to aerodynamically isolate it from the others.

To deal with this situation, the National Research Council developed a test method approximately 20 years ago in which the interior leakage could be eliminated, or at least quantified, using additional blowers (sometimes called "masking blowers") in zones adjacent to the test zone (Shaw, 1980; Shaw and Reardon, 1990). This permits the interior leakage to be eliminated since the pressure differential across interior partitions can be kept at zero while the test zone is depressurized relative to ambient. The basic test configurations are shown in Figs. A-18 and A-19, which illustrate how the method would be used to isolate an individual room, or floor, within a building. While conceptually very simple, the major limitation of this test method is the practical difficulty of accurately adjusting air flows to exactly maintain a zero pressure differential across the interior zones, and with controlling leakage across partitions. Since inter-zone leakage almost always exists, any adjustment of one blower's speed invariably affects the flow rates through the others. Given that as many as five blowers may be required, this can require delicate adjustment and considerable patience. Other practical problems have been identified, for example if hand-held radios are used for communication between the various blower operators (since they are usually in different zones and thus physically separated), experience has shown that these devices generate electrical interference which can be detected by micromanometers and result in erroneous readings.

Alternatively, rather than simultaneously depressurizing all of the adjacent zones, the method can be used with just two blowers to sequentially calculate the leakage through each interior partition. However, this must be performed with great care to prevent erroneous results (basically because the partition leakage, which may be relatively small, must be calculated as the difference between two large numbers - an experimentally undesirable situation; and because of diagonal leakage). In theory, the method can be used to estimate the flow coefficient and flow exponent of the test area, although for the reasons described, the accuracy of the results is likely to be less than that achievable using single-zone test procedures.

Despite these problems, the balanced fan depressurization method has been successfully used on several buildings. An evaluation of the technique for multiplex housing is described by Flanders (1992). Bahnfleth et al (1999) investigated the uncertainty of the test method and proposed the same restrictions discussed in the Chapter above dealing with CGSB-149.15. The balanced fan pressurization technique has never been formalized as an official test method by any standards writing body. Due to the limitations discussed above, it has never been widely adopted by practitioners for non-research applications.

A-3.2.7 Lstiburek Technique

Lstiburek has also worked on the problem of quantifying inter-zonal air flows in multi-zone buildings and has proposed a method by which various pressure fields are measured in the building and air-flow relationships developed from them (Lstiburek, 2000). Modifications are made as necessary to select zones to adjust the pressure fields in a known fashion. The measured building air pressure field can be used with network analysis to solve flow and leakage regimes as an alternative to using estimated or measured leakage areas and measured air flows. He has also suggested that the technique can be useful for diagnostic investigations of air leakage-related problems. Further development of this technique is now underway (Olson, 2000).

A-3.2.8 Nylund Technique

Nylund investigated the problems of determining the airtightness of the exterior envelope of a single zone within a multi-zone building (1980). He proposed a test method by which inter-zone leakage could be accounted for using a series of computations based on measurement of the indoor-to-outdoor pressure differentials in zones adjacent to the test zone while the latter was being tested. However, his method required two significant assumptions: that the airtightness (C and n) of all zones was the same and that the inter-zone leakage was much smaller than that through the exterior envelope. His method was investigated by Love and Passmore (1987) for the case of row houses (for which the first assumption is more likely to be reasonable) who concluded that it appeared to provide reasonable accuracy - at least for the application considered. No other references were identified describing successful application of the technique.

A-3.2.9 Blasnik Technique

In the early 1990's, Blasnik developed a technique which has proven useful for diagnosing indirect air leakage paths in houses (Blasnik and Fitzgerald, 1993 and Bohac, D., 2002). Known as the Blasnik Technique or Zone Pressure Diagnostics, it relies on the principle that the pressure differentials across the interior and exterior surfaces (boundaries) of a series leakage path provide an estimate of the interior and exterior leakage areas of the flow path. The technique works on the basis of depressurizing the test zone and then measuring not only the indoor-to-outdoor pressure differential but also the intermediate pressure differential between the zone (or outdoors) and an adjacent, buffer zone (such as an attached garage or an unheated attic). If the flow conditions between test and buffer zones are then intentionally modified, a new set of pressure relations are established which can be easily quantified by re-measuring the pressure differentials. The modification can take the form of adding a hole of known size to one side of the flow path, or by introducing a large hole between the test and buffer zones, or by estimating the physical size of intentional openings between the buffer zone and the outdoors (such as by estimating the area of the roof vents serving an attic).

However, to solve the relevant equations, the technique makes a series of assumptions about the flow characteristics: first, the added hole behaves as an orfice with a characteristic flow exponent (see Eq. 1) equal to 0.50; second, that the discharge coefficients for the interior and exterior surfaces are equal; and third, that the inside and outside surfaces of the series flow path behave with "typical" flow characteristics, i.e. their flow exponents are both equal to 0.65. With respect to the latter assumption, it has been found from thousands of airtightness tests that actual buildings will exhibit flow exponents ranging from 0.50 to 1.00 with virtually any value between these extremes being possible. The value of 0.65 is often used to represent a typical flow exponent (when the actual value is unknown), however individual buildings may have values significantly different values.

Nonetheless, the technique has been used relatively extensively and has proven to be a useful technique for field investigations and for providing answers to otherwise unsolvable questions.

A-3.3 BUILDING COMPONENT TEST METHODS

A-3.3.1 ASTM E 283, *Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen*

ASTM E 283 was first published in 1965 and was probably the first significant test standard dealing with air leakage (ASTM, 1991). It is a laboratory test method which requires the test specimen to be installed in a chamber from which air is exhausted or supplied. One critical aspect of the test procedure is determining the extraneous leakage through non-specimen portions of the chamber (which can be determined by sequential masking or by testing a specimen known to have zero leakage). Obviously, this is most critical with specimens that have very low leakage rates since the extraneous leakage becomes a larger percentage of the overall air flow into or out of the chamber. The test results can be expressed at any pressure differential or, if none is specified, at 75 Pa. The analysis can also be adapted to measure the air leakage over a variety of pressure differentials, thereby permitting the flow coefficient and flow exponent to be calculated. Although the analysis procedure is not specified in the standard, it could easily be adapted from one of the whole-building airtightness test methods. Although the title refers only to windows, curtain walls and doors, it can also be used to test other types of building components.

A-3.3.2 ASTM E 783, *Field Measurement of Air Leakage Through Installed Exterior Windows and Doors*

This test procedure is very similar to ASTM E 283 but is intended for field applications (ASTM, 1993). The experimental set-up is basically the same as E 283 with the major difference being that a special test chamber has to be constructed and attached over the test specimen. Under normal field conditions, a single test chamber can generally be re-used two or three times, after which it normally has to be replaced. Generally, the biggest challenges encountered using E 783 are affixing the chamber over the specimen so as to adequately limit extraneous leakage and then quantifying the extraneous leakage which remains. The test procedure, analysis methods and methods of reporting results are the same as E 283. It can also be adapted to permit calculation of C and n, and used to test other types of building components.

A-3.4 QUALITATIVE TEST METHODS

The preceding test methods have all been quantitative procedures whose goal is determination of the specific air leakage rate of the building, zone or component. There also exist qualitative test methods which are intended for quality control purposes, for example during construction or renovations when information on the presence, location and relative magnitude of leaks is extremely valuable.

A-3.4.1 ASTM E 1186, *Air Leakage Site Detection in Building Envelopes and Air Retarder Systems*

This standard, originally released in 1987 and then re-approved in 1998 (with additions), describes a variety of methods for finding the locations of air leakage sites on the building envelope (ASTM, 1998). Seven different methods are described:

1) Combined building depressurization (or pressurization) and infrared scanning;
2) Building depressurization (or pressurization) and smoke tracers;
3) Building depressurization (or pressurization) and air-flow measuring devices;
4) Generated sound and sound detection;
5) Tracer gas detection;
6) Chamber depressurization (or pressurization) and smoke tracers; and
7) Chamber depressurization (or pressurization) and leak detection liquids.

The E1186 procedures have several advantages relative to the quantitative test procedures. First, some permit leakage locations to be identified during the construction process so that corrective action can be taken, preferably not only at the offending location but at others which use the same detail. While the quantitative methods can also be used for quality control purposes, most of them require the building envelope to be sufficiently airtight that the building, or zone, can be adequately depressurized. Thus, design faults or construction problems may not be identified and corrective action is difficult and expensive. Some of the qualitative techniques are quite economical and can be used to test, literally, thousands of details on a building. For example, test equipment is now commercially available which uses the chamber depressurization with leak detection fluids approach (Knight, 2001). It has been specifically designed for field testing of repetitive details such as masonry ties. Training is relatively easy and the time required to perform a single test is less than a minute for a one-man crew.

A-3.5 EQUIPMENT

A-3.5.1 High-capacity Blower Systems

The critical element in large building airtightness testing is the capacity of the blower system since large buildings usually require a much greater flow capacity than that available from standard residential blower doors. For example, the National Research Council designed and built a system with an air-flow capacity of about 23 m^3/s (50,000 ft^3/min) and used it to test a number of office buildings in Ottawa (Shaw and Jones, 1979). This unit was hand-built specifically for NRC and only one was constructed. The connection to the building was made with 0.9 m (3') flexible ducting and a temporary plywood door plug. It is currently stored in Ottawa

A similar device was built by the (then) National Bureau of Standards in the United States in the early 1980's. Their system utilized a 7.55 m^3/s (16,000 ft^3/min) axial fan powered by a 7,000 W, 230 V single-phase, gasoline-powered generator (Hunt, 1984). Flow rates were measured using a pitot static flow monitoring assembly with built-in flow straightener mounted approximately one fan diameter upstream from the fan.

In England in the 1980's, British Gas plc developed a system which used a 5.6 m^3/s (11,800 ft^3/min) fan, powered by a 12.5 HP generator to test larger industrial buildings. They also constructed a larger unit with a reported capacity of 41.7 m^3/s (88,000 ft^3/min) at 50 Pa (Lilly, 1987). It is not known if these units are still in active use. The British Research

Establishment also developed a blower system called the BREFAN. This was a smaller version of the NRC unit, with a capacity of 5.5 m^3/s (11,600 ft^3/min) at 50 Pa, but operated using standard 220 V power supplies and was intended for use in combinations of multiple units. Plans may be underway for a commercial firm to manufacture up to ten additional examples of the system since proposed changes to the English building regulations may significantly increase the demand for such systems, especially for commercial (as opposed to research) purposes. In addition, the Building Services Research and Information Association (which is a member-based organization) have developed a test rig known as the "Fan Rover". This consisted of a 30 m^3/s (63,500 ft^3/min) fan mounted on a trailer which used the rear power take-off of a Land Rover vehicle to power the fan, thus avoiding the need to access power on-site. It used a built-in pitot tube assembly to measure flow rates as low as 3 m^3/s (6,350 ft^3/min). Numerous large buildings have apparently been tested using this rig.

Other than the activities discussed above, there are no known manufacturers of single, high-capacity blower systems suitable for airtightness testing of large buildings. However, some of the blower door manufacturers (see below) are actively developing systems which would permit multiple numbers of their standard residential blower doors to be ganged together, with up to three per doorway, to give significantly higher flow rates than are presently available. Further, the capacity of their blower doors is also being improved. With such a combination, flow capacities in the order of 13 m^2/s (27,000 ft^3/min) per doorway are anticipated. Multiple doorway set-ups could also be utilized so even greater flow capacities are possible. Presumably, these combination systems would have some form of integrated control and flow measuring systems. They are designed to operate on 110 V, so a separate power supply would not be needed, although access to a separate 110 V circuit for each fan would be required. An opportunity may also become available from manufacturers of positive ventilation fans used by fire departments to control and remove smoke during fires. These units have flow rates up to about 14 m^3/s (30,000 ft^3/min) and can be easily transported on a hand cart. They cost approximately $2,000 to $3,000. Canada Mortgage and Housing Corporation plans to evaluate one of these units on an actual building (Hill, 2001).

A-3.5.2 Blower Doors

Residential-style blower doors consist of a combined blower, air-flow measuring device and size-adjustable door assembly which allows the unit to be installed in a convenient doorway of the building. They have been successfully used for quantitative testing of individual zones or floors within large buildings as well as qualitative examinations for quality control purposes. They operate on standard 110 V or 220 V, single-phase power, and are small and light enough to be handled by a single person and transported in a compact car. Typical calibrated flow ranges vary from about 14 L/s to 2,500 L/s (30 to 5,300 ft^3/min). Their flow measurement accuracy is typically +/- 3% with a digital micromanometer and +/- 5% with an aneroid-type gauge. Set-up time (exclusive of building preparation) is 20 to 30 minutes. The cost of a single unit (without pressure-measuring equipment) starts at about $2,500 to $3,000, depending on the options selected.

There are three known North American manufacturers of residential-style blower door equipment and each can supply the full complement of test equipment including blowers, pressure gauges, analysis software, hoses, etc. These are: a) Infiltec of Falls Church, Virginia; b) Retrotec of Bellingham, Washington; and c) The Energy Conservatory of Minneapolis, Minnesota. All have been in operation since the 1980's and have manufactured tens of thousands of blower doors. Hundreds are now in use in Canada, mainly for quality control and energy auditing purposes (mainly with the R-2000 and EnerGuide for Houses Programs).

A-3.5.3 Flow-Measuring Systems

Blower doors use calibrated orifice plates to measure the air flow rate. Several different sizes of orifice plates are usually supplied, thereby permitting a wide range of flow rates to be measured. Larger capacity fan systems have generally used some type of pitot tube assembly.

Air flow rates can also be measured using various types of tracer gas techniques. This method is based on establishing a relationship between the concentration of the tracer and the air change rate within the zone or building. It is particularly applicable to larger buildings. The most common types of gases which have been used as tracers are SF_6 and N_2O. The most widely used versions of this technique are the: a) tracer gas decay (in which the leakage rate is derived from the rate at which the initial tracer concentration decays); b) constant tracer gas concentration (in which the air flow rate is inferred from the rate at which the tracer has to be injected into the air to maintain a constant concentration); and c) constant tracer gas emission (in which the leakage rate is related to the tracer gas concentration associated with a fixed release rate).

A-3.5.4 Pressure-Measuring Devices

The most inexpensive pressure-measuring devices are Magnehelic gauges, which are aneroid-type devices. They are inexpensive (about $50) and easy to use, but are relatively inaccurate and subject to mechanical hysteresis. In most applications, they have been replaced by digital micromanometers which are much more accurate, cover a range of pressure differentials, have built-in pressure dampening capabilities and maintain remarkably stable accuracy. Micromanometers can also be used to produce an electrical output signal for input to a data-acquisition system. Micromanometers can typically resolve to 0.1 Pascals with an accuracy of +/- 1% of the pressure reading or +/- 2 counts, whichever is greater. Most units have two input channels which can be selected without disconnecting the hoses, thereby permitting both the envelope pressure differential and the pressure signal from the blower door to be efficiently measured. Prices start at about $750. In addition, a six-channel digital micromanometer is now commercially available which is quite useful for monitoring multiple pressure differentials, particularly when time coordination between individual measurements is critical (such as the dynamic response of different zones to applied leakage drivers).

It is often useful to be able to measure the pressure differential across the building envelope or across individual components within the envelope to determine the fraction of the total envelope load which is being resisted by each component. Such measurements may be required at a number of locations. In new construction, small diameter capillary tubing can be permanently installed to facilitate such measurements (NRC, 1986). This is particularly useful in large buildings which do not have operable windows.

Another type of useful instrumentation (for investigations if not formal tests) are portable pressure transducers with attached data loggers. These devices are quite small, reasonably inexpensive and permit a single pressure differential to be monitored with the data stored in a data logger that can be downloaded to a personal computer. They have the ability to store several thousand data points and thus are ideal for applications where continuous monitoring is necessary.

A-3.5.5 Smoke Wands and Puffers

Smoke wands and puffers are used as aids in identifying air leakage locations while the building is pressurized or depressurized. Most tests are performed while the building is depressurized, however, some practitioners find it easier to pinpoint holes - particularly small ones - when the building is positively pressurized. A typical smoke wand can produce several hundred smoke plumes. They are available from all of the blower door manufacturers and cost $20 to $40 each.

A-3.5.6 Leak Detectors

Another product which has become available within the last few years is the AIR-SURE air leakage detection device (a.k.a. "bubble gun") manufactured by Retro-Specs Ltd. of Winnipeg, Manitoba. It is designed for testing of masonry ties, air/vapour barrier joints and other small air barrier details. It consists of a hand-held, clear plastic half dome with built-in, battery-powered vacuum pump. To use the device, a small amount of a soapy, leak detection fluid is applied over the area to be checked and the bubble gun is placed tight over the area. The vacuum pump is then activated which depressurizes the space inside the plastic dome up to 500 Pa. Formation of bubbles identifies the air leakage locations. Cost of the complete unit is about $4,500. The system is designed to be used in accordance with ASTM E 1186.

A-3.6 AIRTIGHTNESS TESTING COSTS

The cost of performing various types of airtightness tests varies with the unique circumstances and complexity of the individual building, market forces, location, reporting requirements, etc. Table A-1 provides a rough indication of the retail cost of some of the tests described above. The information came from a selection of airtightness testers (Woods, 2000 and Dumont, 2001) and the author's own experiences. It is assumed that the building is located in the same city as the testing firm. However, given the specialized nature of this work, that may not always be a valid assumption, in which case the costs would rise accordingly. Many, but not all, of these services are commercially available in most Canadian locations.

A-3.7 AIRTIGHTNESS PERFORMANCE TARGETS

A-3.7.1 2005 National Building Code of Canada - Part 5

The National Building Code of Canada (NBC) is the model code used throughout the country. While jurisdiction for building codes rests with the provinces, all reference the NBC directly or use it as the basis for their provincial codes.

Airtightness requirements for large buildings are covered under Part 5 "Environmental Separation" of the 2005 NBC. During the last code cycle, which culminated in the 1995 NBC, major quantitative and qualitative revisions were introduced to improve airtightness. These stipulate that sheet- and panel-type materials that are intended to provide the principal resistance to air leakage must have a NLR_{75} not greater than 0.02 $L/s{\bullet}m^2$. Part 5 also includes airtightness requirements for windows, doors and skylights, through references to performance standards for these products. Qualitative requirements are also included in Part 5 which mandate that the air barrier must be continuous across joints and connections, between different building assemblies and around penetrations through the building assembly.

In addition, the Appendix to the 2005 NBC provides *recommendations* on the maximum desirable air leakage rates for the "air barrier system". These are summarized in Table A-2; note that they vary depending on the warm side relative humidity levels which are anticipated (i.e. the interior environment's relative humidity level). They were derived from basic research conducted at NRC and are intended to control moisture deposition caused by air exfiltration.

The terminology used in the NBC - "air barrier system" - is important to note. Part 1 of the NBC defines an "air barrier system" as "the assembly installed to provide a continuous barrier to the movement of air". Many people have interpreted the air barrier to consist of every part of the building envelope which restricts air leakage, including windows, doors, etc. However, the separately published *User's Guide* to Part 5 of the 1995 NBC prefers a different interpretation when it states (on page 5.4-4) that the values shown in Table A-2...

> "are for air barrier systems in opaque, insulated portions of the building envelope. They are not for whole buildings, since windows, doors and other openings are included. The table is provided for guidance when testing air barrier systems as portions of an envelope." (NRC, 1999).

This means that a whole-building airtightness test, such as would be conducted using CGSB-149.10 or CGSB-149.15, would not necessarily provide a clear answer as to whether the building met the *recommended, but not mandatory* values shown in Table A-2, unless the windows, doors and other openings were masked for the test or the total building leakage (including that through windows, doors and other openings) was still less than the product of opaque wall area multiplied by the maximum, recommended values. Also, it is very important to note that the Appendix is not a mandatory part of the Code but is intended to offer explanatory material to aid in interpretation. The decision to not include a formal quantitative requirement in the body of the NBC was made because it was felt to be too difficult to justify formal limits given the current level of knowledge.

A-3.7.2 2005 National Building Code of Canada - Part 9

Part 9 of the NBC deals with housing and small buildings which have a floor area not exceeding 600 m^2 per floor and up to three storeys in height. Thus, some buildings which might be considered "large" (up to 1,800 m^2 or 19,368 ft^2) could be constructed under Part 9. The airtightness requirements of Part 9 are less stringent, and less explicit, than those found in Part 5 and consist of a series of qualitative requirements to improve the continuity of the air barrier. No quantitative requirements are included, nor is there requirement for testing. Interestingly, at least one provincial jurisdiction (Manitoba) has incorporated quantitative airtightness requirements in its building code, although this was introduced as a benchmark against which consumer complaints (of excessive leakage) could be arbitrated rather than as target against which all houses were to be tested (Klassen, 2000).

A-3.7.3 Model National Energy Code for Buildings (MNECB)

The Model National Energy Code for Buildings, published in 1997, is a code of minimum regulations for energy efficiency in buildings. It is not part of the NBC but is a stand-alone code which provinces have the option of adopting. To date, only a few jurisdictions in Canada have adopted it as part of their building regulations. The MNECB requires that buildings meet the airtightness requirements of Part 5 of the 1995 NBC, as well as some additional requirements for windows, doors and fireplace doors. No specific requirements for airtightness testing are included (NRC, 1997).

A-3.7.4 C-2000 Program

The C-2000 Program is a national, voluntary program delivered by Natural Resources Canada whose goal is to encourage the construction of highly energy-efficient commercial buildings and can be described as a commercial building equivalent of the R-2000 Program (see below). Although the C-2000 Program is limited to office buildings, its program criteria have been applied to a similar program for MURBs called the Ideas Challenge, which is jointly operated by NRCan and CMHC. Launched in 1994, the C-2000 Program uses an energy target which is set at 50% of the ASHRAE 90.1 requirements for office buildings and 55% for residential construction (Larsson and Clark, 2000). As of 2000, seven C-2000 buildings had been built and 14 designed. The C-2000 Program does not have formal airtightness requirements, although it is recommended that the guidelines in the 1995 NBC should be followed (Deschenes, 2001). However, one of the C-2000 buildings, in Dundas, Ontario, was constructed with a declared airtightness NLR_{75} target of 1.0. The final measured NLR_{75} was 1.18 $L/s{\bullet}m^2$ (Enermodal Engineering Ltd., 2000).

A-3.7.5 Commercial Building Incentives Program (CBIP)

The CBIP Program is also a national, voluntary program delivered by Natural Resources Canada. It was derived from the C-2000 Program but is much larger in scale; all C-2000 projects are now also enrolled in the CBIP Program. As of 2000, there were over 300 buildings underway or complete which were registered in CBIP. The program has similar, although somewhat less demanding, technical requirements compared to C-2000. CBIP does not have any formal airtightness requirements, although it is recommended that the guidelines in the 1995 NBC should be followed (Deschenes, 2001).

A-3.7.6 R-2000 Program

The R-2000 Program is a national, voluntary program which is primarily focussed on single-detached houses. However, it can also be applied to Multi-Unit Residential Buildings provided they fall within the scope of Part 9 of the NBC. The program has its own set of technical requirements which include quantitative criteria for airtightness plus the requirement that all buildings receive an airtightness test to demonstrate compliance (NRCan, 2000). For multi-unit dwelling units, the airtightness test is performed on each unit in the building and interior leakage (from adjacent units) is treated as equivalent to exterior leakage. This approach was adopted mainly to simplify the testing and compliance process since the only alternative procedure, the balanced fan depressurization technique, was seen as too complicated and expensive (Cooper, 1988). Also, suite-to-suite leakage is very undesirable in MURBs. However, the R-2000 Standard detached houses have recently been revised and further revisions are also anticipated to the requirements which apply to MURBs. This may include changes to the airtightness requirements and test methods.

A-3.7.7 ASHRAE

In its 1997 Handbook of Fundamentals, the American Society of Heating, Refrigeration and Air-Conditioning Engineers summarizes the then-available literature on commercial building envelope leakage and suggests that typical leakage rates per unit of exterior wall area, at 75 Pa, (i.e., NLR_{75}) are 0.5, 1.5 and 3.0 $L/s{\bullet}m^2$ for tight, average and leaky wall respectively. These values were taken from Tamura and Shaw (1976) and while useful are now rather dated and are based on a very limited sample size.

A-3.7.8 NAAMM

The National Association of Architectural Metal Manufacturers (NAAMM) is an American industry organization which represents producers of such products as metal curtain walls and architectural components manufactured from various materials. It suggests a maximum leakage rate per unit of exterior wall area (exclusive of leakage through operable windows, at a pressure differential of 75 Pa (i.e., NLR_{75}), of 0.3 $L/s{\bullet}m^2$ (ASHRAE, 1997)).

A-3.7.9 BSRIA

In England, the Building Services Research and Information Association issued Specification 10/98 *Air Tightness Specifications* in 1998 which contains a series of recommendations for new buildings (Potter, 1998). These were expressed using a reference pressure differential of 50 Pa and are summarized in Table A-3. Also included are the NLR_{50} leakage rates adjusted to a pressure differential of 75 Pa using an assumed n-value of 0.65. This is done to standardize these with other data in this document. Note also that total envelope area is believed to have been used for normalization purposes. The BSRIA recommendations are believed to be voluntary.

A-3.7.10 CIBSE

In England, the Chartered Institution of Building Services Engineers issued a technical memoranda titled *Testing Buildings For Air Leakage, TM23:2000* which contains a series of airtightness recommendations (CIBSE, 2000). These were also expressed using a reference of 50 Pa and are summarized in Table A-4 along with the same leakage rates adjusted to a pressure differential of 75 Pa using an assumed n-value of 0.65. It is believed that these recommendations are currently being considered as possible references under Part L of the United Kingdom Building Regulations (which deals with energy efficiency) and would apply to new buildings and those undergoing significant modification or renovation. Compliance would presumably be demonstrated through testing.

A-3.7.11 Other International Airtightness Standards

Limb summarized various other international whole-building and component airtightness standards, mainly for European countries (Limb, 1994). Most of these apply to detached housing.

A-3.8 SPECIFICATIONS

A-3.8.1 Canadian National Master Construction Specification

The Canadian National Master Construction Specification, published by Construction Specifications Canada, is the model document referenced by specification writers in both the private and public sectors (such as Public Works and Government Services Canada) (CSC, 1999). In late 1999, they released specifications for two new sections dealing with air barriers. Section 07271 "Air Barrier (Descriptive Proprietary)" is a master specification for air/vapour materials and systems. Its content includes quality assurance procedures (including references to the National Air Barrier Association's Professional Contractor Quality Assurance Program), contractor and applicator qualifications, requirements for pre-installation meetings, warranties, material requirements (sheet materials, sealants, adhesives and accessories), and execution (NABA, 1997a). Section 07272 "Air Barriers (Performance)" specifies appropriate quantitative and qualitative air leakage test procedures, quality assurance procedures (including references to the NABA Professional Contractor Quality Assurance Program), mock-up requirements, warranties, materials and execution.

A-3.8.2 NABA Specification 10.02-97

The National Air Barrier Association (NABA) has developed a specification for the application of air/vapour barrier membranes on new or existing buildings (NABA, 1997b). Basically, this document requires air barrier contractors to be certified under the NABA Professional Contractor Quality Assurance Program and to adhere to the program's requirements. Specification 10.02-97 applies to most site-applied air/vapour materials and systems including air barrier membranes which are adhered to concrete, masonry, wood or drywall surfaces, and to connections between these components and windows, doors, floor slabs, lintels, roofing and waterproofing membranes. It includes qualifications for air barrier contractors and installers, testing requirements, documentation requirements, independent verification, inspections and other requirements.

A-3.9 QUALITY CONTROL AND COMMISSIONING PROCEDURES

Achieving a high quality, durable and functional building envelope with low air leakage requires a comprehensive systems approach to design and construction. This begins with definition of clear performance requirements for the building envelope. It then proceeds to preparation of design details, drawings, specifications, including testing and inspection requirements. It may also involve the construction, testing and evaluation of mock-ups to validate specific details and provide feedback to contractors. A proposed format for this process has been suggested which begins with a pre-design stage definition of the environmental loads and specifications for the building envelope, continues to the conceptual design and preparation of tender documents (drawings and specifications) and then ends with the building envelope certification and final commissioning to verify that the performance objectives have been achieved (Quirouette and Scott, 1993; Morrison Hershfield Ltd., 1995).

A-3.9.1 NABA Professional Contractor Quality Assurance Program

The National Air Barrier Association was established in 1995 to promote and expand the use of effective air and vapour barrier systems. NABA has been active in trades training and other related activities. One of its key activities has been the creation of a "Professional Contractor Quality Assurance Program" to improve trade quality and increase consumer confidence (NABA, 1997b). This program is based on ISO 9002 principles which fundamentally require the work objectives to be defined in advance and then demonstrated to have been met. The quality assurance program requires the use of NABA-certified contractors for installation of air barriers. It also establishes detailed requirements for records which have to be maintained on the job site which documents the air barrier installation (which individuals did the work, when it was done, environmental conditions at the time of installation, etc.) and also provides for third-party compliance checking of air barrier installations.

A-3.10 RATIONALE FOR AIRTIGHTNESS STANDARDS

The literature survey yielded few explicit explanations for the rationale behind the various standards described in this Chapter. The recommended airtightness requirements in the 1995 National Building Code of Canada Appendices were developed to control moisture deposition in the building envelope caused by air exfiltration, although the other benefits (energy savings, controlled indoor environment, etc.) were also seen as worthwhile benefits. The qualitative requirements in Part 9 of the 1995 NBC have a similar rationalization. The Model National Energy Code, the Commercial Building Incentives Program, and the C-2000 and R-2000 Programs are all primarily predicated on the need to save energy although the other benefits, mainly the environmental aspects (greenhouse gases), are acknowledged. Specifications, such as the Canadian National Master Specification and those produced by NABA, are largely based on protecting the building envelope from moisture damage.

The rationalization for British standards is believed to be heavily based on environmental reasons, primarily the need to reduce greenhouse gases.

Table A-1

Typical Airtightness Testing Costs (Proskiw and Phillips, 2001)

Airtightness Test	Approximate Cost
Whole-building airtightness test to CGSB-149.10 of single-zone commercial structure, using portable blower doors.	\$2,000 to \$4,000
Whole-building airtightness test to CGSB-149.10 of multi-zone structure, using trailer-mounted blower.	\$7,500 to \$10,000
Whole-building airtightness test to CGSB-149.15 of single- or multi-zone structure, using the building's mechanical system.	\$8,000 to \$12,000
Single-zone airtightness test, using balanced fan depressurization technique, of multi-zone structure.	\$4,000 to \$6,000
Window/wall airtightness test to ASTM E 783 using site-installed chamber.	\$2,000 to \$5,000
Qualitative examination of single zone within a multi-zone structure using portable blower doors.	\$300 to \$800
Qualitative smoke test of individual construction details.	\$250 to \$600
Blower door test on a house.	\$150 to \$300

Table A-2

2005 NBC (Appendices) Air Leakage Recommendations

Warm Side Relative Humidity at 21 °C	Recommended Maximum System Normalized Leakage Rate (L/s•m^2 at 75 Pa)
< 27%	0.15
27% to 55%	0.10
> 55%	0.05

Table A-3

BSRIA Airtightness Recommendations For New Buildings

(Proskiw and Phillips, 2001)

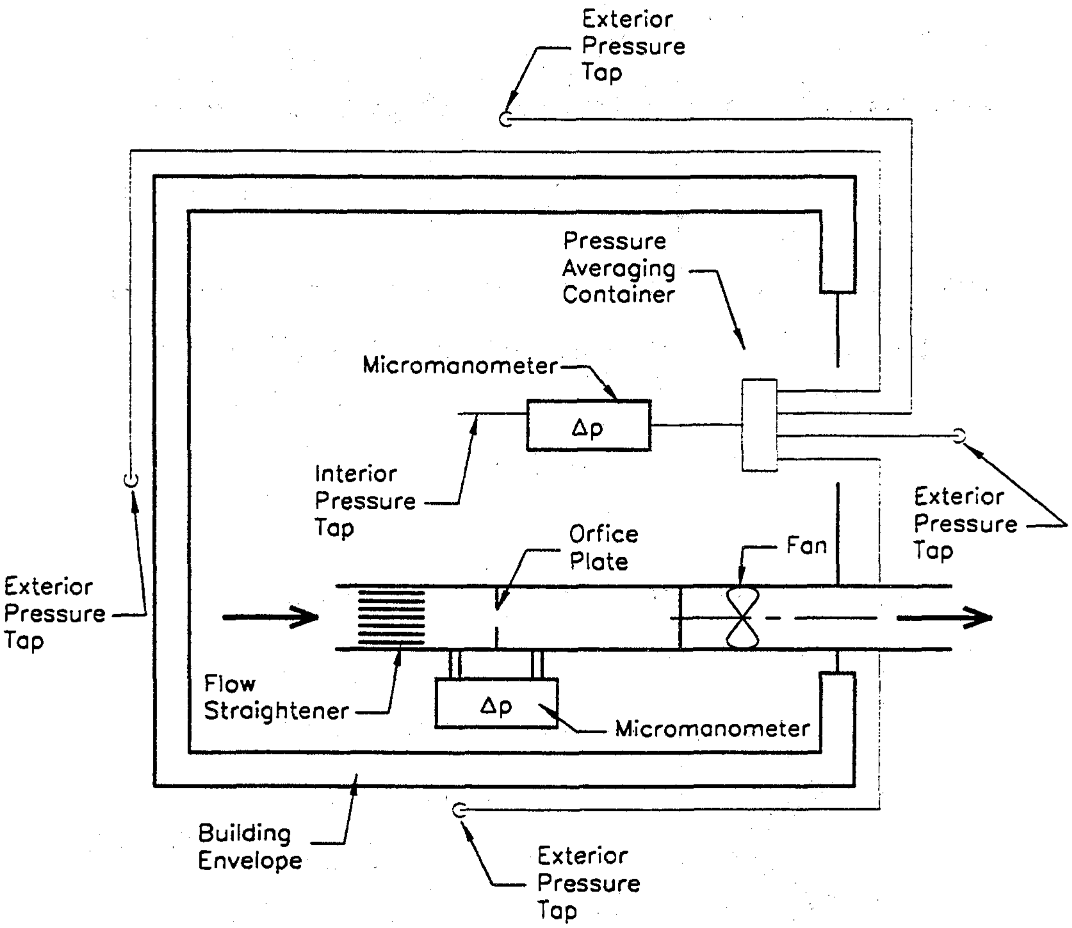
	BSRIA Recommendations, NLR_{50} (L/s•m^2)		BSRIA Recommendations, Adjusted To NLR_{75} (L/s•m^2) (assuming n=0.65)	
	Normal	Best Practice	Normal	Best Practice
Offices				
- Naturally ventilated	2.78	-	3.62	-
- Air-conditioned/low energy	1.39	0.83	1.81	1.08
Factories/warehouses	2.78	-	3.62	-
Superstores	1.39	0.83	1.81	1.08
Museums and archival stores	0.56	0.39	0.73	0.51
Cold stores	0.28	0.14	0.36	0.18

Table A-4

CIBSE Airtightness Recommendations for New Buildings

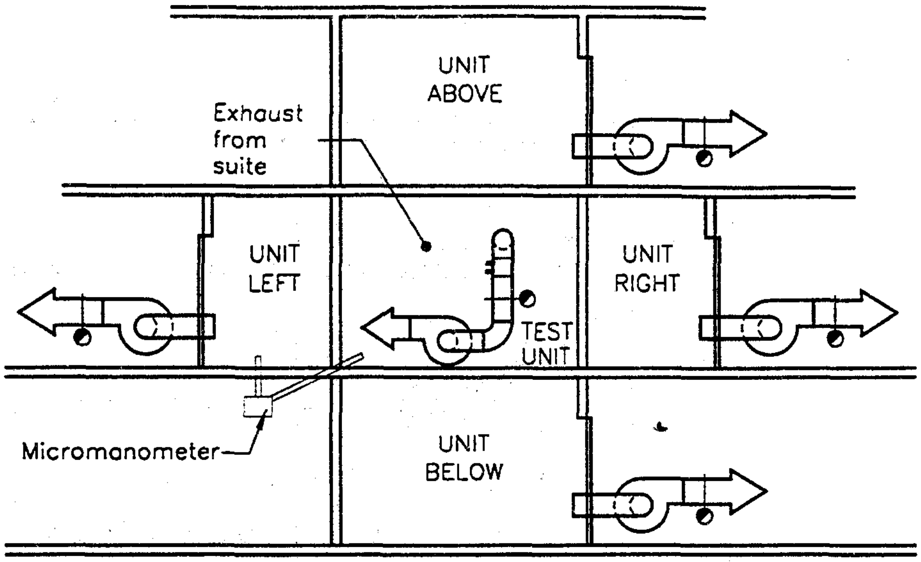
(Proskiw and Phillips, 2001)

	CIBSE Recommendations, NLR_{50} (L/s•m^2)		CIBSE Recommendations, Adjusted To NLR_{75} (L/s•m^2) (assuming n=0.65)	
	Normal	Best Practice	Normal	Best Practice
Offices				
- Naturally ventilated	1.94	0.97	2.52	1.26
- With balanced mechanical ventilation	0.97	0.56	1.26	0.73
Superstores	0.83	0.42	1.08	0.55
Industrial	2.78	0.97	3.62	1.26



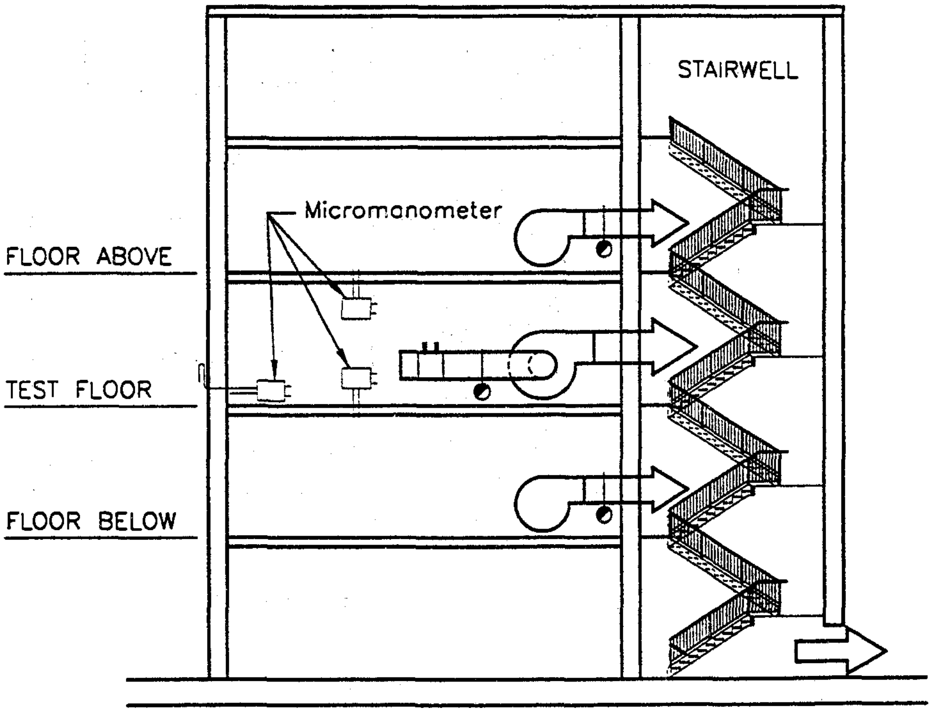
CGSB 149.10 TEST SET-UP

Fig. A-16



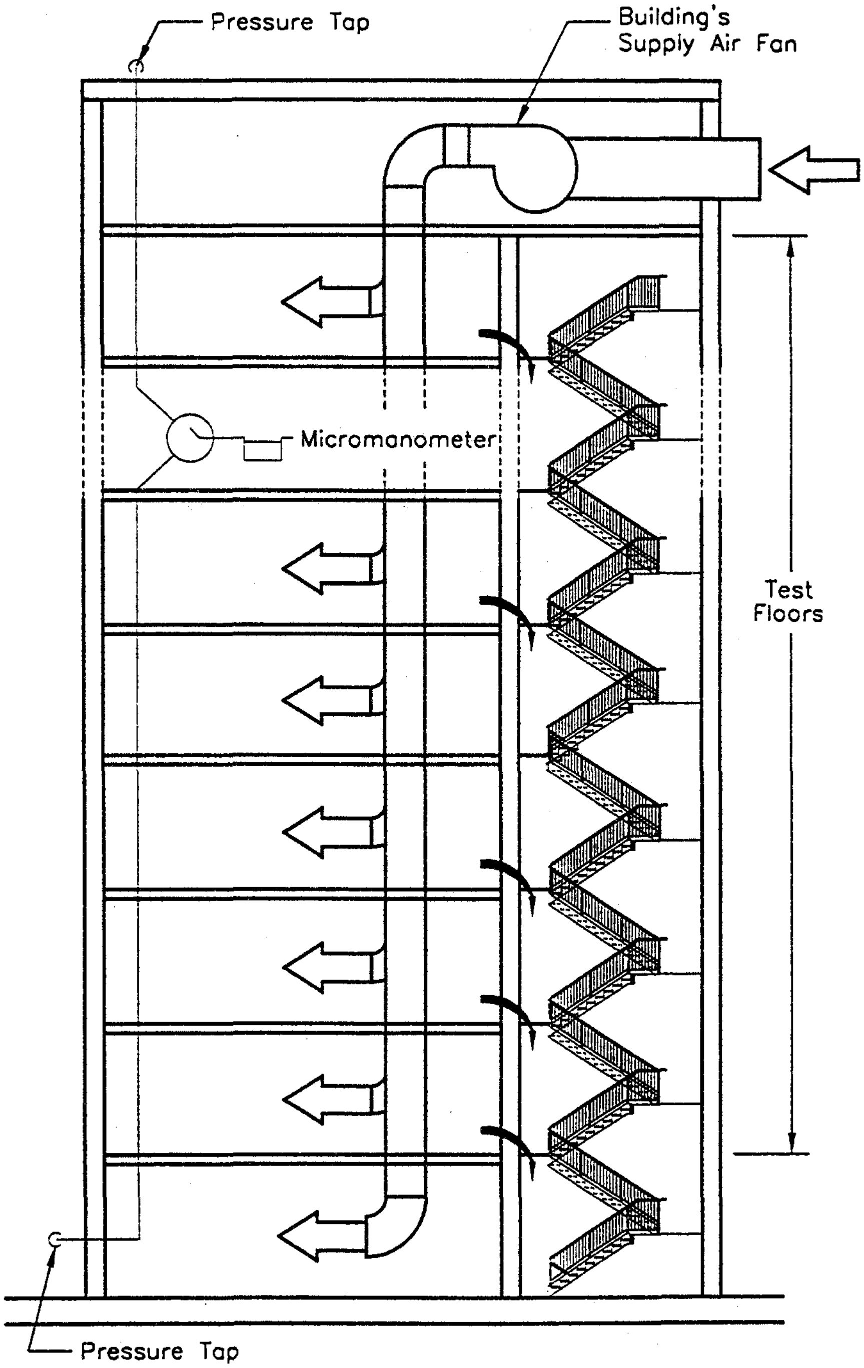
BALANCED FAN DEPRESSURIZATION TECHNIQUE USED TO TEST INDIVIDUAL SUITE

Fig. A-17



BALANCED FAN DEPRESSURIZATION TECHNIQUE USED TO TEST INDIVIDUAL FLOOR

Fig. A-18



CGSB 149.15 TEST SET-UP

Fig. A-19

APPENDIX B

LABORATORY TEST RESULTS

TEST: 1.1 (a)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	N/G	N/G			
1	3	0.972	0.536	5.0	24.0	35.6
1	4	0.721	1.959	10.3	32.9	44.1
1	5	0.607	3.660	14.8	39.3	50.3
2	3	N/G	N/G			
2	4	N/G	N/G			
2	5	N/G	N/G			
3	4	N/G	N/G			
3	5	N/G	N/G			
4	5	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	3	0.972	0.536	5.0	24.0	35.6	1.28	Pass
1	4	0.721	1.959	10.3	32.9	44.1	0.12	Pass
1	5	0.607	3.660	14.8	39.3	50.3	1.16	Pass
Mean		0.767	2.052	10.0	32.1	43.3	= PREDICTED LEAKAGE	
Std. Dev.		0.152	1.277	4.0	6.3	6.0		
Coeff. of Variation		20%	62%	40%	20%	14%		

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
60.0	43.8	4.094	3.780
46.7	37.8	3.844	3.632
51.7	39.9	3.945	3.686
40.0	33.6	3.689	3.515
48.4	38.2	3.879	3.643
37.1	32.8	3.614	3.490
44.9	36.6	3.804	3.600
33.3	31.0	3.506	3.434
42.7	35.3	3.754	3.564
32.6	29.8	3.484	3.395

Regression Output:

Constant		1.278	
Std Err of Y Est		0.010	
R Squared		0.994	0.997
No. of Observations		10.000	
Degrees of Freedom		8.000	
X Coefficient(s)	0.61032593		
Std Err of Coef.	0.01676612		

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.610

C= 3.590

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
14.6	39.1	50.1

TEST: 1.1 (b)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	N/G	N/G			
1	3	N/G	N/G			
1	4	0.927	0.7	6.1	27.0	39.3
1	5	N/G	N/G			
2	3	N/G	N/G			
2	4	0.778	1.5	9.0	31.4	43.0
2	5	N/G	N/G			
3	4	N/G	N/G			
3	5	N/G	N/G			
4	5	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	4	0.927	0.718	6.1	27.0	39.3	1.00	Pass
2	4	0.778	1.495	9.0	31.4	43.0	1.00	Pass
Mean		0.853	1.107	7.5	29.2	41.1	= PREDICTED LEAKAGE	
Std. Dev.		0.075	0.389	1.4	2.2	1.9		
Coeff. of Variation		9%	35%	19%	8%	5%		

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
58.2	44.0	4.064	3.784
46.1	38.1	3.831	3.640
54.4	42.3	3.996	3.745
42.8	36.2	3.757	3.589
50.8	40.6	3.928	3.704
44.6	37.5	3.798	3.624
34.3	31.9	3.535	3.463
39.9	34.9	3.686	3.552
30.8	29.0	3.428	3.367

Regression Output:

Constant	1.1822571383582	
Std Err of Y Est	0.0079928287187	
R Squared	0.9968672045199	0.99843
No. of Observations	9	
Degrees of Freedom	7	

X Coefficient(s)	0.64159256
Std Err of Coef.	0.01359433

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.642
C= 3.262

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
14.3	40.1	52.1

TEST: 1.1 (c)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	N/G	N/G			
1	3	N/G	N/G			
1	4	0.619	3.675	15.3	41.4	53.2
1	5	0.596	4.208	16.6	43.3	55.2
1	6	0.613	3.806	15.6	41.9	53.7
2	3	N/G	N/G			
2	4	N/G	N/G			
2	5	N/G	N/G			
2	6	N/G	N/G			
3	4	N/G	N/G			
3	5	N/G	N/G			
3	6	N/G	N/G			
4	5	0.547	5.461	19.2	46.4	57.9
4	6	0.607	3.921	15.9	42.1	53.9
5	6	0.666	2.935	13.6	39.7	52.0

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	4	0.619	3.675	15.3	41.4	53.2	0.60	Pass
1	5	0.596	4.208	16.6	43.3	55.2	0.45	Pass
1	6	0.613	3.806	15.6	41.9	53.7	0.34	Pass
4	5	0.547	5.461	19.2	46.4	57.9	1.94	Fail
4	6	0.607	3.921	15.9	42.1	53.9	0.23	Pass
5	6	0.666	2.935	13.6	39.7	52.0	1.22	Pass
Mean		0.608	4.001	16.0	42.5	54.3		
Std. Dev.		0.035	0.760	1.7	2.1	1.9		
Coeff. of Variation		6%	19%	11%	5%	3%		

SUMMARY OF RESULTS (AFTER APPLYING CHAUVENET'S CRITERION):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	
1	4	0.619	3.675	15.3	41.4	53.2	
1	5	0.596	4.208	16.6	43.3	55.2	
1	6	0.613	3.806	15.6	41.9	53.7	
4	6	0.607	3.921	15.9	42.1	53.9	
5	6	0.666	2.935	13.6	39.7	52.0	
Mean		0.620	3.709	15.4	41.7	53.6	= PREDICTED LEAKAGE
Std. Dev.		0.024	0.425	1.0	1.2	1.0	
Coeff. of Variation		4%	11%	6%	3%	2%	

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
85.5	55.0	4.449	4.007
56.6	43.1	4.036	3.764
76.0	51.3	4.331	3.938
49.9	40.6	3.910	3.704
64.1	45.5	4.160	3.818
42.3	35.8	3.745	3.578
53.5	41.5	3.980	3.726
35.8	32.2	3.578	3.472
42.8	36.2	3.757	3.589
28.5	29.0	3.350	3.367
33.8	32.2	3.520	3.472
22.6	24.2	3.118	3.186

Regression Output:			
Constant		1.335	
Std Err of Y Est		0.015	
R Squared		0.996	0.9982
No. of Observations		12.000	
Degrees of Freedom		10.000	
X Coefficient(s)	0.6009628		
Std Err of Coef.	0.01141562		

ACTUAL INTER-ZONE LEAKAGE CHARCTERISTICS

n= 0.601
C= 3.799

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
15.2	39.9	50.9

TEST: 1.1 (d)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.740	1.975	10.9	35.7	48.2
1	3	N/G	N/G			
1	4	N/G	N/G			
1	5	0.507	6.701	21.5	48.7	59.8
2	3	N/G	N/G			
2	4	N/G	N/G			
2	5	N/G	N/G			
2	6	N/G	N/G			
3	5	0.753	1.671	9.5	31.8	43.1
3	4	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.740	1.975	10.9	35.7	48.2	0.31	Pass
1	5	0.507	6.701	21.5	48.7	59.8	1.35	Pass
3	5	0.753	1.671	9.5	31.8	43.1	1.04	Pass
Mean		0.667	3.449	14.0	38.7	50.4	= PREDICTED LEAKAGE	
Std. Dev.		0.113	2.303	5.4	7.2	7.0		
Coeff. of Variation		17%	67%	39%	19%	14%		

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
56.0	42.7	4.025	3.754
24.3	25.6	3.190	3.243
64.2	46.4	4.162	3.837
31.0	29.7	3.434	3.391
73.0	49.8	4.290	3.908
35.9	32.1	3.581	3.469
85.9	55.0	4.453	4.007
44.1	36.7	3.786	3.603
79.5	52.5	4.376	3.961
40.5	35.4	3.701	3.567

Regression Output:		
Constant	1.307	
Std Err of Y Est	0.007	
R Squared	0.999	0.9997
No. of Observations	10.000	
Degrees of Freedom	8.000	

X Coefficient(s)	0.60694957
Std Err of Coef.	0.00527571

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n=	0.607
C=	3.695

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
14.9	39.7	50.8

TEST: 2.1 (a)

SUMMARY OF RESULTS (ALL PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.560	4.841	17.6	43.3	54.3
1	3	0.850	0.927	6.6	25.8	36.4
1	4	0.604	3.722	15.0	39.5	50.5
1	5	N/G	N/G			
1	6	N/G	N/G			
2	3	N/G	N/G			
2	4	0.498	6.878	21.7	48.3	59.1
2	5	0.646	3.035	13.4	38.0	49.4
2	6	N/G	N/G			
3	4	N/G	N/G			
3	5	N/G	N/G			
3	6	0.499	6.173	19.5	43.5	53.2
4	5	N/G	N/G			
4	6	N/G	N/G			
5	6	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS:

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.560	4.841	17.6	43.3	54.3	0.55	Pass
1	3	0.850	0.927	6.6	25.8	36.4	2.01	Fail
1	4	0.604	3.722	15.0	39.5	50.5	0.00	Pass
2	4	0.498	6.878	21.7	48.3	59.1	1.22	Pass
2	5	0.646	3.035	13.4	38.0	49.4	0.16	Pass
3	6	0.499	6.173	19.5	43.5	53.2	0.39	Pass
Mean		0.610	4.263	15.6	39.7	50.5		
Std. Dev.		0.120	1.990	4.9	7.0	7.0		
Coeff. of Variation		20%	47%	31%	18%	14%		

SUMMARY OF RESULTS (AFTER APPLYING CHAUVENET'S CRITERION):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	
1	2	0.560	4.841	17.6	43.3	54.3	
1	4	0.604	3.722	15.0	39.5	50.5	
2	4	0.498	6.878	21.7	48.3	59.1	
2	5	0.646	3.035	13.4	38.0	49.4	
3	6	0.499	6.173	19.5	43.5	53.2	
Mean		0.561	4.930	17.4	42.5	53.3	= PREDICTED LEAKAGE
Std. Dev.		0.058	1.442	3.0	3.6	3.4	
Coeff. of Variation		10%	29%	17%	8%	6%	

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
92.5	57.3	4.527	4.048
52.3	40.7	3.957	3.706
56.0	42.9	4.025	3.759
32.7	30.7	3.487	3.424
62.4	45.9	4.134	3.826
36.7	33.4	3.603	3.509
68.6	47.6	4.228	3.863
40.2	34.5	3.694	3.541
74.5	51.0	4.311	3.932
42.6	36.2	3.752	3.589
82.6	53.8	4.414	3.985
48.8	39.5	3.888	3.676

Regression Output:			
Constant		1.336	
Std Err of Y Est		0.008	
R Squared		0.998	0.9992
No. of Observations		12.000	
Degrees of Freedom		10.000	
X Coefficient(s)	0.6004049		
Std Err of Coef.	0.00759794		

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.600
C= 3.802

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
15.2	39.8	50.8

TEST: 2.1 (b)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.571	4.558	17.0	42.5	53.6
1	3	0.615	3.528	14.5	39.1	50.2
1	4	0.779	1.411	8.5	29.7	40.8
1	5	0.562	4.807	17.5	43.3	54.4
1	6	N/G	N/G			
2	3	N/G	N/G			
2	4	N/G	N/G			
2	5	0.577	4.412	16.7	42.2	53.3
2	6	N/G	N/G			
3	4	N/G	N/G			
3	5	0.677	2.532	12.0	35.8	47.1
3	6	N/G	N/G			
4	5	N/G	N/G			
4	6	0.612	3.431	14.0	37.6	48.2
5	6	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.571	4.558	17.0	42.5	53.6	0.89	Pass
1	3	0.615	3.528	14.5	39.1	50.2	0.12	Pass
1	4	0.779	1.411	8.5	29.7	40.8	1.99	Fail
1	5	0.562	4.807	17.5	43.3	54.4	1.06	Pass
2	5	0.577	4.412	16.7	42.2	53.3	0.81	Pass
3	5	0.677	2.532	12.0	35.8	47.1	0.57	Pass
4	6	0.612	3.431	14.0	37.6	48.2	0.33	Pass
Mean		0.628	3.526	14.3	38.6	49.6		
Std. Dev.		0.1	1.1	3.0	4.5	4.5		
Coeff. of Variation		11%	32%	21%	12%	9%		

SUMMARY OF RESULTS (AFTER APPLYING CHAUVENET'S CRITERION):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	
1	2	0.571	4.558	17.0	42.5	53.6	
1	3	0.615	3.528	14.5	39.1	50.2	
1	5	0.562	4.807	17.5	43.3	54.4	
2	5	0.577	4.412	16.7	42.2	53.3	
3	5	0.677	2.532	12.0	35.8	47.1	
4	6	0.612	3.431	14.0	37.6	48.2	
Mean		0.602	3.878	15.3	40.1	51.1	= PREDICTED LEAKAGE
Std. Dev.		0.0	0.8	1.9	2.8	2.8	
Coeff. of Variation		6%	20%	13%	7%	6%	

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
93.6	58.1	4.539	4.062
38.9	34.1	3.661	3.529
62.5	45.6	4.135	3.820
21.0	22.5	3.045	3.114
69.0	48.8	4.234	3.888
26.2	26.7	3.266	3.285
73.5	50.7	4.297	3.926
28.4	27.7	3.346	3.321
80.0	53.1	4.382	3.972
31.0	29.9	3.434	3.398
86.4	55.0	4.459	4.007
36.0	32.3	3.584	3.475

Regression Output:

Constant	1.237	
Std Err of Y Est	0.012	
R Squared	0.999	0.99943
No. of Observations	12.000	
Degrees of Freedom	10.000	

X Coefficient(s)	0.62422076
Std Err of Coef.	0.00666473

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.624

C= 3.445

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
14.5	39.6	51.0

TEST: 2.2 (a)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.842	0.785	5.5	21.1	29.7
1	3	0.743	1.372	7.6	25.1	33.9
1	4	0.695	1.810	9.0	27.4	36.4
1	5	N/G	N/G			
1	6	0.980	0.368	3.5	17.0	25.3
1	7	N/G	N/G			
2	3	N/G	N/G			
2	4	N/G	N/G			
2	5	0.522	4.220	14.0	32.5	40.2
2	6	0.788	1.027	6.3	22.4	30.8
2	7	0.933	0.502	4.3	19.3	28.2
3	4	N/G	N/G			
3	5	N/G	N/G			
3	6	0.614	2.740	11.3	30.3	38.8
3	7	0.830	0.875	5.9	22.5	31.5
4	5	N/G	N/G			
4	6	N/G	N/G			
4	7	0.718	1.639	8.6	27.2	36.4
5	6	N/G	N/G			
5	7	N/G	N/G			
6	7	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.842	0.785	5.5	21.1	29.7	0.74	Pass
1	3	0.743	1.372	7.6	25.1	33.9	0.17	Pass
1	4	0.695	1.810	9.0	27.4	36.4	0.71	Pass
1	6	0.980	0.368	3.5	17.0	25.3	1.71	Pass
2	5	0.522	4.220	14.0	32.5	40.2	1.55	Pass
2	6	0.788	1.027	6.3	22.4	30.8	0.50	Pass
2	7	0.933	0.502	4.3	19.3	28.2	1.08	Pass
3	6	0.614	2.740	11.3	30.3	38.8	1.25	Pass
3	7	0.830	0.875	5.9	22.5	31.5	0.35	Pass
4	7	0.718	1.639	8.6	27.2	36.4	0.71	Pass
Mean		0.767	1.534	7.6	24.5	33.1	= PREDICTED LEAKAGE	
Std. Dev.		0.132	1.116	3.1	4.6	4.6		
Coeff. of Variation		17%	73%	40%	19%	14%		

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
104.3	52.3	4.647	3.957
58.6	37.1	4.071	3.614
54.1	35.8	3.991	3.578
33.5	26.2	3.512	3.266
63.3	38.7	4.148	3.656
36.1	28.9	3.586	3.364
71.1	41.9	4.264	3.735
41.8	30.6	3.733	3.421
78.9	44.1	4.368	3.786
45.8	32.9	3.824	3.493
87.4	47.2	4.470	3.854
49.4	34.4	3.900	3.538
95.8	50.1	4.562	3.914
54.6	36.1	4.000	3.586

Regression Output:

Constant	1.254	
Std Err of Y Est	0.014	
R Squared	0.996	0.99789
No. of Observations	14.000	
Degrees of Freedom	12.000	

X Coefficient(s)	0.58167666
Std Err of Coef.	0.01092591

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.582
C= 3.506

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
13.4	34.1	43.2

TEST: 2.2 (b)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.569	3.711	13.8	34.4	43.3
1	3	N/G	N/G			
1	4	0.626	2.646	11.2	30.6	39.5
1	5	0.676	1.980	9.4	27.9	36.7
1	6	N/G	N/G			
2	3	N/G	N/G			
2	4	0.520	4.899	16.2	37.5	46.3
2	5	0.514	5.071	16.6	37.9	46.7
2	6	0.638	2.541	11.0	30.8	39.9
3	4	N/G	N/G			
3	5	N/G	N/G			
3	6	N/G	N/G			
4	5	N/G	N/G			
4	6	0.842	0.817	5.7	22.0	31.0
5	6	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.569	3.711	13.8	34.4	43.3	0.55	Pass
1	4	0.626	2.646	11.2	30.6	39.5	0.19	Pass
1	5	0.676	1.980	9.4	27.9	36.7	0.74	Pass
2	4	0.520	4.899	16.2	37.5	46.3	1.12	Pass
2	5	0.514	5.071	16.6	37.9	46.7	1.20	Pass
2	6	0.638	2.541	11.0	30.8	39.9	0.10	Pass
4	6	0.842	0.817	5.7	22.0	31.0	1.84	Fail
Mean		0.626	3.095	12.0	31.6	40.5		
Std. Dev.		0.104	1.438	3.6	5.2	5.2		
Coeff. of Variation		17%	46%	30%	16%	13%		

SUMMARY OF RESULTS (AFTER APPLYING CHAUVENET'S CRITERION):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	
1	2	0.569	3.711	13.8	34.4	43.3	
1	4	0.626	2.646	11.2	30.6	39.5	
1	5	0.676	1.980	9.4	27.9	36.7	
2	4	0.520	4.899	16.2	37.5	46.3	
2	5	0.514	5.071	16.6	37.9	46.7	
2	6	0.638	2.541	11.0	30.8	39.9	
Mean		0.591	3.475	13.0	33.2	42.0	= PREDICTED LEAKAGE
Std. Dev.		0.061	1.185	2.7	3.7	3.7	
Coeff. of Variation		10%	34%	21%	11%	9%	

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
105.2	52.1	4.656	3.953
44.3	31.6	3.791	3.453
72.9	42.0	4.289	3.738
26.4	23.5	3.273	3.157
80.8	44.5	4.392	3.795
34.4	27.0	3.538	3.296
86.9	46.8	4.465	3.846
35.9	27.9	3.581	3.329
93.7	48.4	4.540	3.879
36.7	28.8	3.603	3.360
99.5	50.3	4.600	3.918
40.9	29.6	3.711	3.388

Regression Output:			
Constant		1.263	
Std Err of Y Est		0.009	
R Squared		0.999	0.99956
No. of Observations		12.000	
Degrees of Freedom		10.000	
X Coefficient(s)	0.57718933		
Std Err of Coef.	0.00541031		

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.577
C= 3.535

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
13.4	33.8	42.7

TEST: 2.2 (c)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	N/G	N/G			
1	3	N/G	N/G			
1	4	0.706	1.483	7.5	23.5	31.3
1	5	N/G	N/G			
1	6	N/G	N/G			
2	3	N/G	N/G			
2	4	N/G	N/G			
2	5	0.697	1.913	9.5	29.2	38.8
2	6	N/G	N/G			
3	4	N/G	N/G			
3	5	N/G	N/G			
3	6	N/G	N/G			
4	5	N/G	N/G			
4	6	0.866	0.633	4.6	18.7	26.6
5	6	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	4	0.706	1.483	7.5	23.5	31.3	0.19	Pass
2	5	0.697	1.913	9.5	29.2	38.8	1.31	Pass
4	6	0.866	0.633	4.6	18.7	26.6	1.12	Pass
Mean		0.756	1.343	7.2	23.8	32.2	= PREDICTED LEAKAGE	
Std. Dev.		0.078	0.532	2.0	4.3	5.0		
Coeff. of Variation		10%	40%	28%	18%	16%		

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
108.9	53.3	4.690	3.976
61.5	38.8	4.119	3.658
51.3	34.8	3.938	3.550
30.6	25.7	3.421	3.246
61.8	38.8	4.124	3.658
36.0	27.7	3.584	3.321
73.9	43.5	4.303	3.773
42.5	31.5	3.750	3.450
86.0	47.1	4.454	3.852
49.1	34.1	3.894	3.529
98.1	50.5	4.586	3.922
54.8	36.6	4.004	3.600

```
Regression Output:
Constant                                      1.256
Std Err of Y Est                              0.010
R Squared                                     0.998   0.99907
No. of Observations                          12.000
Degrees of Freedom                           10.000

X Coefficient(s)      0.58258281
Std Err of Coef.      0.00793628
```

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.583
C= 3.510

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
13.4	34.3	43.4

TEST: 3.1 (a)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.861	1.013	7.4	29.4	41.7
1	3	0.971	0.593	5.5	26.5	39.2
1	4	0.724	2.022	10.7	34.3	46.0
1	5	N/G	N/G			
1	6	0.811	1.299	8.4	31.0	43.1
2	3	0.846	1.083	7.6	29.6	41.8
2	4	0.917	0.792	6.5	28.6	41.5
2	5	N/G	N/G			
2	6	N/G	N/G			
3	4	0.554	4.899	17.5	42.8	53.6
3	5	N/G	N/G			
3	6	0.782	1.487	9.0	31.7	43.5
4	5	N/G	N/G			
4	6	0.865	1.014	7.4	29.9	42.4
5	6	N/G	N/G			

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.861	1.013	7.4	29.4	41.7	0.50	Pass
1	3	0.971	0.593	5.5	26.5	39.2	1.13	Pass
1	4	0.724	2.022	10.7	34.3	46.0	0.61	Pass
1	6	0.811	1.299	8.4	31.0	43.1	0.14	Pass
2	3	0.846	1.083	7.6	29.6	41.8	0.48	Pass
2	4	0.917	0.792	6.5	28.6	41.5	0.55	Pass
3	4	0.554	4.899	17.5	42.8	53.6	2.54	Fail
3	6	0.782	1.487	9.0	31.7	43.5	0.04	Pass
4	6	0.865	1.014	7.4	29.9	42.4	0.31	Pass
Mean		0.815	1.578	8.9	31.5	43.6		
Std. Dev.		0.114	1.237	3.4	4.5	3.9		
Coeff. of Variation		14%	78%	38%	14%	9%		

SUMMARY OF RESULTS (AFTER APPLYING CHAUVENET'S CRITERION):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	
1	2	0.861	1.013	7.4	29.4	41.7	
1	3	0.971	0.593	5.5	26.5	39.2	
1	4	0.724	2.022	10.7	34.3	46.0	
1	6	0.811	1.299	8.4	31.0	43.1	
2	3	0.846	1.083	7.6	29.6	41.8	
2	4	0.917	0.792	6.5	28.6	41.5	
3	6	0.782	1.487	9.0	31.7	43.5	
4	6	0.865	1.014	7.4	29.9	42.4	
Mean		0.847	1.163	7.8	30.1	42.4	= PREDICTED LEAKAGE
Std. Dev.		0.072	0.415	1.5	2.2	1.8	
Coeff. of Variation		8%	36%	19%	7%	4%	

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
34.7	31.6	3.547	3.453
53.7	41.7	3.983	3.731
21.2	22.9	3.054	3.131
32.6	30.4	3.484	3.414
32.7	30.4	3.487	3.414
50.7	40.6	3.926	3.704
30.1	28.8	3.405	3.360
46.5	38.2	3.839	3.643
27.5	27.9	3.314	3.329
43.0	35.9	3.761	3.581
23.8	25.0	3.170	3.219
36.8	33.5	3.605	3.512

Regression Output:		
Constant	1.198	
Std Err of Y Est	0.011	
R Squared	0.997	0.99852
No. of Observations	12.000	
Degrees of Freedom	10.000	

X Coefficient(s)	0.63685322
Std Err of Coef.	0.01097225

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.637
C= 3.313

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
14.4	40.0	51.8

TEST: 3.1 (b)

SUMMARY OF RESULTS (ALL DATA PAIRS):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
1	2	0.549	5.0710	18.0	43.4	54.3
1	3	0.651	2.9741	13.3	38.0	49.4
1	4	N/G	N/G			
1	5	0.538	5.3811	18.6	44.1	54.9
1	6	N/G	N/G			
1	7	0.509	6.3050	20.4	46.2	56.8
2	3	0.834	1.2475	8.5	32.6	45.7
2	4	N/G	N/G			
2	5	0.524	5.7890	19.3	45.0	55.6
2	6	N/G	N/G			
2	7	N/G	N/G			
3	4	N/G	N/G			
3	5	N/G	N/G			
3	6	N/G	N/G			
3	7	N/G	N/G			
4	5	N/G	N/G			
4	6	0.704	2.4623	12.5	38.7	51.4
4	7	0.671	2.8982	13.6	40.0	52.5
5	6	N/G	N/G			
5	7	N/G	N/G			
6	7	0.633	3.4565	14.8	41.1	53.2

N/G = no good

SUMMARY OF RESULTS (BAD DATA PAIRS REMOVED):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	(Q75-Mean) /(Std. Dev.)	PASS/FAIL? (Chauvenet's Crit.)
1	2	0.549	5.0710	18.0	43.4	54.3	0.50	Pass
1	3	0.651	2.9741	13.3	38.0	49.4	0.99	Pass
1	5	0.538	5.3811	18.6	44.1	54.9	0.70	Pass
1	7	0.509	6.3050	20.4	46.2	56.8	1.28	Pass
2	3	0.834	1.2475	8.5	32.6	45.7	2.15	Fail
2	5	0.524	5.7890	19.3	45.0	55.6	0.92	Pass
4	6	0.704	2.4623	12.5	38.7	51.4	0.37	Pass
4	7	0.671	2.8982	13.6	40.0	52.5	0.04	Pass
6	7	0.633	3.4565	14.8	41.1	53.2	0.16	Pass
Mean		0.624	3.954	15.4	41.0	52.6		
Std. Dev.		0.100	1.635	3.7	4.0	3.2		
Coeff. of Variation		16%	41%	24%	10%	6%		

SUMMARY OF RESULTS (AFTER APPLYING CHAUVENET'S CRITERION):

DATA PAIRS		n	C	Q10 (l/s)	Q50 (l/s)	Q75 (l/s)	
1	2	0.549	5.0710	18.0	43.4	54.3	
1	3	0.651	2.9741	13.3	38.0	49.4	
1	5	0.538	5.3811	18.6	44.1	54.9	
1	7	0.509	6.3050	20.4	46.2	56.8	
2	5	0.524	5.7890	19.3	45.0	55.6	
4	6	0.704	2.4623	12.5	38.7	51.4	
4	7	0.671	2.8982	13.6	40.0	52.5	
6	7	0.633	3.4565	14.8	41.1	53.2	
Mean		0.597	4.292	16.3	42.1	53.5	= PREDICTED LEAKAGE
Std. Dev.		0.071	1.406	2.9	2.9	2.2	
Coeff. of Variation		12%	33%	18%	7%	4%	

C-3 LEAKAGE CHARACTERISTICS

Delta P (Pa)	Q (Q)	ln(Delta P)	ln(Q)
56.9	44.0	4.041	3.784
19.4	21.9	2.965	3.086
53.8	42.9	3.985	3.759
15.6	18.6	2.747	2.923
50.9	40.9	3.930	3.711
14.3	17.9	2.660	2.885
48.8	39.7	3.888	3.681
19.9	22.5	2.991	3.114
44.6	37.5	3.798	3.624
16.0	19.3	2.773	2.960
42.4	36.5	3.747	3.597
14.7	18.6	2.688	2.923
38.2	34.1	3.643	3.529
10.9	14.5	2.389	2.674

Regression Output:

Constant		1.131	
Std Err of Y Est		0.013	
R Squared		0.999	0.9995
No. of Observations		14.000	
Degrees of Freedom		12.000	
X Coefficient(s)	0.65776566		
Std Err of Coef.	0.006035		

ACTUAL INTER-ZONE LEAKAGE CHARACTERISTICS

n= 0.658
C= 3.099

ACTUAL INTER-ZONE LEAKAGE

Q10 (l/s)	Q50 (l/s)	Q75 (l/s)
14.1	40.6	53.0