RESEARCH REPORT

AIR LEAKAGE CHARACTERISTICS, TEST METHODS AND SPECIFICATIONS FOR LARGE BUILDINGS

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REPORT

AIR LEAKAGE CHARACTERISTICS, TEST METHODS AND SPECIFICATIONS FOR LARGE BUILDINGS

Prepared For

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EXECUTIVE SUMMARY

A literature survey was conducted to identify measured airtightness values for various types of large buildings including Multi-Unit Residential Buildings (MURBs); offices; schools; commercial, industrial and institutional structures. Data was identified for 192 buildings in Canada, the United States, Great Britain and Sweden. Information was also collected on various quantitative and qualitative airtightness test methods, performance targets, specifications and quality control procedures.

The results of the survey showed that virtually all large buildings, including those built within the last few years, are quite leaky and would not meet the current recommendations contained in the Appendices of the 1995 National Building Code of Canada (NBC). Typical leakage rates were found to be 10 to 50 times those referenced in the NBC. Despite this, the technology now exists to design, build and verify large building airtightness. Design details have been developed and are widely available to the architectural and engineering communities, standards have been established which identify how tight the building (or portions of its envelope) should be, quantitative and qualitative testing methods have been prepared and are commercially available in most parts of the country. Finally, quality control systems are available to integrate the theory into the practical realm of the construction site.

The results of the literature survey were used to develop recommendations on measures which could be taken to improve the airtightness in large buildings. These included: a) the adoption of quantitative, whole-building airtightness requirements in the NBC and other standards (as opposed to non-mandatory recommendations), b) an investigation of how the current NBC recommendations are being enforced by building officials across Canada, c) establishment of a national database on large building airtightness, d) on-going provision of industry training programs, e) establishment of educational activities for building owners and property managers, and f) other measures which would create a demand for airtight construction.

RÉSUMÉ

Le dépouillement documentaire effectué visait à cerner les valeurs d'étanchéité à l'air mesurées à l'égard de différents grands bâtiments, dont des collectifs d'habitation, des bureaux, des écoles, ainsi que des bâtiments commerciaux, industriels et institutionnels. Les données recueillies touchaient 192 bâtiments situés au Canada, aux États-Unis, en Grande-Bretagne et en Suède. Il a a également permis de se renseigner sur les méthodes d'essai quantitatives et qualitatives, les objectifs de performance, les caractéristiques et les méthodes de contrôle de la qualité.

Les résultats du dépouillement montrent que presque tous les grands bâtiments, y compris ceux qui ont été construits ces dernières années, sont peu étanches au point qu'ils ne seraient pas conformes aux recommandations que contiennent les annexes du Code national du bâtiment du Canada (CNBC) de 1995. Les taux de fuites d'air types, a-t-on constaté, étaient de 10 à 50 fois plus élevés que ceux dont fait état le CNBC. Malgré cela, la technologie actuelle permet de concevoir, de construire et de vérifier l'étanchéité à l'air des grands bâtiments. Les détails de conception élaborés sont faciles d'accès pour les ingénieurs et les architectes, les normes élaborées permettent d'établir à quel point le bâtiment (ou de certaines parties de son enveloppe) devrait être étanche, sans compter que les méthodes d'essai quantitatives et qualitatives mises au point sont facilement accessibles dans toutes les régions du pays. Enfin, des systèmes de contrôle de la qualité permettent d'allier la théorie et le côté pratique sur le chantier de construction.

Les résultats du dépouillement documentaire ont servi à formuler des recommandations portant sur les mesures à adopter dans le but d'améliorer l'étanchéité des grands bâtiments. Ce sont : a) l'adoption d'exigences quantitatives d'étanchéité à l'air de tout le bâtiment dans le CNBC et des normes (par opposition à des recommandations facultatives); b) une enquête portant sur la façon dont les agents du bâtiment de l'ensemble du pays mettent en application les recommandations courantes du CNBC ; c) l'établissement d'une base de données nationale sur l'étanchéité à l'air des grands bâtiments; d) l'instauration de programmes continus de formation au sein de l'industrie; e) l'établissement de programmes d'enseignement à l'intention des propriétaires et gestionnaires immobiliers; et f) d'autres mesures susceptibles de susciter une demande pour des bâtiments étanches à l'air.

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INTRODUCTION

1.1 BACKGROUND

Airtightness is a basic performance characteristic of all buildings and has tremendous importance for those located in extreme environments such as Canada's. In a heating climate, envelope air leakage can produce a number of undesirable effects upon building durability and performance. These include: interstitial moisture deposition within the envelope due to air exfiltration, the creation of cold drafts, the movement of outdoor pollutants into the building, increased energy costs and the transmission of outdoor noise into the structure. Moisture damage due to air exfiltration may be the most serious consequence of air leakage. To occur, three conditions must be satisfied: a) physical pathways (i.e., holes or cracks) must be present through the envelope, b) a suitable pressure differential must exist across the envelope and c) there must be sufficiently high moisture levels in the indoor air. In cooling climates, the situation is somewhat reversed and moisture movement is more likely to occur from the hot, humid outdoors, through the envelope, into the cool (air-conditioned) interior of the building. In either case, unintentional air leakage is undesirable.

Since no structure is perfectly airtight, air leakage and its undesirable effects cannot be eliminated but only controlled within manageable limits.

Any meaningful discussion about air leakage requires a *quantitative* understanding of typical building leakage rates. Determining the airtightness of smaller structures, such as detached houses, is a relatively simple procedure. The required equipment (blower doors and high-quality micromanometers) is commercially available, established testing protocols exist and there are dozens of trained practitioners across the country capable of performing the test. As a result, there now exists a large knowledge base of airtightness data for this class of buildings. These same methods can also be used for qualitative, quality control examinations to identify air leakage locations during the construction process so that corrective action can be taken.

Unfortunately, the situation for large buildings is more complex and far less advanced. In theory, the test procedures used on houses can be applied to large buildings. 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 a large building can require an expensive fan system, possibly with its own power supply. Environmental factors such as wind and the indoor-to-outdoor temperature differentials often have a more significant influence on large buildings than on houses. Obtaining access to all areas (zones) in a large building can be difficult, particularly in existing structures. If the test structure is physically attached to adjacent buildings, alternate procedures may have to be employed to perform the test. As a result, comparatively few large buildings have had their airtightness measured.

While the knowledge base on large building airtightness data is much smaller than that for detached houses, the need for such information is at least as great. Large buildings usually operate with greater pressure differentials across their envelopes, thus increasing the probability of damaging impacts. The stack effect is larger since it increases with building height. Wind forces are more pronounced because the building protrudes farther into the earth's boundary layer. The mechanical systems in large buildings are more likely to induce envelope leakage since they are more powerful than those in low-rise structures. In addition, large buildings are more frequently mechanically humidified during the heating season which increases the potential for moisture deposition due to air leakage. Since the amount of moisture transport is a function of the three factors previously mentioned (airtightness, envelope pressure differentials and the indoor relative humidity), the potential threat facing large buildings in a heating climate is significant.

While the knowledge base of large building airtightness data is much smaller than that for detached houses, much useful information does exist although not in an organized format. For this reason, Canada Mortgage and Housing Corporation (CMHC) initiated the project described in this report to identify, document and summarize the existing airtightness data for large buildings.

1.2 STUDY OBJECTIVES

This project was carried out to provide a baseline review of the existing literature on airtightness test data, test methods and recommended performance targets for large buildings, particularly Multi-unit Residential Buildings (MURBs) and commercial office buildings. The specific goals of the project were:

- To identify ranges in airtightness levels that have been documented for MURB and commercial office buildings, both nationally and internationally. Also, to identify the available information on other types of buildings such as schools, offices, industrial and institutional buildings;
- To identify airtightness performance targets and their supporting rationale;
- To identify air leakage test methods, specifications, quality control and commissioning procedures currently available to the building industry;
- To make recommendations regarding the degree to which the airtightness levels in large buildings, particularly MURBs and office buildings, could be improved and what would be required to súpport such improvements.

SECTION 2
OVERVIEW OF THE LITERATURE SURVEY

2.1 DESCRIPTION OF THE LITERATURE SURVEY

To meet the project objectives, an extensive literature survey was carried out of potential sources of information, both nationally and internationally. These included:

- Canada Mortgage and Housing Corporation;
- National Research Council of Canada;
- Natural Resources Canada;
- Public Works and Government Services Canada;
- Saskatchewan Research Council;
- National Air Barrier Association;
- American Society of Heating, Refrigeration and Air-Conditioning Engineers;
- American Society for Testing and Materials;
- National Institute of Standards and Technology;
- Lawrence Berkeley Laboratory;
- Florida State Research Centre;
- Air Infiltration and Ventilation Centre.

One of the key information sources was the "Airbase" database maintained by the Air Infiltration and Ventilation Centre in England. This is a CD-based collection which currently contains 13,188 abstracts on various topics relating to air infiltration, mechanical and natural ventilation and airtightness. Various searches were made of the database to identify possible technical papers which might be of interest, of which approximately 100 were obtained and reviewed. Also, Persily investigated the issue of large building airtightness and was able to identify data on 139 buildings (Persily, 1999).

2.2 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 the air passes through the envelope. Building airtightness is commonly determined 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 power law function shown in Eq. 1.

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

where

Q = air leakage (l/s)

C = flow coefficient (l/s•Pa^n)

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

n = flow exponent (dimensionless)

Equation (1) is an empirical relationship which has been found to reliably describe the leakage behaviour of buildings. A common problem encountered in the literature review was that researchers used a variety of methods to express their results and to report other relevant data. With respect to airtightness, the most common methods were those shown in Eqs. (2) to (6).

Air Change Rate at 50 Pa

$$AC/HR_{50} = \frac{\text{(Total leakage at 50 Pa, expressed in building or zone volumes)}}{\text{Volume of the building or zone}} \tag{2}$$

Air Change Rate at 75 Pa

$$AC/HR_{75} = \frac{\text{(Total leakage at 75 Pa, expressed in building or zone volumes)}}{\text{Volume of the building or zone}} \tag{3}$$

The units used in Eqs. (2) and (3) to express results are "air changes per hour" at a pressure differential of 50 Pa or 75 Pa, respectively.

Normalized Leakage Rate at 25 Pa

$$NLR_{25} = \frac{\text{(Total leakage at a pressure differential of 25 Pa)}}{\text{Envelope area}} \quad (\text{l/s}\bullet\text{m}^2) \tag{4}$$

Normalized Leakage Rate at 50 Pa

$$NLR_{50} = \frac{\text{(Total leakage at a pressure differential of 50 Pa)}}{\text{Envelope area}} \quad (\text{l/s}\bullet\text{m}^2) \tag{5}$$

Normalized Leakage Rate at 75 Pa

$$NLR_{75} = \frac{\text{(Total leakage at a pressure differential of 75 Pa)}}{\text{Envelope area}} \quad (\text{l/s}\bullet\text{m}^2) \tag{6}$$

The definition of "envelope area" in Eqs. (4) to (6) also varied among the researchers. Some of the earliest data was reported using the area of just the exterior walls (including doors and windows) without any consideration of the foundation or roof - presumably because of the belief that leakage through the latter was sufficiently small that it could be ignored. Other researchers, particularly those in Great Britain and a few in the United States, reported airtightness data on the basis of the above-grade portions of the envelope, i.e., walls, windows, doors and the roof. British data was generally reported using Eq. (5) with the "envelope area" consisting of the above-grade area; the resulting value was often referred to as the "Air Leakage Index". Occasionally the total envelope area was used and was referred to as the "Air Permeability".

Most North American data of recent vintage was reported on the basis of total envelope area (above and below grade). When data was encountered in one of the alternate formats, corrections were applied wherever possible to convert it to the format used in this report (i.e., total envelope area, as discussed below). 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.

2.3 METHOD OF DATA PRESENTATION USED IN THIS REPORT

In this report, airtightness data is reported using the Normalized Leakage Rate at an indoor-to-outdoor pressure differential of 75 Pa (NLR_{75}), i.e., Eq. (6). The normalizing area for the NLR_{75} was defined as the total envelope area, including above-grade and below-grade components. This method was chosen for consistency with the method used in the 1995 National Building Code of Canada. It was also the most common method found in the literature for expressing airtightness data.

The airtightness data collected during the survey was sub-divided on the basis of building type and is discussed separately for each type in the following sections of this report. The data was also sub-divided on the basis of country of origin (to reflect local design and construction practices).

In a number of cases, multiple test data was available for the same building, usually because repeat tests had been performed after remedial measures were carried out (to reduce air leakage) or because separate tests were performed on various zones in the building. In these instances, both sets of data were included in the analysis but group averages were calculated using the pre-retrofit data only. A separate commentary was made about the impact of the sealing measures.

A classification system was also established to account for the differences in test procedures and the method used to express the airtightness data. With respect to the former, in some cases the test was conducted on only a portion of the building, such as an individual floor or suite in a multi-zone building, rather than on the entire structure. Therefore, it was decided to show these separately (as discussed below). With respect to the method used to express data, in some instances it was reported using an alternate area (such as the exterior walls) to normalize the air leakage, and could not be corrected to the preferred format of total envelope area. Once again, these were shown separately.

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

Data contained herein was extracted from the source documents as reported by the original authors without any attempt to convert from one data type to another. Generally, the analysis in this report includes all of the available data. However, in several instances, a more detailed analysis was performed on the Type 1 data because it was the most numerous and highest quality.

2.4 CATEGORIZATION OF BUILDING TYPES

The airtightness data collected during the survey was organized in a spreadsheet, then sub-divided and categorized on the basis of the following building type:

- Multi-Unit Residential Buildings (MURBs);
- Office buildings;
- Schools;
- Commercial buildings;
- Industrial buildings;
- Institutional buildings.

2.5 SUMMARY OF AIRTIGHTNESS DATA

The literature review identified approximately 75 references containing quantitative airtightness data which was ultimately used in the study. From these, airtightness data was identified for 192 individual buildings, predominately in Canada and the United States with lesser numbers from Great Britain and Sweden. Data from other countries was also identified but was not usable for a variety of reasons.

A summary of the building data is provided in Table 1, and a more complete listing is given in Appendix A. It is worth noting that this is not a definitive list of all the data which exists on large building airtightness, but simply that which could be identified, collected and analyzed within the scope of the project. Additional information is known to exist, although it could not be obtained for this project. Given sufficient resources, it could likely be acquired. In addition, it must be remembered that airtightness testing of large buildings is on-going in many countries, so new data will continue to become available.

2.6 OVERVIEW OF CANADIAN AND INTERNATIONAL ACTIVITIES

The following is a brief history of activities related to airtightness testing in large buildings.

2.6.1 Canada

Canada, primarily through the efforts of the National Research Council (NRC), was one of the original pioneers in airtightness testing of large buildings. Beginning in the early 1970's, they investigated the airtightness characteristics of eight office buildings, ranging in height from nine to 25 storeys, located in the Ottawa area (Tamura and Shaw, 1976). To develop the necessary pressure differentials, they used the building's own mechanical system to positively pressurize the structures. In the late 1970's, NRC developed a portable, high-capacity exhaust system which could be used to provide the depressurization. The system was trailer-mounted and had its own power supply. With an air-flow capacity of 23 m^3/s (50,000 ft^3/min), it was capable of testing many bigger buildings, including those whose mechanical systems could not be adapted, or did not have sufficient capacity, to perform the tests. Additional studies of airtightness were performed over the next 20 years on various types of buildings including schools (Shaw and Jones, 1979), supermarkets (Shaw, 1981) and apartment buildings (Shaw, Magee and Rousseau, 1991). NRC also studied the long-term airtightness performance of large buildings including those which had been retrofitted to reduce air leakage (Shaw, 1982; and Shaw and Reardon, 1995).

Beginning in the early 1990's, CMHC decided to expand the knowledge base by sponsoring a series of field studies to assess airtightness, air movement and air quality in Multi-Unit Residential Buildings. The work was contracted to local engineering or testing firms in such cities as Vancouver, Victoria, Winnipeg, Toronto, Ottawa, Montreal and St. John's. This not only increased the number of buildings which had been tested but expanded the geographic distribution beyond that investigated by NRC, since all of their work had been performed on buildings in the Ottawa area.

An interesting by-product of this initial research by NRC and CMHC was the emergence of a small, but growing, market for airtightness testing services in large buildings - along with the development of firms capable of providing these services in a competitive environment. The need for these services has been created by the growing recognition within the construction

Table 1 (a)
Summary of Airtightness Data (Based on Country)

Building Type	Number of Buildings				
	Canada	United States	Great Britain	Sweden	Total
MURBs	23				23
Office buildings	8	7	25		40
Schools	11	14			25
Commercial buildings	18	68			86
Industrial buildings			7	9	16
Institutional buildings	2				2
Total	62	89	32	9	192

Table 1 (b)
Summary of Airtightness Data (Based on Building and Data Type)

Building Type	Number of Buildings			
	Type 1 Data	Type 2 Data	Type 3 Data	Total
MURBs	12	3	8	23
Office buildings	27	13		40
Schools	25			25
Commercial buildings	76	10		86
Industrial buildings	5	11		16
Institutional buildings	2			2
Total	147	37	8	192

industry of the importance of airtightness and the need to provide a higher level of quality control than has been available in the past. Interestingly, it appears that most or all of the firms providing these services for large buildings developed their expertise providing similar services for single-detached housing. In 1995, the Appendices of the National Building Code of Canada were modified to include "recommended" airtightness levels for the building envelopes of large buildings (i.e., those not covered by Part 9). However, adoption and enforcement appears to have been sporadic. The need for commercial services is expected to increase, perhaps significantly, as the implications of these new recommendations are adopted.

2.6.2 United States

Historically, most American activity has also been reserach-driven, typically by such organizations as the National Bureau of Standards (now the National Institute of Standards and Technology). In the mid-1980s, NBS performed pressurization testing on seven federal office buildings located across the United States (Persily and Grot, 1986). They used the building's mechanical system to pressurize the buildings and measured air flow rates using the constant-injection, tracer gas technique. In the early 1990's, other researchers tested a group of 13 schools as part of a radon research project (Brennan et al, 1992). Their tests were performed using multiple, portable blower doors, the building's mechanical system or a combination of the two. In 1996, Florida State Solar Research Centre published a major study of the airtightness of 69 commercial and school buildings in Florida constructed using a variety of wall systems including masonry, metal, framing and pre-manufactured systems (Cummings et al, 1996). Most of the buildings tested were relatively small, with an average floor area of only 1,161 m^2. Depressurization was provided using one to six portable blower doors.

2.6.3 Great Britain

One of the most surprising discoveries of this project was the significant progress which has been made in airtightness testing of large buildings in Great Britain. These efforts have been spearheaded by the Building Services Research and Information Association (BSRIA) and the British Research Establishment (roughly equivalent to the National Research Council in Canada) and the University of Wales, which have been active in the field since the mid-1980's. Although full details were not available for this report, these organizations have apparently tested 384 commercial buildings, as of late 2000 (CIBSE, 2000)! Most of the testing has been carried out using portable fan systems such as the "BREFAN" developed by BRE (Perera et al, 1989). This is a multi-fan pressurization system which uses a series of identical fans, each of which draws less than 3 kW of electrical power, thereby permitting conventional 13 amp. electrical sockets to be used (standard British electrical service has a voltage of 220 V). Each unit is capable of moving 5.5 m^3/s (11,600 cfm) at 50 Pa. There are currently estimated to be about five such rigs in existence although plans apparently exist to construct a number of additional units (Lawson, 2000). While most testing in Great Britain has been performed for research purposes, commercial testing services are becoming increasingly available.

At present, Part L of the United Kingdom Building Regulations, which deals with energy efficiency, is being updated. It is anticipated that the new version may include quantitative airtightness requirements for large buildings. Presumably, compliance would have to be demonstrated through testing.

2.6.4 Sweden

In the mid-1980's, the Swedish National Testing Institute developed test methods and equipment suitable for use on large buildings. The equipment included 8 m^3/s (17,000 ft^3/min) trailer-mounted fans while flow measurements were provided using the constant-flow tracer gas technique (Lundin, 1986). This type of set-up was used to test nine industrial buildings in Sweden using two of these rigs. Additional tests on office buildings and other types of structures is also believed to have been carried out in the 1970's.

2.6.5 Other Countries

Airtightness testing of large buildings has also been conducted in a few other countries although the data was either unavailable in English or was reported in a format inconsistent with that used in this report. For example, a sample of classrooms in twelve schools was tested in New Zealand, however, no provision was made for inter-zone leakage through interior partitions (Bassett and Gibson, 1999). Similar work was performed on schools in the Netherlands (Schijndel, 1990). Testing was also carried out on Israeli apartment buildings although the results were reported on the basis of Equivalent Leakage Area per unit window crack length (Poreh, 1993).

2.7 BUILDING COMPONENT AIRTIGHTNESS DATA

The scope of this report was restricted to whole-building airtightness data. Information on the air leakage characteristics of building components, such as doors and windows, joints, intersections and penetrations was excluded because the leakage characteristics of components cannot be easily extrapolated to provide meaningful results on the overall performance of the entire envelope. However, various references were identified which contain component airtightness data and these may be of interest to the reader. These references include: Shaw (1980), Gulay (1991), Colliver et al (1992), Orme et al (1994), Proskiw (1995), ASHRAE (1997) and Edwards (1999). Some of these references also include data on the airtightness characteristics of interior components such as partition walls, elevator and stairway shafts. This information is often used for modelling purposes (ventilation, air quality, smoke control, etc.) where the air leakage behaviour of both the exterior envelope and interior components is of interest.

SECTION 3
AIRTIGHTNESS DATA: MULTI-UNIT RESIDENTIAL BUILDINGS

3.1 BUILDING DESCRIPTIONS

Airtightness data was identified for 23 Multi-Unit Residential Buildings, plus two for which the results were reported using air change rate data. All were located in Canada, in various locations (Victoria, Vancouver, Winnipeg, Flin Flon, Toronto, Ottawa, Dundas and Montreal). Age of the buildings at the time of the test ranged from brand-new to 36 years. Over one-half were constructed in the 1990's. Physically, they varied in height from single-storey structures to 21-storey apartment blocks. Types of wall construction varied and included: wood frame, masonry, reinforced concrete, brick veneer/steel studs and EIFS. Building volumes, when reported, ranged from 2,001 m^3 to 43,515 m^3. Three of the buildings were retrofitted to reduce air leakage, and both pre- and post-retrofit data was available.

3.2 TEST METHODS

The test method employed varied depending on the building size and the equipment available to the team conducting the tests. In about three-quarters of the buildings, depressurization tests were performed on the entire structure using either the NRC-style, trailer-mounted exhaust equipment or portable blower doors, thereby measuring the airtightness of the entire envelope. The remaining buildings were tested using the balanced depressurization method in which only the airtightness of the exterior walls in individual suites or floors was measured (see section on Airtightness Test Methods). In about half the cases, the airtightness data was reported on the basis of total envelope area while in the remaining instances, the exterior wall area was used to normalize the data.

3.3 AIRTIGHTNESS DATA

The MURB airtightness data is summarized in Table 2 and Figure 1 and is sub-divided into the three data types previously discussed. For those buildings retrofitted to reduce air leakage, the pre-retrofit data was used for averaging purposes since most Canadian MURBs have not been retrofitted and it was felt that the pre-retrofit data was the most representative.

Type 1 Data - The average NLR_{75} for the 12 MURBs in which the whole building was tested and the total envelope area was used for area normalization, was 3.19 $l/s{\bullet}m^2$ with a standard deviation of 1.24 $l/s{\bullet}m^2$. The most airtight building in this group, which had a measured NLR_{75} of 1.18 $l/s{\bullet}m^2$, had been constructed as part of the IDEAS Challenge/C-2000 Program (see section on Airtightness Performance Targets, Specifications, Quality Control and Commissioning Procedures).

Type 2 Data - Slightly higher (but still similar) results were observed for those buildings in which the exterior wall area was used as the normalizing area. The mean NLR_{75} was 4.00 $l/s{\bullet}m^2$ with a standard deviation of 0.60 $l/s{\bullet}m^2$. The most airtight building had a NLR_{75} of 3.15 $l/s{\bullet}m^2$.

Type 3 Data - MURBs which had individual suites or floors tested, and which had their results expressed using the suite or floor exterior wall area in the calculation of the NLR_{75}, also reported similar results. The average NLR_{75} was 4.30 $l/s{\bullet}m^2$ with a standard deviation of 2.73 $l/s{\bullet}m^2$.

Table 2
Summary of Airtightness Data - MURBs

Country	Number of Buildings	NLR_{75} ($l/s \cdot m^2$)			Area Used In NLR_{75}
		Mean	Range	Std. Dev.	
Canada					
Type 1 Data	12	3.19	1.18 to 6.37	1.24	Total envelope
Type 2 Data	3	4.00	3.15 to 4.50	0.60	Exterior walls
Type 3 Data	8	4.30	0.83 to 10.00	2.73	Exterior walls of suites or floors

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

Interestingly, when multiple data from individual buildings were examined, the NLR_{75} varied by a factor of up to three among individual floors or suites within a specific building. Even when the complexity of the test procedure is acknowledged and the difficulty of obtaining repeatable results is appreciated, it appears that significant variations in airtightness can exist over the envelope in a given building.

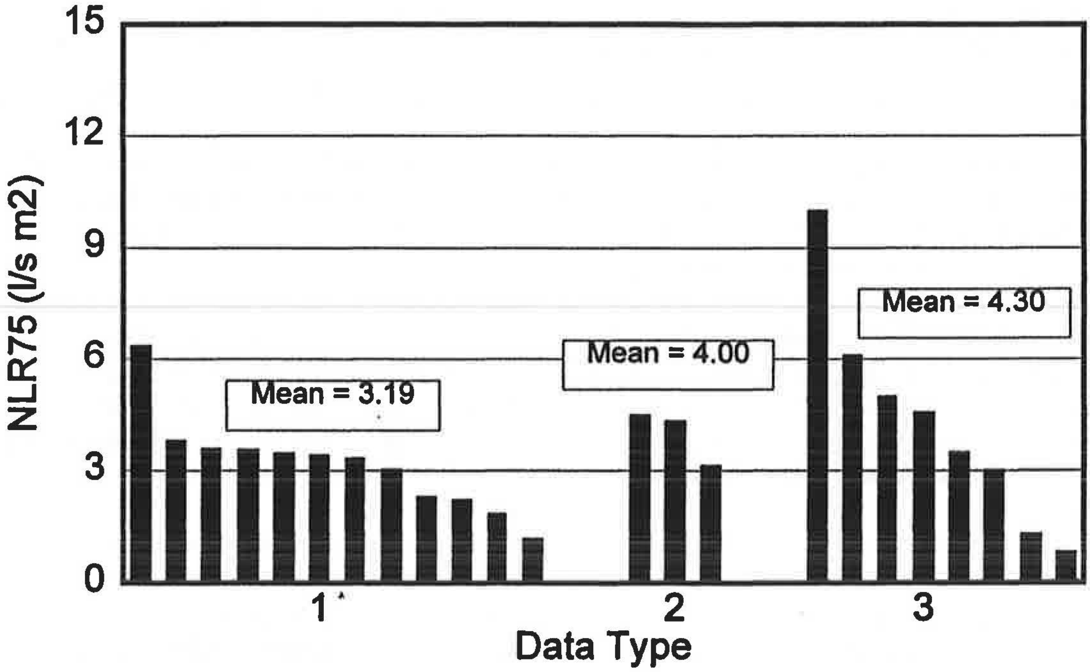
Overall, when the airtightness data was compared to the recommendations contained in the Appendix of the 1995 NBC (see section on Airtightness Performance Targets, Specifications, Quality Control And Commissioning Procedures) of 0.10 $l/s \cdot m^2$ (for buildings with relative humidity levels of 27% to 55%), it is obvious that the existing MURB stock in Canada far exceeds the upper limit of what is now considered desirable, typically by a factor of 30 to 40. To be fair, almost none of these buildings were ever designed or constructed to meet the NBC guidelines or to be "airtight" as the term is now used. The one exception was the IDEAS Challenge/C-2000 building which had a target NLR_{75} of 1.00 $l/s \cdot m^2$, plus a quality control protocol and specified test procedure for assessing airtightness. Nonetheless, the data do illustrate that there is considerable room for improvement and the IDEAS Challenge/C-2000 buildings exemplify the types of results which are possible.

3.4 IMPACT OF WALL TYPE

The NLR_{75} data was analysed on the basis of wall type to identify if any patterns existed, although hard conclusions must be tempered by the limited information available on construction details plus the fact that some buildings used more than a single type of wall construction. The results are shown in Table 3. Where pre- and post-retrofit data were available for a building, only the pre-retrofit data was used for the analysis.

With the possible exception of the two MURBs which used reinforced concrete, the method of wall construction was not a reliable predictor of airtightness. This is not to suggest that wall construction does not affect airtightness but rather, at least for the buildings studied, other factors played a more dominant role. For example, the three brick veneer/steel MURBs with

Fig. 1 MURBs



Type 1 Data initially appeared to have been more airtight than most other types of buildings. However, closer examination showed that these results had been skewed by the inclusion of the IDEAS Challenge/C-2000 building in this class (the other two buildings had an average NLR_{75} of 2.83 $l/s\bullet m^2$).

It might have been expected that those buildings which used wood framing would have been tighter than those built with masonry construction since wood frame designers and builders could utilize airtight construction details and techniques which had been developed for detached housing. In contrast, most of the masonry buildings had been constructed prior to the development of techniques intended to limit air leakage. In any event, such a trend was not observed.

Table 3
Impact of Wall Type - MURBs

Data Type	Number of Buildings	Mean NLR_{75} ($l/s\bullet m^2$)
Type 1 Data		
Brick veneer/steel stud	3	2.28
Wood frame	7	3.03
Type 2 Data		
Masonry	3	4.00
Type 3 Data		
Masonry	2	3.27
Reinforced concrete	2	1.07
Brick veneer/steel stud	2	7.50

3.5 IMPACT OF AIR LEAKAGE SEALING

Three of the MURBs in the data set, which had been retrofitted to reduce air leakage, experienced a reduction in their NLR_{75} value of 15%, with individual reductions ranging from 7% to 24%. Two of these buildings are included in Table 2 while the third was a 21-storey apartment block for which the airtightness data was reported using AC/HR_{50} data. Although the sample size is quite small, the fact that these measures were applied by commercial contractors experienced in such work may provide a reasonable first estimate of the efficacy of air leakage sealing in MURBs. However, more data is needed. The test procedure in all three buildings measured the airtightness of the entire envelope, not just a portion of the exterior walls.

3.6 FLOW EXPONENTS

It is also interesting to examine those results for which data was provided on the flow exponent, "n" in Eq. (1). The average n-value for the entire MURB data set was 0.63 which is very close to the "typical" value of 0.65 which is often assumed, and used for, calculation purposes. In contrast, the individual floor/suite data show an average n value of 0.52 (with comparatively little variation), which is closer to the pure orifice flow limit of 0.50. A few of the reported n values were less than 0.5, which is outside the range of acceptable values as defined by such standards as CGSB 149.10 (CGSB, 1986) and CGSB 149.15 (CGSB, 1996). However, the accuracy of these results is difficult to gauge given the complexity of the test and analysis.

SECTION 4
AIRTIGHTNESS DATA: OFFICE BUILDINGS

4.1 BUILDING DESCRIPTIONS

Airtightness data was collected on 40 office buildings located in Canada (Ottawa), Great Britain and the United States. Age of the buildings at the time of the test ranged from brand-new to about 30 years, except for one British building whose vintage was described as "Elizabethan". Physically, they varied in height from two-storey structures to 25 storeys. Types of wall construction included: masonry, concrete panels, curtain walls and pre-fab assemblies. Building volumes, when reported, ranged from 1,951 m^3 to 203,000 m^3. Six of the Canadian office buildings were tested in the early-to-mid 1970's and then again in 1991, giving an elapsed time of 17 to 21 years. Five of these six were also retrofitted prior to the retrofit to reduce air leakage, and both pre- and post-retrofit data was available.

4.2 TEST METHODS

Two types of test methods were used for the office building tests. In about one-third of the cases, depressurization tests were performed on the entire structure using high-capacity, trailer-mounted exhaust fans. Another one-third were tested using the building's own mechanical system to provide the necessary depressurization. In the remaining third of cases, the test method was not reported. In about two-thirds of the cases, the airtightness data was reported on the basis of total envelope area while in the remaining instances, the above-grade area was used to normalize the data. In these latter cases, the data was reported at a pressure differential of 25 Pa but was corrected for this report to the 75 Pa reference condition using a flow exponent of 0.65.

4.3 AIRTIGHTNESS DATA

The airtightness data for office buildings is summarized in Table 4 and Figure 2.

4.3.1 Canada

The Canadian office buildings consisted of eight buildings tested by NRC in the period 1971 to 1974 when the average age of the buildings was two years. Overall, the mean NLR_{75} for the Canadian office buildings was 2.48 l/s•m^2, which was significantly lower than those of the American or British counterparts; however, in all cases, the sample sizes were relatively small. All of the Canadian data was for buildings in Ottawa, whereas the American and British data was more broadly distributed geographically.

4.3.2 United States

The American office buildings displayed a mean NLR_{75}, 5.91 l/s•m^2, which was almost three times that of the Canadian structures. The variation, as expressed by the standard deviation, was over ten times greater than that of the Canadian results, although this was skewed by one of the seven buildings which was significantly leakier than any of the others. If this building is removed from the sample, the mean NLR_{75} decreased to 2.64 l/s•m^2, essentially the same as that of the Canadian structures.

4.3.3 Great Britain

Building data was reported in both Type 1 and 2 formats. The Type 1 buildings were leakier than those in Canada or the United States, with a mean NLR_{75} of 7.55 l/s•m^2 and a standard deviation of 3.51 l/s•m^2. The Type 2 buildings,which consisted of 13 structures, had a slightly smaller NLR_{75} of 6.67 $l/s{\bullet}m^2$ with a standard deviation of 3.48 $l/s{\bullet}m^2$. If the two types had displayed the same airtightness characteristics, slightly larger values would have been expected for the Type 2 buildings because the area used in the calculation was only a portion of the total envelope area. The fact that the opposite occurred likely reflects the limited sample sizes available.

Table 4
Summary of Airtightness Data - Office Buildings

Country	Number of Buildings	NLR_{75} ($l/s{\bullet}m^2$)			Area Used In NLR_{75}
		Mean	Range	Std. Dev.	
Canada Type 1 Data	8	2.48	1.44 to 4.01	0.72	Total envelope
United States Type 2 Data	7	5.91	1.05 to 25.52	8.08	Total envelope
Great Britain					
Type 1 Data	12	7.55	3.59 to 13.59	3.51	Total envelope
Type 2 Data	13	6.67	3.00 to 13.75	3.48	Above-grade

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

4.4 IMPACT OF WALL TYPE

The airtightness data for the office buildings, analysed on the basis of wall type, is shown in Table 5. Where pre- and post-retrofit data was available for a building, only the pre-retrofit data was used for the wall type analysis. The data shown is for the Canadian and British data; wall type information was not available for the American buildings.

For the Type 1 buildings, the tightest structures were those which used curtain wall construction. The leakiest were the masonry structures which displayed a mean NLR_{75} value two to three times greater than any of the other wall systems. Conversely, for the Type 2 buildings, those which used concrete panels were the most leaky, although the variation was not as pronounced as occurred with the Type 1 buildings.

4.5 IMPACT OF AIR LEAKAGE SEALING

Five of the six Canadian office buildings which were re-tested received some form of retrofit. This ranged from partial retrofits of a few floors in which new insulation was applied, to recaulking of windows and structural elements, to the application of new curtain wall cladding. For these five buildings, the mean reduction in the NLR_{75} value was 24% with a range of 4% to 42%. Note that this is almost twice the reduction reported for the MURBs which had received some form of sealing. Interestingly, the one building which was not retrofitted experienced an increase in its NLR_{75} of 18% over a period of 20 years.

Fig. 2 Office Buildings

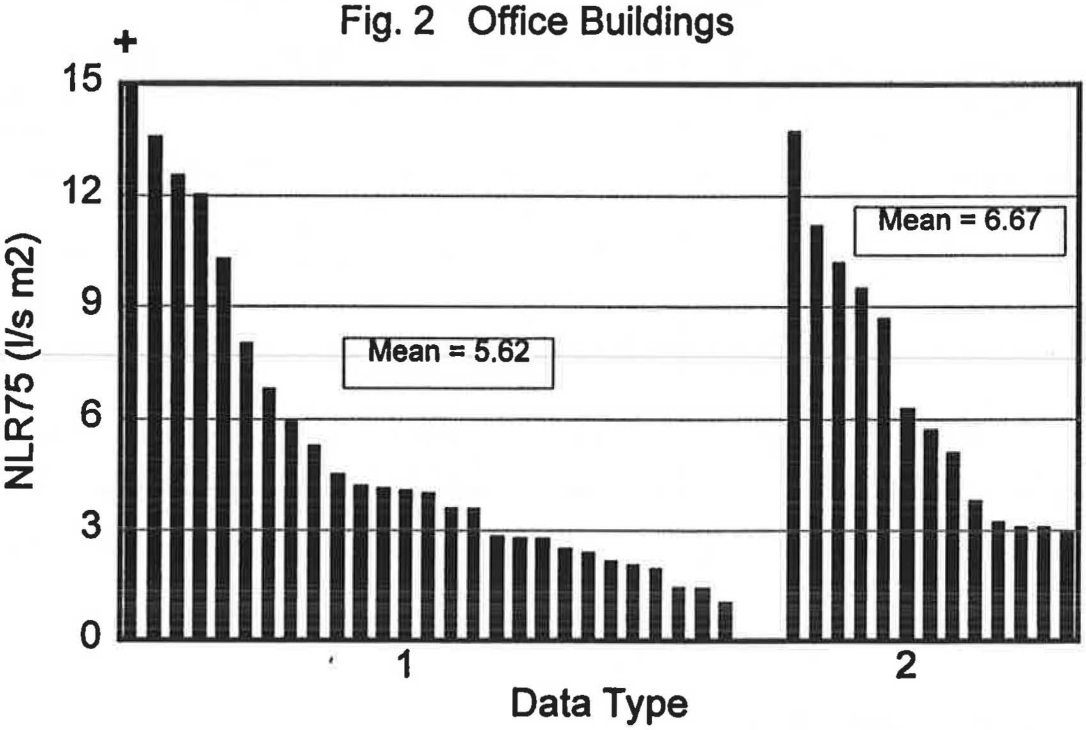


Table 5
Impact of Wall Type - Office Buildings

Data Type	Number of Buildings	Mean NLR_{75} (l/s•m^2)
Type 1 Data		
Masonry	9	8.62
Concrete panels	6	3.14
Curtain walls	4	2.60
Pre-fab	1	3.59
Type 2 Data		
Masonry	3	5.41
Concrete panels	8	7.98
Steel frame	1	5.72

4.6 FLOW EXPONENTS

Flow exponent data was reported for 22 of the U.S. and British buildings (no Canadian data was found). The mean n-value was 0.64 although this included one U.S building which claimed an n value of 2.04. When it was excluded, the mean value dropped to 0.57, with almost identical results reported for the two countries.

SECTION 5
AIRTIGHTNESS DATA: SCHOOLS

5.1 BUILDING DESCRIPTIONS

Airtightness data was collected on 25 schools located in Canada (Ottawa) and the United States. The age of the Canadian schools at the time of the test ranged from about three to 28 years with an average of 12 years. Physically, they were all single-storey, masonry structures. Age, height and wall data was not available for the American buildings. Building volumes for the entire sample of schools, ranged from 2,000 m^3 to 67,000 m^3, with an average of 14,547 m^3. Four of the Canadian schools were re-tested in 1980 after retrofits had been completed to reduce air leakage.

5.2 TEST METHODS

Airtightness tests on the Canadian schools were performed using the NRC high-capacity, trailer-mounted exhaust fan. The American tests were conducted either using portable blower doors (usually several), the building's mechanical system or a combination of the two. All of the data was reported on the basis of total envelope area, or was corrected to this reference point.

5.3 AIRTIGHTNESS DATA

The airtightness data for the schools are summarized in Table 6 and Figure 3.

Table 6
Summary of Airtightness Data - Schools

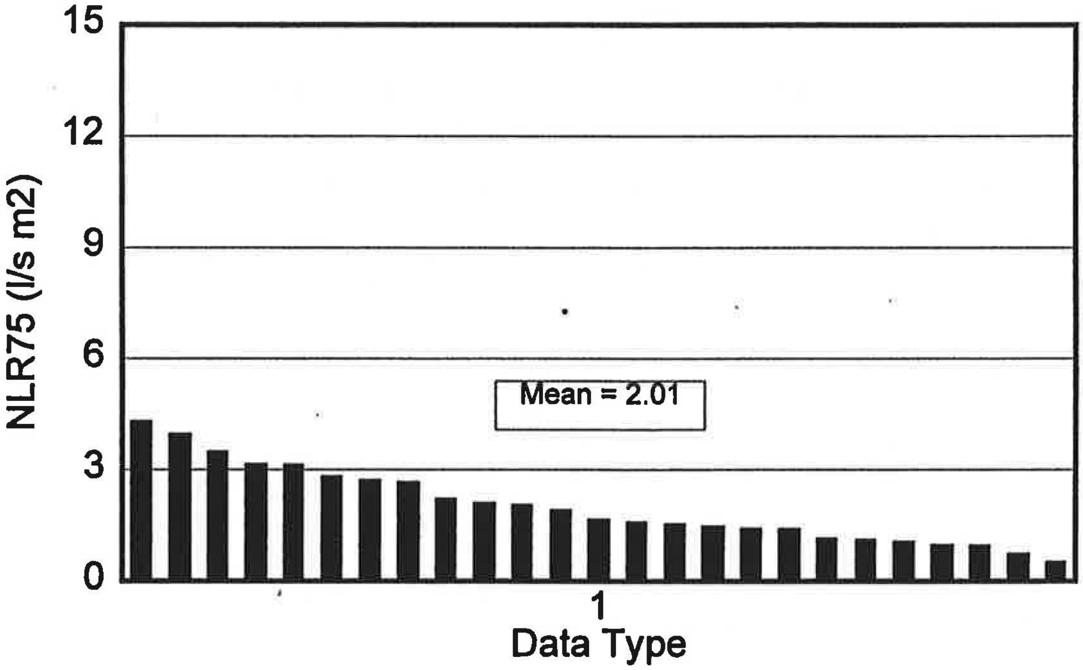
Country	Number of Buildings	NLR_{75} (l/s•m^2)			Area Used In NLR_{75}
		Mean	Range	Std. Dev.	
Canada Type 1 Data	11	1.48	0.74 to 2.11	0.38	Total envelope
United States Type 2 Data	14	2.44	0.53 to 4.33	1.15	Total envelope

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

5.3.1 Canada

Overall, the mean NLR_{75} for the Canadian schools was 1.48 l/s•m^2, which was significantly lower than that of the American buildings, however, in all cases the sample sizes were relatively small. All of the Canadian data was from buildings in Ottawa, whereas the American and British data was more broadly distributed geographically. Pre-retrofit data is used in Table 6 for the four schools which were retrofitted.

Fig. 3 Schools



5.3.2 United States

The American schools displayed a mean NLR_{75}, 2.44 $l/s \cdot m^2$, which was almost double that of the Canadian buildings. The variation, as expressed by the standard deviation, was also considerably larger than that experienced in Canada.

5.4 IMPACT OF WALL TYPE

Wall type data was available for roughly one-half of the buildings. As shown in Table 7, all of these reported masonry construction.

Table 7
Impact of Wall Type - Schools

Data Type	Number of Buildings	Mean NLR_{75} ($l/s \cdot m^2$)
Type 1 Data Masonry	12	1.62

5.5 IMPACT OF AIR LEAKAGE SEALING

Four of the Canadian schools received some form of retrofit. These consisted of a variety of measures including: the addition of rigid insulation to the walls, window and wall caulking, window replacement, the application of plaster to leaky masonry walls, and the repair or replacement of leaky dampers on the air-handling systems. For these four buildings, the mean reduction in the NLR_{75} value was 11% with a range of 3% to 23%. This is less than was achieved with either the MURBs or office buildings which had been retrofitted to reduce air leakage, although the initial leakage rates of the schools was also significantly lower than either of these two other types.

5.6 FLOW EXPONENTS

The mean flow exponent, which was reported for 14 of the U.S. schools, was 0.63.

SECTION 6
AIRTIGHTNESS DATA: COMMERCIAL BUILDINGS

6.1 BUILDING DESCRIPTIONS

Commercial buildings were considered to be those which are primarily devoted to mercantile activities (or equivalent) and which the public accesses on a regular basis. Airtightness data was obtained for 87 commercial buildings: 10 in Ottawa, eight in various locations in Saskatchewan, and 68 in Florida. The Canadian buildings included 10 supermarkets plus a variety of other types including: a post office, court house, library, radio station, etc. The age of the Canadian buildings at the time of the test ranged from brand-new to 70 years with an average of 19 years. Physically, they were all relatively low-rise structures (estimated at three storeys or less), constructed using masonry or concrete panels, although complete data was not available. Volumes ranged from 1,718 m^3 to 9,630 m^3 with a mean of 3,940 m^3.

The 68 American buildings included government buildings, libraries, small business offices, churches and hotels. While this is an impressive sample size, all of the buildings were located in one geographic area - Florida. They ranged in age from two to 65 years, with a mean of 21 years. Wall construction included: masonry, frame, metal, manufactured walls, or combinations of these. Building volumes ranged from 178 m^3 to 8,683 m^3, with an average of 1,819 m^3.

6.2 TEST METHODS

Airtightness tests on the Canadian commercial buildings were performed using the NRC high-capacity, trailer-mounted exhaust fan or portable blower doors. The American tests were all conducted using one or more portable blower doors. The Ottawa data was reported on the basis of exterior wall area while all the remaining data were reported on the basis of, or corrected to, total envelope area.

6.3 AIRTIGHTNESS DATA

The airtightness data for the commercial buildings is summarized in Table 8 and Figure 4.

6.3.1 Canada

The Type 1 and 2 buildings displayed dramatically different airtightness results, possibly the result of their age and method of construction. Those in Type 2 were built between 1955 and 1979 and were all supermarkets - a class of building which is often quite leaky. Their mean NLR_{75} was 13.95 l/s•m^2, which was significantly greater than the Type 1 buildings which had an average NLR_{75} of 1.35 l/s•m^2. In fact, one had an NLR_{75} of 0.23 l/s•m^2, one of the lowest airtightness values identified in the literature. This was a library built as part of the C-2000 Program. It should also be remembered that the Type 2 buildings were normalized on the basis of exterior wall area only. Since supermarkets tend to have large roof and floor areas (which often have very leaky intersections with the walls), the equivalent NLR_{75} values, normalized using total envelope area, would likely only be a fraction of the values shown in Table 8.

6.3.2 United States

The 68 American buildings displayed a mean NLR_{75}, 6.14 l/s•m^2, which was almost five times that of the Canadian buildings in Type 1, and about twice those in Type 2. The variation was also considerably larger than that of the Canadian Type 1 buildings.

Table 8
Summary of Airtightness Data - Commercial Buildings

Country	Number of Buildings	NLR_{75} (l/s•m^2)			Area Used In NLR_{75}
		Mean	Range	Std. Dev.	
Canada					
Type 1 Data	8	1.35	0.23 to 2.14	0.59	Total envelope
Type 2 Data	10	13.95	5.80 to 20.40	5.04	Exterior walls
United States					
Type 1 Data	68	6.18	0.73 to 24.56	4.42	Total envelope

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

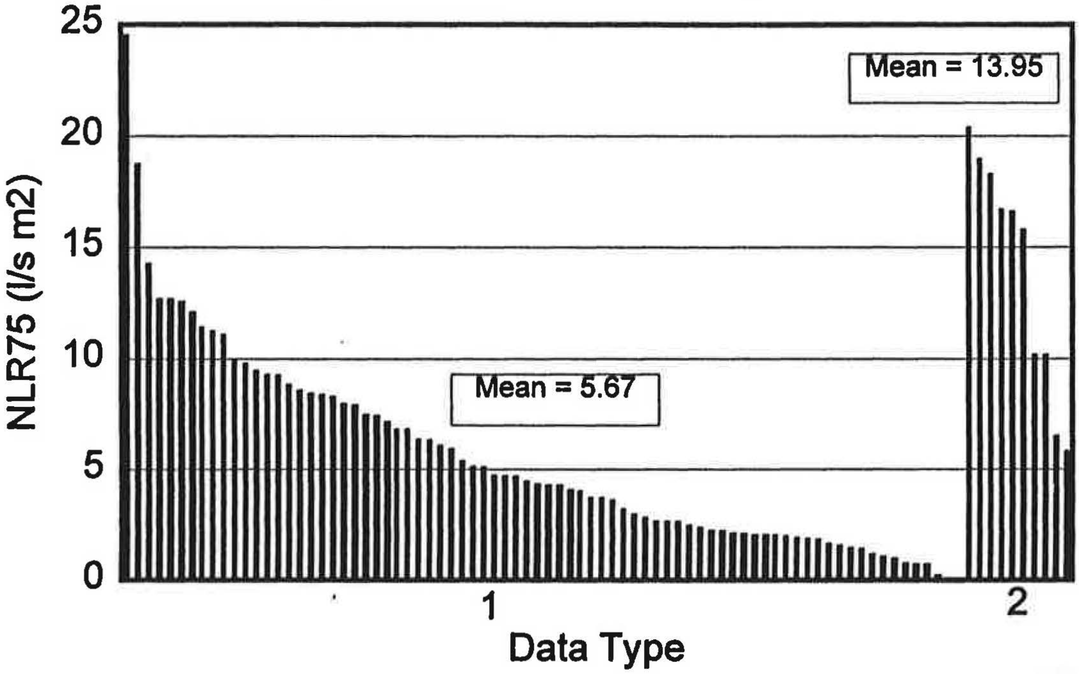
6.4 IMPACT OF WALL TYPE

The impact of wall type on the commercial buildings is summarized in Table 9. Once again, considerable variation was observed among the various wall types. Type 1 buildings constructed with masonry, manufactured buildings and metal structures displayed NLR_{75} values about one-half those of the masonry/frame and frame buildings. For the Type 2 data, the masonry and concrete panel buildings were both quite leaky.

Table 9
Impact of Wall Type - Commercial Buildings

Data Type	Number of Buildings	Mean NLR_{75} (l/s•m^2)
Type 1 Data		
Masonry	37	4.34
Masonry/frame	15	9.87
Frame	7	9.84
Manufactured	5	4.16
Metal	4	4.86
Type 2 Data		
Masonry	8	13.18
Concrete panels	2	17.05

Fig. 4 Commercial Buildings



6.5 FLOW EXPONENTS

The Canadian buildings in Type 1 and the American buildings had very similar mean flow exponents - 0.62 and 0.61, respectively. Flow exponent data was not reported for the Canadian Type 2 buildings.

SECTION 7
AIRTIGHTNESS DATA: INDUSTRIAL BUILDINGS

7.1 BUILDING DESCRIPTIONS

Airtightness data was found for 16 industrial buildings in Great Britain and Sweden; some limited information was also identified on a few French buildings, however, the data was not expressed in a compatible format so they were not included in this report. No data on Canadian buildings was identified. Three of the British buildings received repeat tests after they were retrofitted to reduce air leakage. Data on their age and physical construction was very limited; where available, their construction was described as using concrete elements, steel framing or steel cladding. Volumetric data was available for about one-half of the buildings, which ranged from 4,690 m^3 to 61,127 m^3 with a mean of 20,613 m^3.

7.2 TEST METHODS

In about one-half of the cases, information was provided on the method used to perform the airtightness tests; in all cases these were performed using large capacity exhaust fans.

7.3 AIRTIGHTNESS DATA

The airtightness data for the industrial buildings is summarized in Table 10 and Figure 5.

Table 10
Summary of Airtightness Data - Industrial Buildings

Country	Number of Buildings	NLR_{75} (l/s•m^2)			Area Used In NLR_{75}
		Mean	Range	Std. Dev.	
Great Britain					
Type 1 Data	5	6.95	5.34 to 9.37	1.78	Total envelope
Type 2 Data	2	22.52	21.94 to 23.11	0.59	Above-grade
Sweden					
Type 2 Data	9	1.45	0.72 to 2.78	0.62	Exterior walls and roof

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

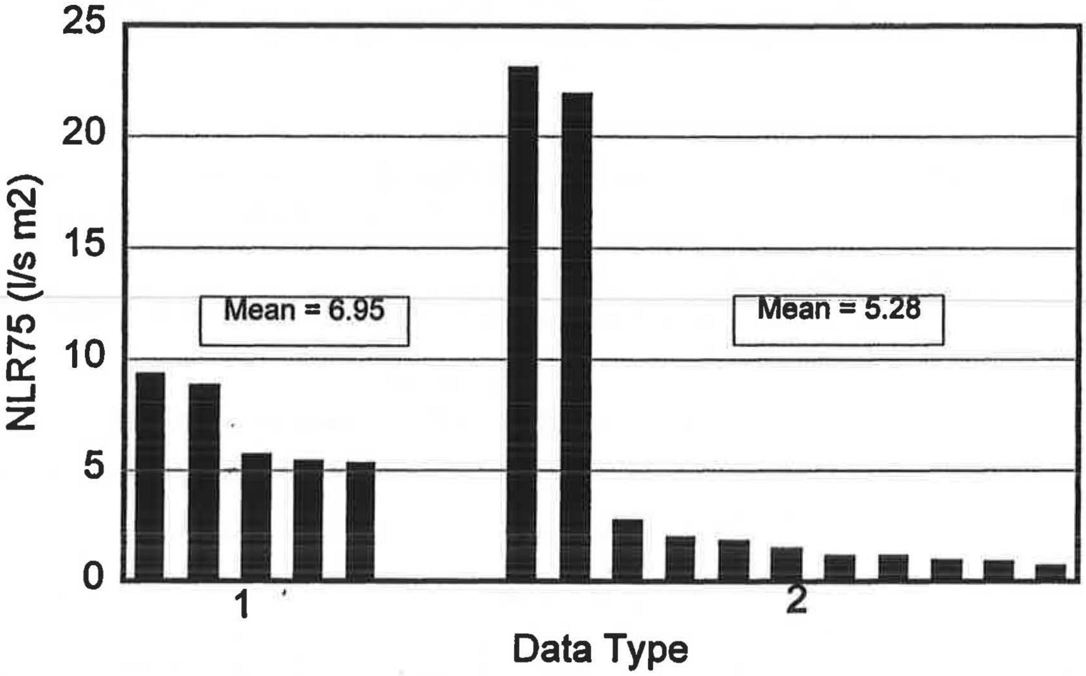
7.3.1 Great Britain

The mean NLR_{75} for the British industrial buildings was quite large, although the Type 2 data was based on above-grade area only. Given the geometric shape of most industrial buildings, it is probable that this value would be reduced somewhat if it were converted to the Type 1 format.

7.3.2 Sweden

The Swedish NLR_{75} data suggested much tighter construction, averaging less than one-quarter of those from Great Britain, which may reflect Sweden's concern with airtightness.

Fig. 5 Industrial Buildings



7.4 IMPACT OF WALL TYPE

The impact of wall type is shown in Table 11. When pre- and post-retrofit data was available, only the former was used in the wall type analysis.

Table 11
Impact of Wall Type - Industrial Buildings

Data Type	Number of Buildings	Mean NLR_{75} ($l/s \cdot m^2$)
Type 1 Data Steel cladding	3	5.51
Type 2 Data		
Concrete elements	6	1.57
Steel frame	3	1.22

7.5 IMPACT OF AIR LEAKAGE SEALING

The three British buildings which were retrofitted to reduce air leakage experienced a mean reduction in their NLR_{75} values of 16%.

7.6 FLOW EXPONENTS

Only two of the buildings (both British) had flow exponent data reported, and their mean value was 0.58.

SECTION 8
AIRTIGHTNESS DATA: INSTITUTIONAL BUILDINGS

8.1 BUILDING DESCRIPTIONS

A very limited amount of data was identified for two institutional buildings, both indoor swimming pools located in Winnipeg, one of which had received an extensive retrofit to its exterior walls to correct serious building envelope problems. Both pre- and post-retrofit tests were performed on this structure. The two buildings were 21 to 30 years in age at the time of the tests and both were built using masonry construction with steel framing. Their volumes were 2,728 m^3 and 6,853 m^3 respectively.

8.2 TEST METHODS

Both buildings were physically connected to other structures (which were not of interest from an airtightness perspective), so a new test method was developed and used to isolate the exterior envelope leakage of swimming pools themselves (see section on Airtightness Test Methods).

8.3 AIRTIGHTNESS DATA

The airtightness data for the institutional buildings are shown in Table 12.

Table 12
Summary of Airtightness Data - Institutional Buildings

Country	Number of Buildings	NLR_{75} (l/s•m^2)			Area Used In NLR_{75}
		Mean	Range	Std. Dev.	
Canada Type 1 Data	2	0.86	0.55 to 1.16	0.30	Total envelope

Type 1 Data - Test performed on whole building; total envelope area used to calculate NLR_{75}.
Type 2 Data - Test performed on whole building; alternate area used to calculate NLR_{75}.
Type 3 Data - Test performed on individual floors or suites; exterior wall area of floors or suites used to calculate NLR_{75}.

8.3.1 Canada

The data in Table 12 show the pre-retrofit data only. The mean NLR_{75} was 0.86 l/s•m^2 with a standard deviation of 0.30 l/s•m^2. Although these values are very low relative to most other buildings described in this report, high indoor relative humidity levels had resulted in significant envelope damage after only two to three decades of use. This demonstrates the importance of considering the interior relative humidity, as well as requirements for occupant comfort, energy efficiency, etc., when defining a building's airtightness requirements.

8.4 IMPACT OF WALL TYPE

The impact of wall type is shown in Table 13.

Table 13
Impact of Wall Type - Institutional Buildings

Data Type	Number of Buildings	Mean NLR_{75} ($l/s \cdot m^2$)
Type 1 Data Masonry	2	0.86

8.5 IMPACT OF AIR LEAKAGE SEALING

In early 2000, the first of the two buildings underwent an extensive retrofit to its exterior wall system, which effectively resulted in stripping the existing walls down to the structural steel framing. A new masonry wall with a sandwiched membrane air barrier was installed and extensive efforts were taken to identify and seal any air leaks which existed. This resulted in the NLR_{75} decreasing from 0.55 $l/s \cdot m^2$ to 0.044 $l/s \cdot m^2$, a reduction of 92%! This was not only the tightest structure identified in the entire literature survey but also meant that the building met the recommended airtightness guidelines of the 1995 NBC Appendices (for high humidity environments) of 0.05 $l/s \cdot m^2$.

8.6 FLOW EXPONENTS

No data was reported.

SECTION 9
COMPARATIVE ANALYSIS OF AIRTIGHTNESS DATA

9.1 METHODS OF COMPARISON

To provide insight into the effect of different variables upon airtightness, a series of comparisons were carried out based on building type, wall type, building age, number of storeys, etc. In most cases, these comparisons were performed using only the Type 1 data since it allowed the most unambiguous comparisons.

9.2 IMPACT OF BUILDING TYPE

The total set of NLR_{75} data (i.e., Type 1, 2 and 3 Data), categorized on the basis of building type, is summarized in Table 14, while Figure 6 plots the same data for the Type 1 buildings only. These illustrate that there is little correlation between airtightness and building type; in fact, in almost all cases, significant variations appear among buildings within a given type. The only exception was the institutional buildings which had a sample size of just two.

Table 14
Impact of Building Type

Building Type (No. in Sample)	Mean NLR_{75} (l/s•m^2)		
	Type 1 Data	Type 2 Data	Type 3 Data
MURBs			
Canada (12)	3.19		
Canada (3)		4.00	
Canada (6)			3.23
Office Buildings			
Canada (8)	2.48		
U.S. (7)	5.91		
Great Britain (12)	7.55		
Great Britain (13)		6.67	
Schools			
Canada (11)	1.48		
U.S. (14)	2.44		
Commercial			
Canada (8)	1.35		
U.S. (68)	6.18		
Canada (10)		13.95	
Industrial			
Great Britain (5)	6.95		
Great Britain (2)		22.52	
Sweden (9)		1.45	
Institutional			
Canada (2)	0.86		

9.3 IMPACT OF WALL TYPE

The airtightness data for the Type 1 buildings was compared on the basis of the dominant wall type used in the structure and as described in the literature. In many cases, the wall types reported were not very descriptive, so it is difficult to draw firm conclusions about the precise impact of wall type. In addition, leakage through other portions of the envelope (such as floor, roofs, windows, etc.) are included in the overall airtightness data. Nonetheless, the comparison, which is summarized in Table 15 and Figure 7, showed a wide variation in NLR_{75} values among the different wall systems reported. Had more information been available, it is likely that the number of wall types could have been consolidated.

The three leakiest types were those reported as: frame (believed to be steel), steel frame/masonry and steel cladding, respectively. The three tightest types reported were: brick veneer/steel stud, curtain walls and wood frame construction. Interestingly, the mean NLR_{75} for the leakiest type (frame) was over four times that of the tightest (brick veneer/steel stud).

Table 15
Impact of Wall Type (Type 1 Buildings Only)

Wall Type (Description as provided by original authors)	Number	Mean NLR_{75} (l/s•m^2)			
		Mean	Standard Deviation	Minimum	Maximum
Frame (A)	7	9.84	4.89	3.62	18.77
Masonry/frame (B)	23	9.63	4.40	2.12	24.56
Steel cladding (C)	3	5.51	0.16	5.34	5.73
Metal (D)	4	4.86	2.53	2.23	8.85
Manufactured (E)	5	4.66	2.64	2.39	9.30
Pre-fab (F)	1	3.59	0.00	3.59	3.59
Masonry (G)	53	3.53	2.72	0.55	11.43
Concrete panel (H)	6	3.14	1.15	2.08	5.30
Wood frame (I)	7	3.03	0.64	1.85	3.60
Curtain wall (J)	4	2.60	1.02	1.44	4.14
Brick veneer/steel stud (K)	3	2.28	0.92	1.18	3.43
Mean	116	4.79	1.92	2.40	8.97

9.4 IMPACT OF BUILDING AGE

Figure 8 shows the variation in NLR_{75} for the Type 1 buildings based on the age of the structure at the time of the airtightness test. Where multiple tests were performed, the data for only the first test was considered. Surprisingly, some structures with very low leakage rates

Fig. 6 Impact Of Building Type
(Type 1 Data Only)

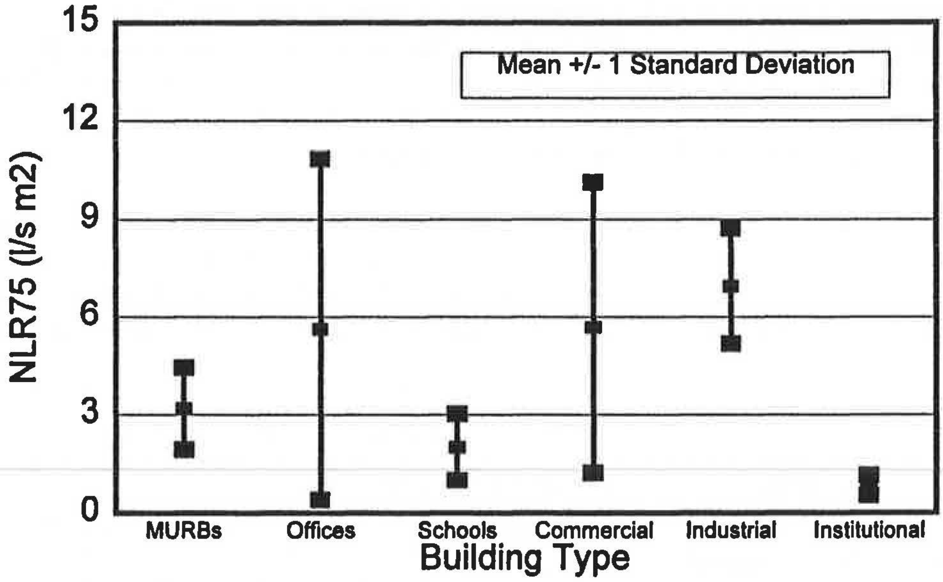
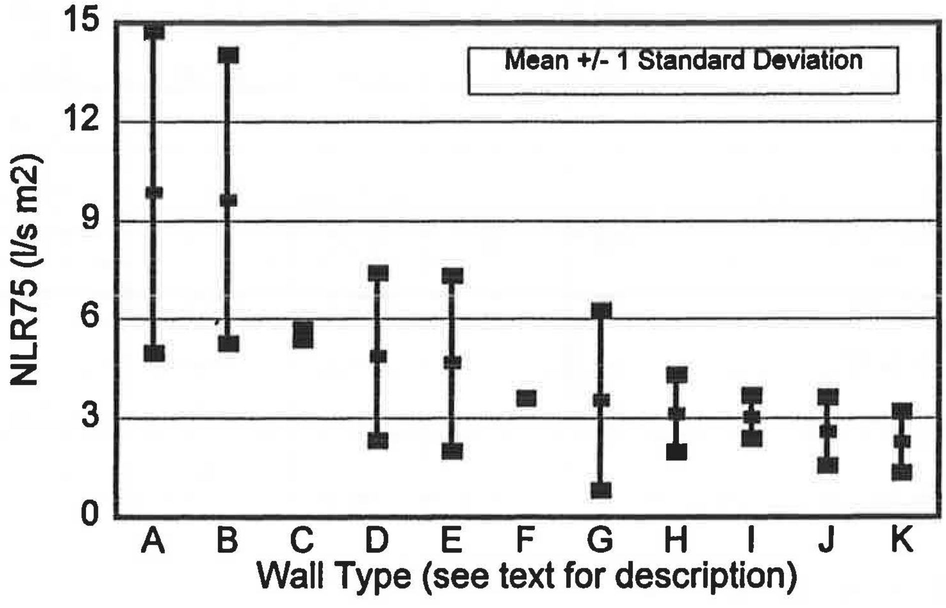


Fig. 7 Impact Of Wall Type
(Type 1 Data Only)



were several decades old. Conversely, many constructed within the last five to ten years displayed very high air leakage rates. These data demonstrate the absence of correlation between airtightness and building age.

9.5 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. Figure 9 shows the impact on airtightness of the year in which the building was constructed. Where multiple tests were performed, only the original test was included. It appears that the year of construction had no significant influence on airtightness. One might have expected to see lower NLR_{75} values commencing in the 1980's as the effect of rising energy costs began to be felt. However, this does not appear to be the case. The three buildings constructed within the last few years, i.e., 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. Two were MURBs and one was a commercial structure. Although the sample size is small, this demonstrates the beneficial impact of adopting and implementing measures to control air leakage.

9.6 IMPACT OF NUMBER OF STOREYS

Figure 10 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 often used. However, the sample size for multi-storey buildings is limited so it is difficult to draw firm conclusions.

9.7 IMPACT OF COUNTRY

The country of origin illustrates local construction practices as well as the influence of building codes which might influence airtightness. Figure 11 compares the NLR_{75} data for the Type 1 buildings in the database 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 commercial buildings from 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.

9.8 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 of the structures were Type 1 buildings and the types consisted of MURBs, office buildings, schools, industrial and institutional buildings.

The impact of air leakage sealing is summarized in Table 16. Reductions in the NLR_{75} values ranged from 3% to 92% (although the latter retrofit consisted of virtually rebuilding the entire exterior wall assembly), with an average reduction of 22%.

Table 16
Impact of Air Leakage Sealing (Type 1 Buildings Only)

Building Type	Number	Mean Reduction in NLR_{75} (l/s•m^2)			
		Mean	Standard Deviation	Minimum	Maximum
MURBs	3	15%	8%	7%	23%
Offices	5	24%	14%	4%	42%
Schools	4	11%	9%	3%	23%
Industrial	3	16%	14%	7%	32%
Institutional	1	92%	n/a	92%	92%
Mean	16	22%	22%	3%	92%

9.9 COMMENTARY

The preceding analysis has demonstrated that building type, wall construction or building age cannot be used - at least in isolation - to predict envelope airtightness in large buildings. Year of construction had no significant influence until 1995 was reached and the influence of the 1995 NBC was demonstrated, provided air leakage control measures were explicitly part of the design objectives. Country of origin appeared to have some influence of the data.

Fig. 8 Impact Of Building Age
(Type 1 Data Only)

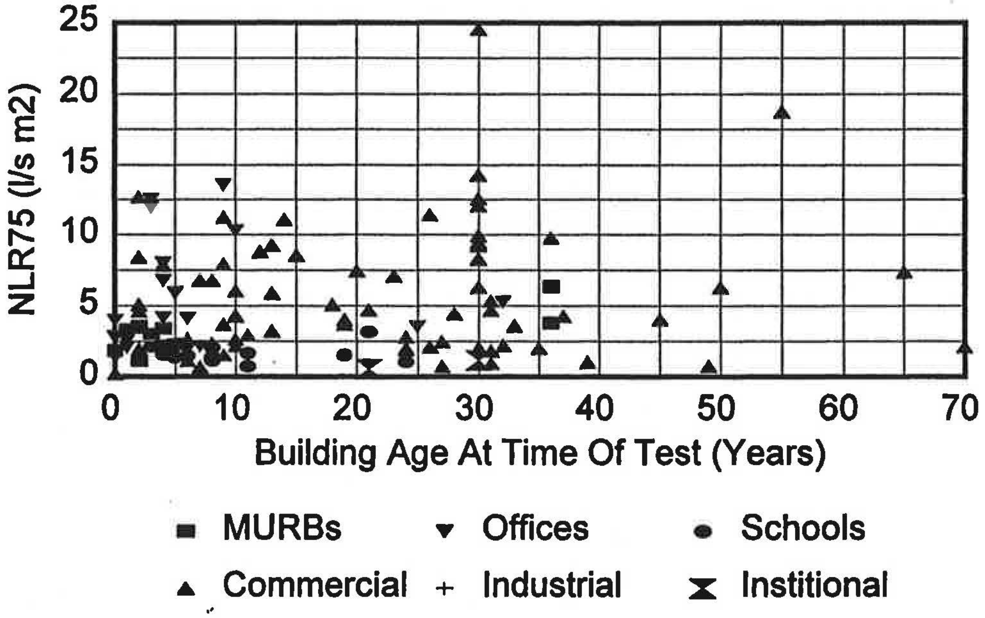


Fig. 9 Year of Construction
(Type 1 Data Only)

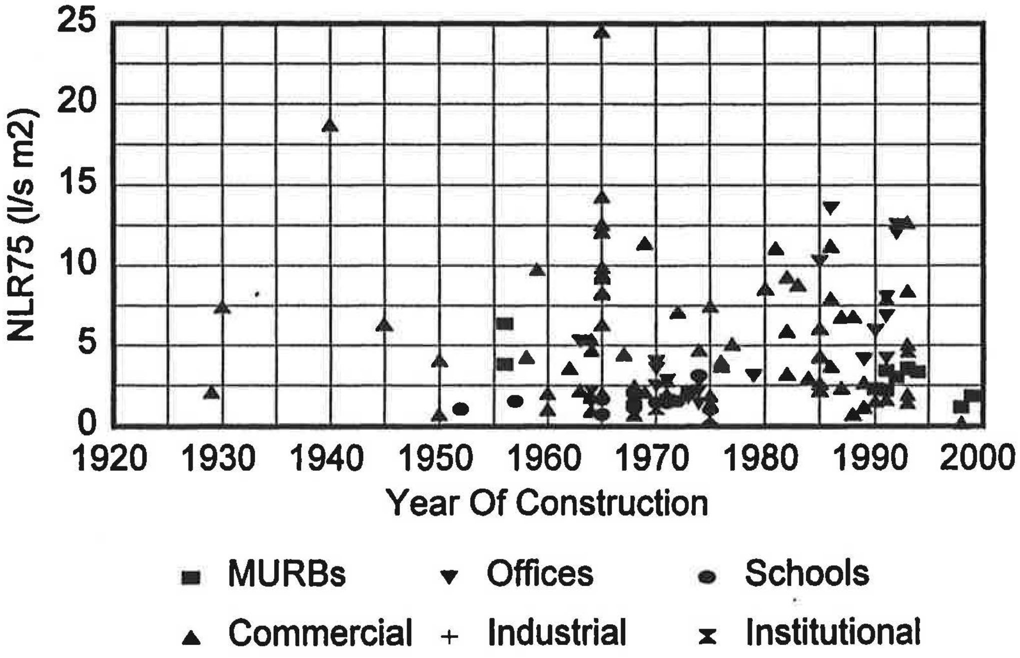


Fig. 10 Impact Of Building Height
(Type 1 Data Only)

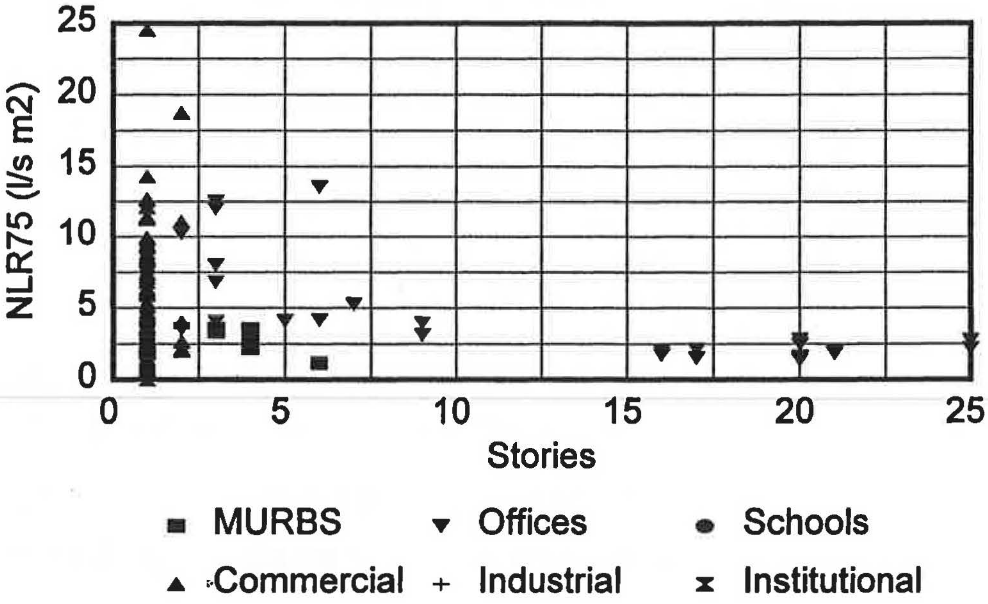
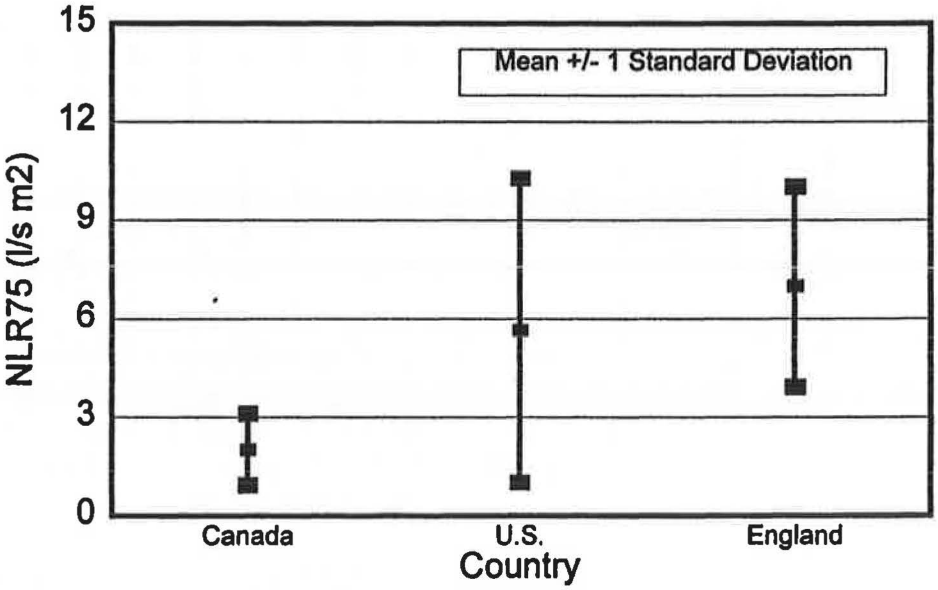


Fig. 11 Impact Of Country
(Type 1 Data Only)



SECTION 10
AIRTIGHTNESS TEST METHODS

10.1 INTRODUCTION

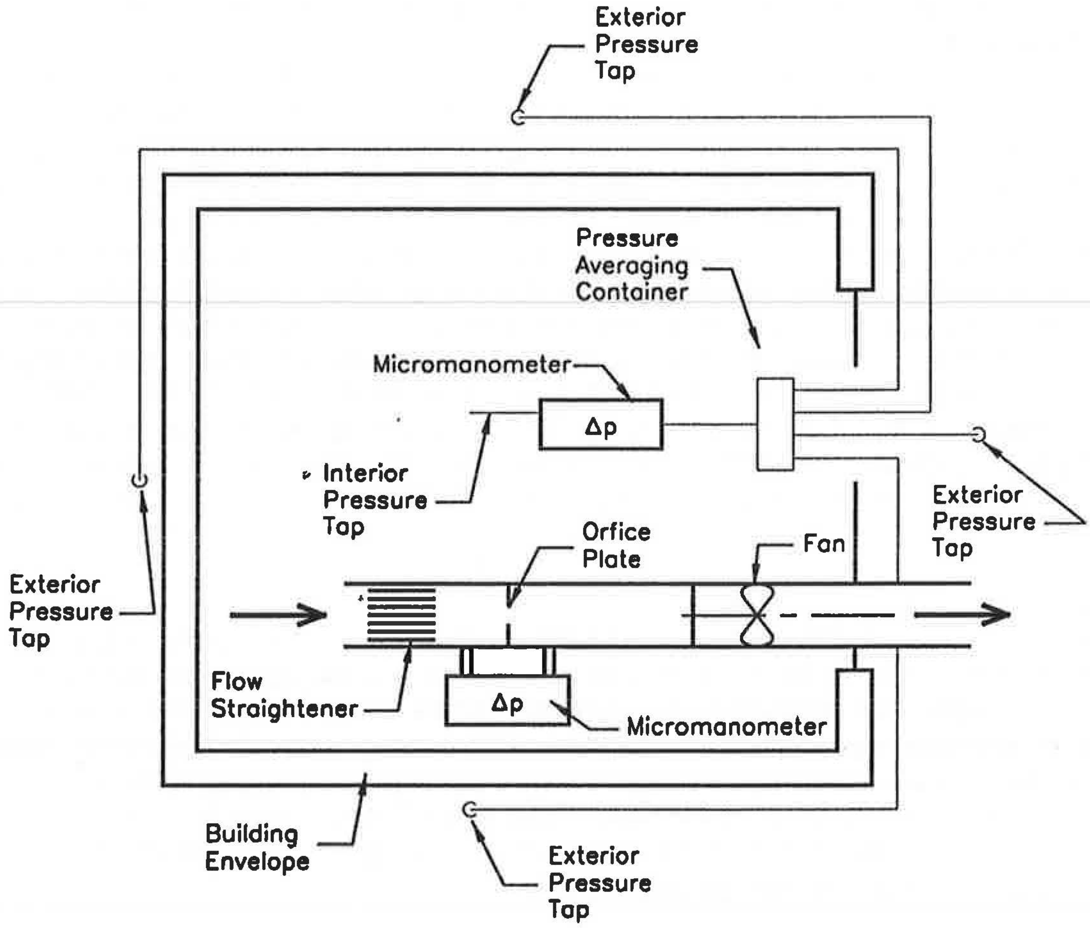
This section describes the various existing and proposed test methods for quantitative and qualitative airtightness testing of large buildings. It also reviews some test procedures used for airtightness testing of building components.

10.2 WHOLE-BUILDING AIRTIGHTNESS TEST METHODS

10.2.1 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. 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 Figure 12, 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 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 expressed 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. 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.



CGSB 149.10 TEST SET-UP
FIGURE 12

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

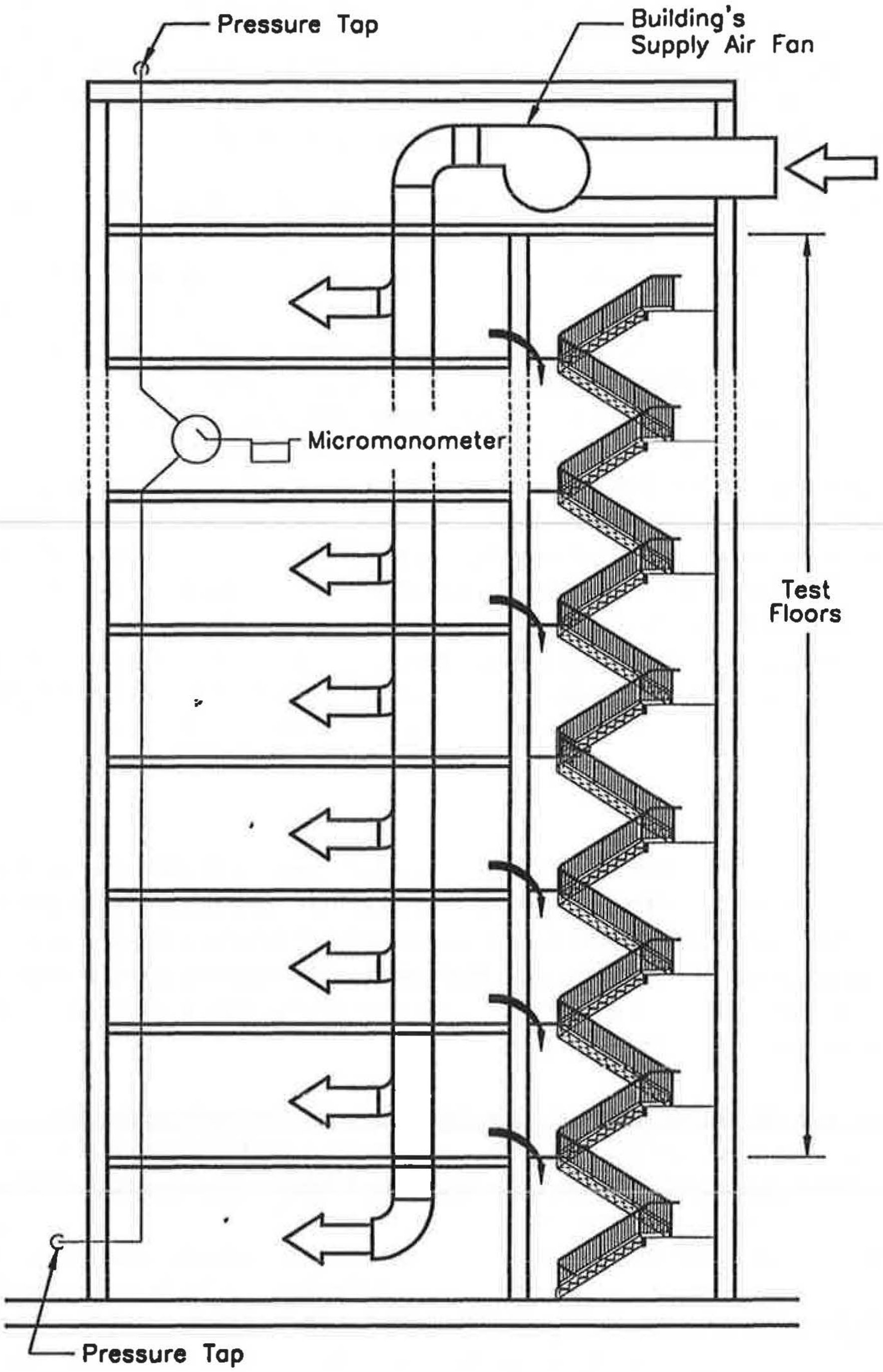
Published in 1996 by the Canadian General Standards Board, this standard describes a test method for determining the airtightness of the building envelope using the building's existing mechanical system to provide the required depressurization. It was written specifically for larger buildings which cannot be tested using CGSB 149.10 because most portable equipment does not have sufficient exhaust capacity to depressurize the building.

As shown in Figure 13, 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, 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) can be calculated. Results are normally expressed at pressure differentials of 10 Pa, 50 Pa and 75 Pa. Bahnfleth et al investigated the uncertainty associated with this test method (1999) and proposed guidelines for improving the precision of the test. These included: establishing the minimum and maximum pressure differentials used in the test to 12.5 Pa and 75 Pa respectively; 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 in accordance with 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.

10.2.3 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. The major differences are that ASTM 779: permits either a pressurization or depressurization test to be performed (which generally produces slightly different airtightness 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.



CGSB 149.15 TEST SET-UP
FIGURE 13

10.2.4 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 (the most common type). It 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) equal to 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.

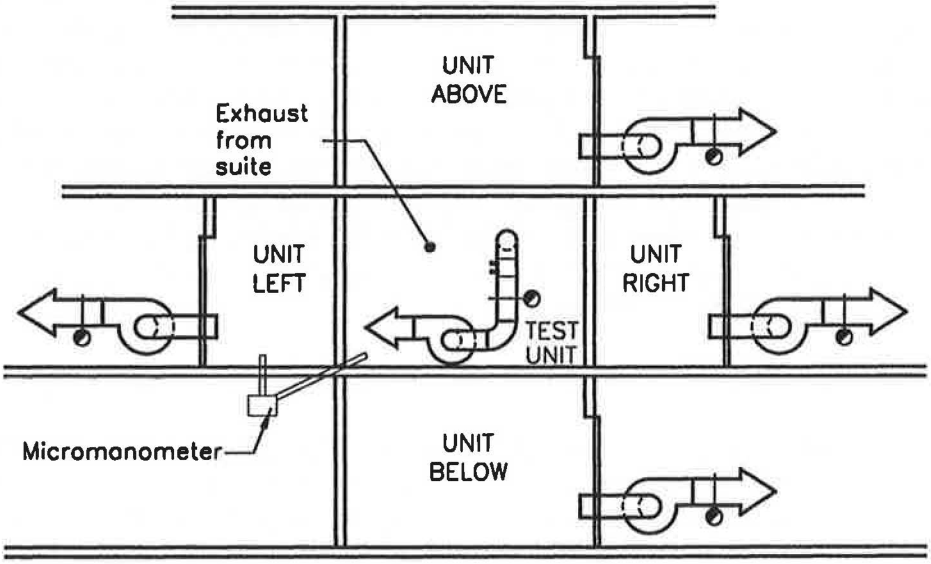
10.2.5 ISO 9972, *Thermal Insulation - Determination of Building Airtightness - Fan Pressurization Method*

Published by the International Standards Organization in 1996, this test method is primarily used in Europe and other parts of the world. 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).

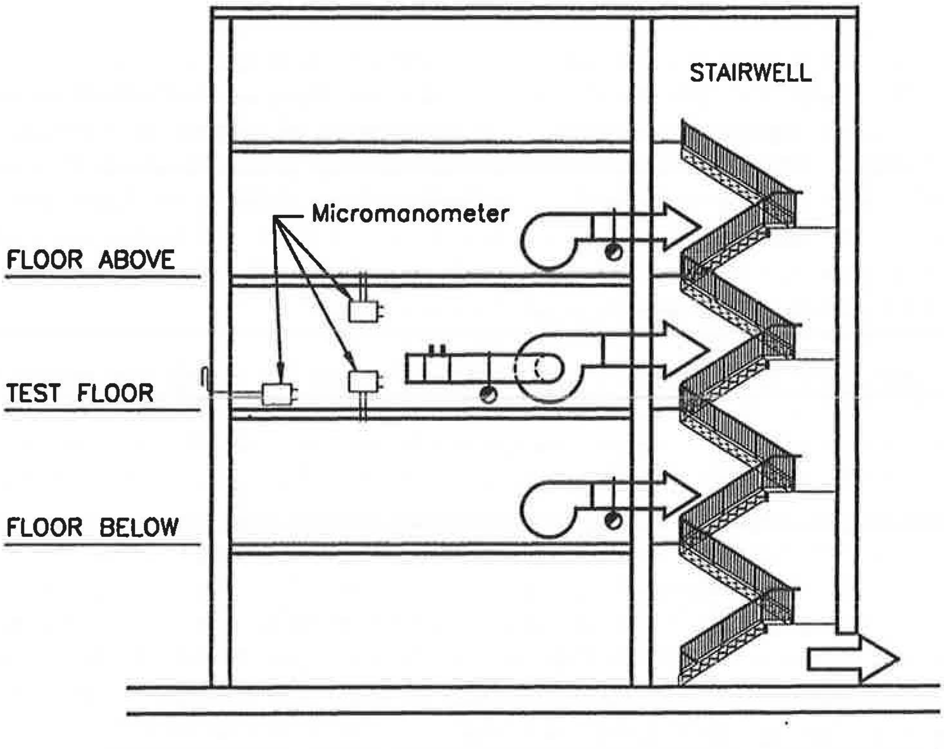
10.2.6 Balanced Fan Depressurization Technique

A situation which commonly arises with large buildings is that several of them 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. Conversely, it is sometimes of interest to determine the exterior envelope leakage of one zone within a multi-zone building, such as a single floor in a multi-storey MURB. Using one of the preceding test methods, for example, to depressurize the single floor of interest would result in both interior and exterior air being exhausted and measured by the flow measuring device. Interior leakage cannot be assumed to be trivial; experience has shown that it often exceeds air leakage through the exterior envelope.

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 was depressurized relative to ambient. The basic test configurations are shown in Figures 14 and 15, 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,



BALANCED FAN DEPRESSURIZATION TECHNIQUE USED TO TEST INDIVIDUAL SUITE
FIGURE 14



BALANCED FAN DEPRESSURIZATION TECHNIQUE USED TO TEST INDIVIDUAL FLOOR
FIGURE 15

this can require delicate adjustment and considerable patience. 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, including on several buildings referenced in this report. 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 section 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.

10.2.7 Multi-zone Test Procedure (Under Development)

This procedure, currently under development by the authors, is also intended to deal with the problem described above of determining the exterior envelope leakage of a single zone within a multi-zone structure. The major difference is that it does not require the pressure differential across the interior partition(s) to be maintained exactly at zero, but rather that it simply be modified from its original state. The "modified" condition can be created using a second blower, or by activation of the building's existing mechanical system. Its advantage over the balanced fan technique is that it does not require a large fan in applications where the leakage of the adjacent space is very large. The new technique has been successfully used on a handful of applications including two of the buildings described in this report.

10.2.8 Lstiburek (Under Development)

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 measure 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).

10.2.9 Nylund Technique

Nylund investigated the problems of determining the airtightness of the exterior envelope of a single zone within a multi-zone building. 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.

10.3 BUILDING COMPONENT TEST METHODS

10.3.1 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. 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.

10.3.2 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. 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 accurately 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.

10.4 QUALITATIVE TEST METHODS

The preceding test methods have all been quantitative procedures whose goal was 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 during construction.

10.4.1 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. 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 E 1186 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.

10.5 EQUIPMENT

10.5.1 High-capacity Blower Systems

Blower systems suitable for airtightness testing of most large buildings usually require a higher flow capacity than that of blower doors made for residential purposes. The NRC, trailer-mounted system, for example, has an air-flow capacity of about 23 m^3/s (50,000 ft^3/min). The NRC unit was hand-built specifically for NRC and was the only one constructed. It is currently stored in Ottawa. The connection to the building was made with 0.9 m (3') flexible ducting and a temporary plywood door plug.

A similar device was built by the (then) National Bureau of Standards in the United States in the 1980's. Their system was a 7.55 m^3/s (16,000 cfm) 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 straightener mounted approximately one fan diameter upstream from the fan.

In England, approximately five examples of the British Research Establishment's BREFAN system were produced. This is a smaller system than the NRC unit, with a capacity of 5.5 m^3/s (11,600 cfm) at 50 Pa, but operates using standard 220 V power supplies and is intended to be used 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" (BSRIA, 1998). This consists of a 30 m^3/s (63,500 cfm) fan mounted on a trailer which uses the rear power take-off of a Land Rover vehicle to power the fan, thus avoiding the need to access power on-site. It uses a built-in pitot tube assembly to measure flow rates as low as 3 m^3/s (6,350 cfm). Numerous large buildings have apparently been tested using this rig. In the 1980's, British Gas plc also developed a system which used a system with a 5.6 m^3/s (11,800 cfm) 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 cfm) at 50 Pa (Lilly, 1987). It is not known if these units are still in active use.

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/s (27,000 cfm) 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 l/s (30,000 cfm) and can be easily transported on a hand cart. They cost approximately $2,000 to $3,000. CMHC plans to evaluate one of these units in the near future on an actual building (Hill, 2001).

10.5.2 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 cfm to 5,300 cfm). 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.

10.5.3 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 one of the 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).

10.5.4 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 and have built-in pressure dampening capabilities. Micromanometers can also be used to produce an electrical signal output which can be sent 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 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.

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.

10.5.5 Smoke Wands and Puffers

Smoke wands and puffers are used as aids in identifying air leakage locations while the building is pressurized or depressurized. Canadian tests are normally 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.

10.5.6 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 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.

10.6 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 17 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 authors' 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.

Table 17
Typical Costs of Various Types of Airtightness Tests (2001)

Airtightness Test	Approximate Cost
Whole-building airtightness test to CGSB 149.10 of single-zone 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

10.7 FINAL COMMENTS

Airtightness testing and air leakage examination procedures, suitable for use on large buildings, exist and can be provided by a small, but growing, number of commercial firms located across the country. Costs are relatively affordable given the potential consequences of excessive air leakage, particularly in large buildings. Testing may also pose logistical problems with respect to conventional construction processes and create some ownership-occupancy-related complications.

Airtightness testing obviously has an important role to play in improving large building airtightness. However, it should be recognized that the real objective of testing is not to determine if the job was properly done, but to insure that it is properly done. Testing a completed building and discovering it fails to meet its airtightness target will often require expensive remedial efforts to correct the situation.

SECTION 11
AIRTIGHTNESS PERFORMANCE TARGETS, SPECIFICATIONS, QUALITY CONTROL AND COMMISSIONING PROCEDURES

11.1 PERFORMANCE TARGETS

Numerous quantitative and qualitative requirements, guidelines and recommendations are known to exist, nationally and internationally, on the subject of large building airtightness. Some of these are mandatory, such as the National Building Code, while others are purely voluntary. This section briefly reviews some of their main features.

11.2 CANADA

11.2.1 1995 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.

Requirements for airtightness of large buildings are covered under Part 5 "Environmental Separation" of the 1995 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 1995 NBC provides *recommendations* on the maximum desirable air leakage rates for the "air barrier system". These are summarized in Table 18; 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 18...

> "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).

Table 18
1995 NBC (Appendices) Recommended Maximum Air Leakage Rates for Air Barrier Systems

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

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 18, 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 is difficult to justify limits given the current level of knowledge and is known to depend on a number of factors.

11.2.2 1995 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 as "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 of 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 a requirement for testing.

11.2.3 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).

11.2.4 C-2000 Program

The C-2000 Program is a national, voluntary program delivered by Natural Resources Canada (NRCan) 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 was limited to office buildings, its program criteria were 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•m^2.

11.2.5 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).

11.2.6 R-2000 HOME Program

The R-2000 HOME Program is a national, voluntary program which is primarily focused 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). From an airtightness perspective, MURBs are currently treated as detached houses with the R-2000 Program. 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 Program's technical requirements for 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.

11.3 INTERNATIONAL

11.3.1 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•m^2 for tight, average and leaky wall respectively. These values were taken from Tamura and Shaw (1976).

11.3.2 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 specifies 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•m^2 (ASHRAE, 1997)).

11.3.3 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 19. 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 report. Note also that total envelope area is believed to have been used for normalization purposes. The BSRIA recommendations are believed to be voluntary.

Table 19
BSRIA Airtightness Recommendations for New Buildings

	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 - Air-conditioned/low energy.	 2.78 1.39	 - 0.83	 3.62 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

11.3.4 CIBSE

In England, the Chartered Institution of Building Services Engineers recently issued a technical memoranda titled *Testing Buildings For Air Leakage, TM23:2000* which contains a series of airtightness recommendations. These were also expressed using a reference of 50 Pa and are summarized in Table 20 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.

11.3.5 Other International Airtightness Standards

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

Table 20

CIBSE Airtightness Recommendations for New Buildings

	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

11.4 SPECIFICATIONS

11.4.1 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). 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. 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.

11.4.2 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, 1997a). Basically, this document requires air barrier contractors to be certified under the NABA Professional Contractor Quality Assurance Program (discussed below) 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.

11.5 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).

11.5.1 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.

11.6 RATIONALE FOR AIRTIGHTNESS STANDARDS

The literature survey yielded few explicit explanations for the rationale behind the various standards described in this section. 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, primarily 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.

SECTION 12
RECOMMENDATIONS FOR IMPROVED AIRTIGHTNESS

12.1 THE CURRENT SITUATION

The importance of airtightness has been widely recognized by knowledgable practitioners for the last 20 years, yet is only now beginning to have an appreciable impact on the design and construction of large buildings. The results of the literature survey clearly showed that the airtightness of virtually all large buildings in Canada, and abroad, is significantly poorer than what is now regarded as appropriate. NLR_{75} values were typically 10 to 50 times those recommended by the 1995 National Building Code Appendices. Although the NBC recommendations only apply to the opaque portions of the air barrier system, the transparent (and other) parts of the envelope usually have low air leakage rates. In fact, only one building in the survey had an NLR_{75} value which was less than the recommended values in the 1995 NBC Appendices. This was a swimming pool which had undergone an extensive retrofit to reduce air leakage. Therefore, it is obvious that considerable improvements are required to improve the airtightness of large buildings. What can be done to expedite this change?

Before considering this question, it should be recognized that the technology now exists to construct a large building to a high level of airtightness - a fact exemplified by the swimming pool described above and by a few of the other buildings in the survey. Airtight design details have been developed and are widely available to the architectural and engineering communities, standards have been established which identify how tight the building (or portions of its envelope) should be, quantitative and qualitative testing methods have been prepared, and quality control systems are available to integrate the theory into the practical realm of the construction site. With the exception of an accepted and commonly-used performance standard (airtightness target), all the components needed to build tight now exist.

The experiences with single-detached housing also provide some useful insight into how the airtightness of large buildings could be improved. Basically, airtightness is not the accidental by-product of other variables, but rather, is the result of a conscious effort which: a) begins in the design stage; b) is implemented on the construction site; and c) is verified through inspections and testing, along with the appropriate feedback provided to contractors. Houses only achieved desired airtightness targets when all of these requirements were satisfied. There is no reason to believe the situation will be different for large structures, although it is more complicated for a number of reasons: the developer may not be the owner, there are larger numbers of trades involved, the designs are more complex, the speed of construction is very quick, the testing and examinations are more complicated, test scheduling is more difficult (to minimize disruption to the trades), testing is more expensive, the entire envelope may not become available for testing at the same time, the required testing contractors and associated equipment may not be available, etc.

12.2 RECOMMENDATIONS FOR IMPROVING THE AIRTIGHTNESS OF LARGE BUILDINGS

12.2.1 Establish Whole-building Airtightness Requirements

The current NBC (Appendices) recommendations for airtightness of opaque portions of the building envelope have only limited value and utility. Since they do not apply to the entire envelope, they cannot be easily evaluated using established testing protocols such as CGSB 149.10 or CGSB 149.15. Further, they are only recommendations - not mandatory requirements, and as such do not carry any weight unless the local building officials or designers choose to adopt them. This creates the situation in which the building code clearly identifies airtightness as an important performance parameter, yet does not specify how overall compliance can be demonstrated. Therefore, it is recommended that the NBC should be modified to establish clear, quantitative requirements for airtightness of large buildings. This may require re-evaluation of the current recommendations to account for air leakage through those portions of the envelope not currently considered. While the NBC airtightness recommendations for large buildings may appear extreme, the authors' experiences have shown that these requirements can usually be met by following the process described above.

In addition, other building standards should be modified to incorporate quantitative airtightness requirements which can be easily verified by testing. It is interesting to note that the cost of a whole-building test, assuming the structure is relatively airtight, is roughly the same as a window test conducted to ASTM E 783. Other standards which should be modified include the Model National Energy Code for Buildings, the Commercial Buildings Incentive Program and the C-2000 Program.

12.2.2 Investigate How the Current NBC Recommendations are Being Handled

The latest edition of the National Building Code was published in 1995 and was adopted by most jurisdictions in the following one to three years. Therefore, the Code has now been in use for three to five years. It would be worthwhile to investigate how various provincial, territorial and municipal authorities implement, and verify, the NBC airtightness requirements. For example, the City of Winnipeg has been actively working with the local design and construction communities to identify responsibilities with respect to airtightness, establish protocols for verifying compliance, and generally working to improve the performance of new buildings. Other jurisdictions may be engaged in similar activities. These should be documented to identify the most successful approaches. Such a study should also explore what building owners, both private and public, are expecting in regards to airtightness.

12.2.3 Establish and Maintain a Database on Large Building Airtightness

Another worthwhile activity would be to establish, maintain and regularly update a national database on large building airtightness. This would be valuable for identifying regional, national and international trends. The data collected as part of the current survey could be used as a starting point and new information added as it becomes available. The database could be used to assess the evolution of large building airtightness as the industry and consumer become more cognizant of its importance. Its geographic scope should probably be restricted to Canada, given the variations in construction styles and building codes which occur between countries. A very similar exercise was recently initiated, by Lawrence Berkeley National Laboratories in the United States, to compile data on the airtightness of houses and mechanical system ductwork (LBNL, 2000). It is worth noting that, in Canada, a number of national surveys of house airtightness have been conducted over the last 15 years which have not only yielded useful data from a research perspective but has also been invaluable for the development of building codes and standards.

12.2.4 Continue to Provide Industry Training Programs

Various public and private organizations provide training and education to the industry on the importance of large building airtightness and how to achieve it. These efforts are directed at all levels of the industry including: designers, contractors, trades, testing organizations, building officials and others. While they are primarily focused on new construction, some efforts have also been directed at retrofit applications, although a much greater effort is probably warranted. Retrofit procedures, costs and the effectiveness of these measures need greater exposure within the industry. Obviously, all of these training efforts should continue since they provide the primary mechanism for information dissemination and have been very successful in the past.

12.2.5 Establish Educational Activities for Building Owners and Property Managers

In addition, it would be extremely valuable for similar educational activities to be developed which are directed at owners and property managers since they are often the primary decision makers with respect to building operations. In practice, building owners probably wield their greatest influence on new construction since they are usually quite involved with the design and construction process. In contrast, property managers have the greatest influence on existing construction since they handle most of the day-to-day operational issues related to building operation, maintenance requirements, etc. Both owners and property managers are primarily interested in the business aspects of building ownership and operation, so educational efforts should be focused on the repercussions of excessive air leakage - higher maintenance costs (due to air leakage/moisture induced damage), higher operating costs (due to excessive energy use), tenant discomfort (which could affect occupancy rates) and potential liability ramifications resulting from personal injury.

12.2.6 Create a Demand for Airtightness

Fundamentally, all of the preceding activities should contribute to a demand for improved airtightness in both new and existing construction. In addition, any other activities which would spur owners, property managers to demand, and the industry to supply, airtightness should be actively pursued. For example, in new construction, owners would benefit from having access to estimates of the potential savings which airtightness would provide while illustrating the dangers of loose construction in terms of higher operating and maintenance costs.

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APPENDIX A

BUILDING DATA

I.D.	Author's Identification (if applicable)	Building Type	Location	Building Characteristics					Year Tested	Test Method	Test Class	C (l/s Pan)	n	NLR75 (l/s m2)		Alternate Area	Reference
				Volume (m3)	Envelope Area (m2)	Stories	Wall Construction	Year Built						Based on Total Envelope Area	Based on Alternate Area		
1	A	School	Canada (Ottawa)	11495			Masonry	1970	1976	1	A			1.49	8.3	Exterior walls	Shaw & Jones, 1979
2	B	School	Canada (Ottawa)	7361			Masonry	1971	1976	1	A			1.43	6.1	Exterior walls	Shaw & Jones, 1979
3	C	School	Canada (Ottawa)	12644			Masonry	1965	1976	1	A			1.67	8.4	Exterior walls	Shaw & Jones, 1979
4 (a)	D (pre-retrofit)	School	Canada (Ottawa)	13307			Masonry	1973	1976	1	A			2.11	11.3	Exterior walls	Shaw & Jones, 1979
4 (b)	D (post-retrofit)	School	Canada (Ottawa)	13307			Masonry	1973	1980	1	A			1.63	8.7	Exterior walls	Shaw, 1982
5 (a)	E (pre-retrofit)	School	Canada (Ottawa)	14054			Masonry	1957	1976	1	A			1.54	7.0	Exterior walls	Shaw & Jones, 1979
5 (b)	E (post-retrofit)	School	Canada (Ottawa)	14054			Masonry	1957	1980	1	A			1.45	6.6	Exterior walls	Shaw, 1982
6 (a)	F (pre-retrofit)	School	Canada (Ottawa)	11314			Masonry	1952	1976	1	A			1.06	6.3	Exterior walls	Shaw & Jones, 1979
6 (b)	F (post-retrofit)	School	Canada (Ottawa)	11314			Masonry	1952	1980	1	A			0.95	5.6	Exterior walls	Shaw, 1982
7	G	School	Canada (Ottawa)	19706			Masonry	1968	1976	1	A			1.16	7.5	Exterior walls	Shaw & Jones, 1979
8	H	School	Canada (Ottawa)	20427			Masonry	1965	1976	1	A			0.74	5.5	Exterior walls	Shaw & Jones, 1979
9	I	School	Canada (Ottawa)	9980			Masonry	1968	1976	1	A			2.06	10.8	Exterior walls	Shaw & Jones, 1979
10 (a)	J (pre-retrofit)	School	Canada (Ottawa)	11900			Masonry	1972	1976	1	A			1.59	8.6	Exterior walls	Shaw & Jones, 1979
10 (b)	J (post-retrofit)	School	Canada (Ottawa)	11900			Masonry	1972	1980	1	A			1.54	8.3	Exterior walls	Shaw, 1982
11	K	School	Canada (Ottawa)	12263			Masonry	1968	1976	1	A			1.41	6.4	Exterior walls	Shaw & Jones, 1979
12	BH	Commercial	Canada (Ottawa)				Masonry	1957	1979	1	B				10.2	Exterior walls	Shaw, 1981
13	CK	Commercial	Canada (Ottawa)				Masonry	1963/1978	1979	1	B				6.5	Exterior walls	Shaw, 1981
14	HC	Commercial	Canada (Ottawa)				Masonry	1978	1979	1	B				20.4	Exterior walls	Shaw, 1981
15	MD	Commercial	Canada (Ottawa)				Masonry	1977	1979	1	B				16.7	Exterior walls	Shaw, 1981
16	MK	Commercial	Canada (Ottawa)				Masonry	1967	1979	1	B				10.2	Exterior walls	Shaw, 1981
17	MS	Commercial	Canada (Ottawa)				masonry	1955	1978	1	B				16.6	Exterior walls	Shaw, 1981
18	OD	Commercial	Canada (Ottawa)				Concrete panel	1979	1979	1	B				18.3	Exterior walls	Shaw, 1981
19	PO	Commercial	Canada (Ottawa)				Concrete panel	1979	1979	1	B				15.8	Exterior walls	Shaw, 1981
20	RM	Commercial	Canada (Ottawa)				Masonry	1957	1979	1	B				5.8	Exterior walls	Shaw, 1981
21	WG	Commercial	Canada (Ottawa)				Masonry	1954	1979	1	B				19.0	Exterior walls	Shaw, 1981
22		MURB	Canada (Ottawa)			5	Masonry	1981	1989	1, 3	B				4.5	Exterior walls	Shaw et al, 1991
23 a)	A	Office	Canada (Ottawa)			9	Concrete panel	1970	1970	2	A			4.01	6.5	Exterior walls	Shaw & Reardon, 1995
23 b)	A	Office	Canada (Ottawa)			9	Concrete panel	1979	1991	2	A			3.15	5.1	Exterior walls	Shaw & Reardon, 1995
24 a)	B	Office	Canada (Ottawa)			17	Concrete panel	1964	1971	2	A			2.18	2.7	Exterior walls	Shaw & Reardon, 1995
24 b)	B	Office	Canada (Ottawa)			17	Concrete panel	1964	1991	2	A			1.53	1.9	Exterior walls	Shaw & Reardon, 1995
25 a)	D	Office	Canada (Ottawa)			20	Curtain wall	1971	1971	2	A			2.84	3.3	Exterior walls	Shaw & Reardon, 1995
25 b)	D	Office	Canada (Ottawa)			20	Curtain wall	1971	1991	2	A			1.64	1.9	Exterior walls	Shaw & Reardon, 1995
26 a)	E	Office	Canada (Ottawa)			21	Curtain wall	1968	1974	2	A			1.97	2.4	Exterior walls	Shaw & Reardon, 1995
26 b)	E	Office	Canada (Ottawa)			21	Curtain wall	1968	1991	2	A			1.89	2.3	Exterior walls	Shaw & Reardon, 1995
27 a)	F	Office	Canada (Ottawa)			16	Concrete panel	1973	1974	2	A			2.08	2.7	Exterior walls	Shaw & Reardon, 1995
27 b)	F	Office	Canada (Ottawa)			16	Concrete panel	1973	1991	2	A			1.77	2.3	Exterior walls	Shaw & Reardon, 1995
28 a)	G	Office	Canada (Ottawa)			25	Concrete panel	1974	1974	2	A			2.79	3.4	Exterior walls	Shaw & Reardon, 1995
28 b)	G	Office	Canada (Ottawa)			25	Concrete panel	1974	1991	2	A			2.21	2.7	Exterior walls	Shaw & Reardon, 1995

I.D	Author's Identification (if applicable)	Building Type	Location	Building Characteristics					Year Tested	Test Method	Test Class	C (l/s Pan)	n	NLR75 (l/s m2)		Alternate Area	Reference
				Volume (m3)	Envelope Area (m2)	Stories	Wall Construction	Year Built						Based on Total Envelope Area	Based on Alternate Area		
29	C	Office	Canada (Ottawa)			20	Concrete panel	1970	1971	2	A			2.50	3.3	Exterior walls	Tamura & Shaw, 1976
30	H	Office	Canada (Ottawa)			20	Curtain wall	1974	1974	2	A			1.44	1.9	Exterior walls	Tamura & Shaw, 1976
31	Anchorage	Office	U.S.	203000	23000					2	A	5944	0.61	3.60			Persily & Grot, 1986
32	Ann Arbor	Office	U.S	34000	6530					2	A	881	0.67	2.40			Persily & Grot, 1986
33	Columbia	Office	U.S.	119000	13800					2	A	5083	0.47	2.80			Persily & Grot, 1986
34	Huron	Office	U.S.	25000	6620					2	A	439	0.64	1.05			Persily & Grot, 1986
35	Norfolk	Office	U.S	62000	12100					2	A	2244	0.74	4.53			Persily & Grot, 1986
36	Pittsfield	Office	U.S	8600	2300					2	A	708	0.36	1.46			Persily & Grot, 1986
37	Springfield	Office	U.S	64000	8240					2	A	28	2.09	25.52			Persily & Grot, 1986
38	Albany	School	U.S	67000	27872					1 +/or 2	A	4294	0.70	3.16			Brennan et al, 1992
39	Administration	School	U.S.	26000	5853					1 +/or 2	A	712	0.34	0.53			Brennan et al, 1992
40	Argentine	School	U.S.	3000	794					1 +/or 2	A	148	0.63	2.83			Brennan et al, 1992
41	Bishop Ryan	School	U.S	17000	6875					1 +/or 2	A	445	0.82	2.23			Brennan et al, 1992
42	CLC	School	U.S	14000	3270					1 +/or 2	A	125	0.75	0.97			Brennan et al, 1992
43	Green Mountain	School	U.S.	8600	2027					1 +/or 2	A	759	0.46	2.73			Brennan et al, 1992
44	Grn. Mountain Gym	School	U.S	5600	1672					1 +/or 2	A	620	0.52	3.50			Brennan et al, 1992
45	Laurel	School	U.S.	7000	3468					1 +/or 2	A	508	0.44	0.98			Brennan et al, 1992
46	Middle School	School	U.S.	22000	9142					1 +/or 2	A	2608	0.61	3.97			Brennan et al, 1992
47	S. Pines	School	U.S.	14000	5704					1 +/or 2	A	239	0.76	1.11			Brennan et al, 1992
48	S. Tama-Gym	School	U.S.	2000	1301					1 +/or 2	A	288	0.50	1.92			Brennan et al, 1992
49	Russell	School	U.S.	9800	4161					1 +/or 2	A	252	0.99	4.33			Brennan et al, 1992
50	Velva	School	U.S.	17000	6875					1 +/or 2	A	1214	0.63	2.68			Brennan et al, 1992
51	1	Industrial	Sweden	36373	6796		Concrete elements			1	B				2.78	Exterior walls, roof	Lundin, 1986
52	2	Industrial	Sweden	61127	9876		Concrete elements			1	B				2.02	Exterior walls, roof	Lundin, 1986
53	3	Industrial	Sweden	31622	5809		Steel frame			1	B				0.98	Exterior walls, roof	Lundin, 1986
54	4	Industrial	Sweden		3150		Steel frame			1	B				1.16	Exterior walls, roof	Lundin, 1986
55	5	Industrial	Sweden	8535	2100		Steel frame			1	B				1.52	Exterior walls, roof	Lundin, 1986
56	6	Industrial	Sweden	10050	2650		Concrete elements			1	B				1.16	Exterior walls, roof	Lundin, 1986
57	7	Industrial	Sweden	6275	1960		Concrete elements			1	B				1.84	Exterior walls, roof	Lundin, 1986
58	8	Industrial	Sweden	12528	2950		Concrete elements			1	B				0.90	Exterior walls, roof	Lundin, 1986
59	9	Industrial	Sweden	29975	6804		Concrete elements			1	B				0.72	Exterior walls, roof	Lundin, 1986
61	Ottawa 'B'	MURB	Canada (Ottawa)	3788	1409	4	Wood frame	1990	mid-1990s	1	A	200	0.62	2.31			Scanada, 1997
62	Ottawa 'R'	MURB	Canada (Ottawa)	6408	1919	4	BV/SS	1991	mid-1990s	1	A	178	0.74	2.23			Scanada, 1997
63	Toronto 'L'	MURB	Canada (Toronto)	10365	3002	4	BV/SS	1991	mid-1990s	1	A	281	0.83	3.43			Scanada, 1997
64	Toronto 'S'	MURB	Canada (Toronto)	2001	890	3	Wood frame	1994	mid-1990s	1	A	166	0.67	3.35			Scanada, 1997
65	Vancouver 'LV'	MURB	Canada (Vancouver)	7466	2599	4	Wood frame	1992	mid-1990s	1	A	511	0.63	3.03			Scanada, 1997
66	Vancouver 'MV'	MURB	Canada (Vancouver)	7966	2890	3	Wood frame	1993	mid-1990s	1	A	766	0.59	3.60			Scanada, 1997
67	Vancouver 'SB'	MURB	Canada (Vancouver)	6739	2409	4	Wood frame	1993	mid-1990s	1	A	593	0.62	3.58			Scanada, 1997

I.D.	Author's Identification (if applicable)	Building Type	Location	Building Characteristics					Year Tested	Test Method	Test Class	C (l/s Pan)	n	NLR75 (l/s m2)		Alternate Area	Reference
				Volume (m3)	Envelope Area (m2)	Stories	Wall Construction	Year Built						Based on Total Envelope Area	Based on Alternate Area		
68	Vancouver 'W'	MURB	Canada (Vancouver)	6138	2139	4	Wood frame	1993	mid-1990s	1	A	421	0.67	3.49			Scanada, 1997
69		MURB (PCH)	Canada (Flin Flon)	3239	1951	1	Wood frame	1999	1999	1	A	208	0.66	1.85			Proskiw, 1999
70	1	Office	England	1951	862	2	Pre-fab	1970	mid-1990s	1	A	227	0.61	3.59			Potter et al, 1995
71	2	Office	England	14109	5131	3	Masonry	Elizabethan	mid-1990s	1	A	1640	0.59	4.08			Potter et al, 1995
72	3	Office	England	39149	8933	6	Steel frame/masonry	1991	mid-1990s	1	A	3980	0.52	4.21			Potter et al, 1995
73	4	Office	England	14856	4457	2	Steel frame/masonry	1985	mid-1990s	1	A	4860	0.52	10.29			Potter et al, 1995
74	5	Office	England	16572	4508	7	Concrete panel	1963	mid-1990s	1	A	1790	0.60	5.30			Potter et al, 1995
75	6	Office	England	10590	2689	3	Steel frame/masonry	1991	mid-1990s	1	A	2720	0.48	8.03			Potter et al, 1995
76	7	Office	England	15360	3328	6	Steel frame/masonry	1986	mid-1990s	1	A	4790	0.52	13.59			Potter et al, 1995
77	8	Office	England	21008	4783	5	Curtain wall/masonary	1989	mid-1990s	1	A	2010	0.53	4.14			Potter et al, 1995
78	9	Office	England	44335	8810	3	Steel frame/masonry	1991	mid-1990s	1	A	4320	0.61	6.83			Potter et al, 1995
79	10	Office	England	10357	2786		Steel frame/masonry	1990	mid-1990s	1	A	1610	0.54	5.95			Potter et al, 1995
80	11	Office	England	20379	5504	3	Steel frame/masonry	1992	mid-1990s	1	A	3670	0.67	12.03			Potter et al, 1995
81	12	Office	England	17577	4724	3	Steel frame/masonry	1992	mid-1980s	1	A	7150	0.49	12.55			Potter et al, 1995
82	1 Research office	Commercial	U.S. (Florida)	1683	1257	1	Masonry	1964	mid-1990s	1	A	69	0.67	0.99			Cummings, 1996
83	2 Auditorium	Commercial	U.S. (Florida)	2549	1264	1	Masonry	1964	mid-1990s	1	A	581	0.54	4.73			Cummings, 1996
84	3 Dentist 1	Commercial	U.S. (Florida)	702	668	1	Masonry	1991	mid-1990s	1	A	414	0.59	7.91			Cummings, 1996
85	4 Church	Commercial	U.S. (Florida)	6148	1682	2	Masonry/frame	1969	mid-1990s	1	A	292	0.58	2.12			Cummings, 1996
86	5 Church hall	Commercial	U.S. (Florida)	958	856	1	Masonry	1987	mid-1990s	1	A	401	0.62	6.82			Cummings, 1996
87	6 Video office	Commercial	U.S (Florida)	4321	1793	2	Masonry	1960	mid-1990s	1	A	277	0.60	2.06			Cummings, 1996
88	7 Business train	Commercial	U.S. (Florida)	6690	3741	1	Masonry	1967	mid-1990s	1	A	1371	0.58	4.48			Cummings, 1996
89	8 Engineer office	Commercial	U.S. (Florida)	224	277	1	Masonry/frame	1980	mid-1990s	1	A	186	0.59	8.58			Cummings, 1996
90	9 Dentist 2	Commercial	U.S. (Florida)	364	412	1	Masonry	1958	mid-1990s	1	A	409	0.34	4.30			Cummings, 1996
91	10 Architect	Commercial	U.S. (Florida)	2903	1487	1	Masonry	1985	mid-1990s	1	A	749	0.50	4.36			Cummings, 1996
92	11 HVAC supply	Commercial	U.S. (Florida)	432	468	1	Masonry/frame	1959	mid-1990s	1	A	278	0.65	9.82			Cummings, 1996
93	12 Sports building	Commercial	U.S. (Florida)	8683	3686	1	Masonry	1986	mid-1990s	1	A	832	0.65	3.74			Cummings, 1996
94	13 Day care	Commercial	U.S (Florida)	819	673	1	Masonry	1969	mid-1990s	1	A	375	0.70	11.43			Cummings, 1996
95	14 Manuf. class	Commercial	U.S. (Florida)	420	459	1	Manufactured	1989	mid-1990s	1	A	93	0.60	2.69			Cummings, 1996
96	15 Health clinic 1	Commercial	U.S. (Florida)	711	616	1	Masonry	1985	mid-1990s	1	A	320	0.49	4.31			Cummings, 1996
97	16 Manuf. office 1	Commercial	U.S. (Florida)	1324	1165	1	Manufactured	1987	mid-1990s	1	A	294	0.52	2.39			Cummings, 1996
98	17 School	School	U.S. (Florida)	6216	3628	1	Masonry	1974	mid-1990s	1	A	632	0.67	3.14			Cummings, 1996
99	18 Stadium complex	Commercial	U.S. (Florida)	8317	4046	2	Masonry	1985	mid-1990s	1	A	650	0.65	2.66			Cummings, 1996
100	19 Pizza restaurant	Commercial	U.S. (Florida)	440	510	1	Masonry/frame	1974	mid-1990s	1	A	235	0.54	4.74			Cummings, 1996
101	20 City hall	Commercial	U.S. (Florida)	1003	801	1	Masonry	1968	mid-1990s	1	A	156	0.59	2.49			Cummings, 1996
102	21 Health clinic 2	Commercial	U.S. (Florida)	616	701	1	Frame	1986	mid-1990s	1	A	337	0.65	7.98			Cummings, 1996
103	22 Sub restaurant	Commercial	U.S. (Florida)	1389	865	1	Masonry	1993	mid-1990s	1	A	96	0.60	1.48			Cummings, 1996
104	23 Mail warehouse	Commercial	U.S. (Florida)	996	806	1	Metal	1983	mid-1990s	1	A	558	0.59	8.85			Cummings, 1996
105	24 Library	Commercial	U.S (Florida)	3501	2131	1	Masonry	1988	mid-1990s	1	A	107	0.62	0.73			Cummings, 1996

I.D.	Author's Identification (if applicable)	Building Type	Location	Building Characteristics					Year Tested	Test Method	Test Class	C (l/s Pan)	n	NLR75 (l/s m2)		Alternate Area	Reference
				Volume (m3)	Envelope Area (m2)	Stories	Wall Construction	Year Built						Based on Total Envelope Area	Based on Alternate Area		
106	25 Sports complex	Commercial	U.S. (Florida)	702	721	1	Masonry	1986	mid-1990s	1	A	431	0.68	11.26			Cummings, 1996
107	26 Realty 1	Commercial	U.S. (Florida)	378	268	1	Frame	1993	mid-1990s	1	A	267	0.59	12.72			Cummings, 1996
108	27 Food office	Commercial	U.S. (Florida)	376	268	1	Frame	1993	mid-1990s	1	A	255	0.60	12.72			Cummings, 1996
109	28 Food warehouse	Commercial	U.S. (Florida)	752	535	1	Frame	1993	mid-1990s	1	A	499	0.51	8.44			Cummings, 1996
110	29 Manuf. office 2	Commercial	U.S. (Florida)	2141	1151	1	Manufactured	1982	mid-1990s	1	A	439	0.74	9.30			Cummings, 1996
111	30 Sail manuf.	Commercial	U.S. (Florida)	688	615	2	Frame	1940	mid-1990s	1	A	1452	0.48	18.77			Cummings, 1996
112	31 Bar and grill	Commercial	U.S. (Florida)	846	651	1	Masonry	1985	mid-1990s	1	A	297	0.60	6.08			Cummings, 1996
113	32 Golf club house	Commercial	U.S. (Florida)	1239	1058	1	Frame	1993	mid-1990s	1	A	441	0.56	4.67			Cummings, 1996
114	33 Chicken rest 1	Commercial	U.S. (Florida)	1164	816	1	Masonry	1993	mid-1990s	1	A	340	0.58	5.10			Cummings, 1996
115	34 HVAC contractor	Commercial	U.S. (Florida)	407	497	1	Masonry/frame	1930	mid-1990s	1	A	302	0.58	7.43			Cummings, 1996
116	35 Chicken rest 2	Commercial	U.S. (Florida)	1505	828	1	Masonry	1985	mid-1990s	1	A	140	0.64	2.68			Cummings, 1996
117	36 Printing 1	Commercial	U.S. (Florida)	5015	3596	1	Masonry	1965	mid-1990s	1	A	430	0.66	2.07			Cummings, 1996
118	37 Realty 2	Commercial	U.S. (Florida)	741	476	1	Masonry	1971	mid-1990s	1	A	101	0.60	2.84			Cummings, 1996
119	38 Interior decorate	Commercial	U.S. (Florida)	1260	923	1	Masonry	1971	mid-1990s	1	A	125	0.63	2.05			Cummings, 1996
120	39 Realty 3	Commercial	U.S. (Florida)	594	575	1	Masonry	1945	mid-1990s	1	A	193	0.68	6.33			Cummings, 1996
121	40 Safety class	Commercial	U.S. (Florida)	697	665	1	Masonry/frame	1965	mid-1990s	1	A	587	0.55	9.48			Cummings, 1996
122	41 Pet grooming	Commercial	U.S. (Florida)	199	242	1	Masonry/frame	1965	mid-1990s	1	A	139	0.62	8.37			Cummings, 1996
123	42 Government office	Commercial	U.S. (Florida)	2611	1431	1	Masonry/frame	1965	mid-1990s	1	A	385	0.82	9.27			Cummings, 1996
124	43 Bar	Commercial	U.S. (Florida)	866	659	1	Masonry/frame	1965	mid-1990s	1	A	649	0.62	14.30			Cummings, 1996
125	44 Safety office	Commercial	U.S. (Florida)	297	389	1	Masonry/frame	1965	mid-1990s	1	A	230	0.70	12.13			Cummings, 1996
126	45 School supply	Commercial	U.S. (Florida)	722	685	1	Masonry/frame	1965	mid-1990s	1	A	329	0.66	8.29			Cummings, 1996
127	46 Court office	Commercial	U.S. (Florida)	1534	931	1	Masonry/frame	1965	mid-1990s	1	A	332	0.98	24.56			Cummings, 1996
128	47 Marshal arts	Commercial	U.S. (Florida)	275	332	1	Masonry/frame	1965	mid-1990s	1	A	98	0.82	9.97			Cummings, 1996
130	49 Retail vacant	Commercial	U.S. (Florida)	280	335	1	Masonry/frame	1965	mid-1990s	1	A	181	0.57	6.34			Cummings, 1996
131	50 Retail vacant	Commercial	U.S. (Florida)	280	243	1	Masonry/frame	1965	mid-1990s	1	A	250	0.58	12.61			Cummings, 1996
132	51 Gas company	Commercial	U.S. (Florida)	1597	1377	1	Masonry	1950	mid-1990s	1	A	388	0.62	4.10			Cummings, 1996
133	52 Tax service	Commercial	U.S. (Florida)	599	522	1	Masonry	1963	mid-1990s	1	A	81	0.62	2.25			Cummings, 1996
134	53 Metal bldg co.	Commercial	U.S. (Florida)	1170	983	1	Metal	1985	mid-1990s	1	A	127	0.68	2.23			Cummings, 1996
135	54 Realty 4	Commercial	U.S. (Florida)	597	650	1	Masonry	1975	mid-1990s	1	A	183	0.76	7.48			Cummings, 1996
136	55 Printing 2	Commercial	U.S. (Florida)	3256	2382	1	Metal	1977	mid-1990s	1	A	915	0.60	5.12			Cummings, 1996
137	56 Plastic fabricate	Commercial	U.S. (Florida)	5858	2885	1	Metal	1982	mid-1990s	1	A	729	0.59	3.23			Cummings, 1996
138	57 Amusement part	Commercial	U.S. (Florida)	2103	1397	2	Masonry	1981	mid-1990s	1	A	1953	0.48	11.10			Cummings, 1996
139	58 Hardware store	Commercial	U.S. (Florida)	1582	1207	1	Masonry	1993	mid-1990s	1	A	166	0.62	2.00			Cummings, 1996
140	59 Carpet store	Commercial	U.S. (Florida)	493	478	1	Masonry	1972	mid-1990s	1	A	146	0.73	7.14			Cummings, 1996
141	60 Manuf. office 3	Commercial	U.S. (Florida)	178	259	1	Manufactured	1984	mid-1990s	1	A	58	0.81	2.99			Cummings, 1996
142	61 Manuf. office 4	Commercial	U.S. (Florida)	299	367	1	Manufactured	1982	mid-1990s	1	A	170	0.59	5.92			Cummings, 1996
143	62 Chinese restaurant	Commercial	U.S. (Florida)	3002	1906	1	Frame	1962	mid-1990s	1	A	169	0.86	3.62			Cummings, 1996
144	63 Police station	Commercial	U.S. (Florida)	2257	1637	1	Masonry	1989	mid-1990s	1	A	285	0.46	1.18			Cummings, 1996

I.D.	Author's Identification (if applicable)	Building Type	Location	Building Characteristics					Year Tested	Test Method	Test Class	C (l/s Pan)	n	NLR75 (l/s m2)		Alternate Area	Reference
				Volume (m3)	Envelope Area (m2)	Stories	Wall Construction	Year Built						Based on Total Envelope Area	Based on Alternate Area		
145	64 School wing 1	Commercial	U.S. (Florida)	3157	2346	1	Masonry	1964	mid-1990s	1	A	262	0.65	1.85			Cummings, 1996
146	65 School wing 2	Commercial	U.S (Florida)	868	539	1	Masonry	1964	mid-1990s	1	A	107	0.52	1.88			Cummings, 1996
147	66 School wing 3	Commercial	U.S. (Florida)	1579	1275	1	Masonry	1964	mid-1990s	1	A	696	0.53	5.38			Cummings, 1996
148	67 Hotel complex	Commercial	U.S. (Florida)	5214	3540	1	Masonry	1976	mid-1990s	1	A	1905	0.45	3.75			Cummings, 1996
149	68 Hotel	Commercial	U.S. (Florida)	2888	1713	2	Masonry	1976	mid-1990s	1	A	477	0.62	4.05			Cummings, 1996
150	69 Conv. store 1	Commercial	U.S. (Florida)	1187	1061	1	Masonry	1988	mid-1990s	1	A	497	0.62	6.82			Cummings, 1996
151	70 Conv. store 2	Commercial	U.S. (Florida)	835	691	1	Masonry	1968	mid-1990s	1	A	31	0.65	0.75			Cummings, 1996
152 (a)	St. Hilda's Towers (V, pret)	MURB	Canada (Toronto)			17	Masonry	1984	1988	1	B				4.4	Exterior walls	Shaw, 1989
152 (b)	St. Hilda's Towers (V, post)	MURB	Canada (Toronto)			17	Masonry	1984	1988	1	B				4.1	Exterior walls	Shaw, 1989
153 (a)	St. Hilda's Towers (D, pre-)	MURB	Canada (Toronto)			14	Masonry	1979	1988	1	B				3.2	Exterior walls	Shaw, 1989
153 (b)	St. Hilda's Towers (D, postt)	MURB	Canada (Toronto)			14	Masonry	1979	1988	1	B				2.7	Exterior walls	Shaw, 1989
154	Court house	Commercial	Canada (Sask.)	6226	2226			1929	1999	1	A	423	0.56	2.14			Dumont, 2000
155	Radio station	Commercial	Canada (Sask.)	2287	1868			1960	1999	1	A	132	0.63	1.06			Dumont, 2000
156	Land titles building	Commercial	Canada (Sask.)	3818	1951			1950	1999	1	A	82	0.68	0.77			Dumont, 2000
157	Youth camp building	Commercial	Canada (Sask.)	1753	1473			1991	1999	1	A	106	0.73	1.65			Dumont, 2000
158	Fire control office	Commercial	Canada (Sask.)	1718	1879			1990	1999	1	A	157	0.68	1.56			Dumont, 2000
159	WB building	Commercial	Canada (Sask.)	2819	1136			1975	1999	1	A	196	0.56	1.93			Dumont, 2000
160	POB	Commercial	Canada (Sask.)	3265	1675			1975	1999	1	A	263	0.51	1.44			Dumont, 2000
161	Library	Commercial	Canada (Sask.)	9630	3982			1998	1998	1	A	61	0.62	0.23			Dumont, 2000
162 (a)	SJCC	Institutional	Canada (Winnipeg)	2728	828	1	Masonry	1975	1996	4	A			0.55			Proskiw, 2000 (a)
162 (b)	SJCC	Institutional	Canada (Winnipeg)	2728	828	1	Masonry	1975/2000	2000	4	A			0.04			Proskiw, 2000 (a)
163	#1	MURB	Canada (Montreal)					1991	1991	3	C				4.58	Exterior walls of suites	Chalifour et al, 1991
164	#2	MURB	Canada (Montreal)					1961	1991	3	C				6.12	Exterior walls of suites	Chalifour et al, 1991
165	Bldg. A - Suite #405	MURB	Canada (Winnipeg)		28	13	Masonry	1973	1991	3	C	12	0.46		3.02	Exterior walls of suites	Gulay et al, 1991
166 (a)	Bldg. B - Suite #509	MURB	Canada (Winnipeg)		28	13	Masonry	1970	1991	3	C	11	0.53		3.91	Exterior walls of suites	Gulay et al, 1991
166 (b)	Bldg. B - Suite #609	MURB	Canada (Winnipeg)		28	13	Masonry	1970	1991	3	C	7	0.66		4.07	Exterior walls of suites	Gulay et al, 1991
166 (c)	Bldg. B - Suite #1009	MURB	Canada (Winnipeg)		28	13	Masonry	1970	1991	3	C	7	0.53		2.55	Exterior walls of suites	Gulay et al, 1991
167 (a)	Bldg. B - Floor #4	MURB	Canada (Victoria)	1375	304	8	Reinforced concrete	1991	1991	3	C	37	0.44		0.81	Exterior walls of suites	Landell, 1991
167 (b)	Bldg. B - Floor #5	MURB	Canada (Victoria)	1375	304	8	Reinforced concrete	1991	1991	3	C	31	0.49		0.85	Exterior walls of suites	Landell, 1991
168 (a)	Bldg. C - Floor #5	MURB	Canada (Victoria)	935	242	10	Reinforced concrete	1991	1991	3	C	62	0.49		2.13	Exterior walls of suites	Landell, 1991
168 (b)	Bldg. C - Floor #6	MURB	Canada (Victoria)	935	242	10	Reinforced concrete	1991	1991	3	C	19	0.58		0.96	Exterior walls of suites	Landell, 1991
168 (c)	Bldg. C - Floor #7	MURB	Canada (Victoria)	935	242	10	Reinforced concrete	1991	1991	3	C	23	0.51		0.85	Exterior walls of suites	Landell, 1991
169	77 Governors Road	MURB	Canada (Dundas)	24320	6826	6	BV/SS and EIFS	1998	2000	1	A	879	0.51	1.18			Enermodal, 2000
170	Apartment Building A	MURB	Canada (Montreal)	5321	1955			1956	1992	1	A	448	0.77	6.37			Lawton, 2000
171	Apartment Building B	MURB	Canada (Montreal)	4831	1834			1956	1992	1	A	443	0.64	3.83			Lawton, 2000
172	NECP	Institutional	Canada (Winnipeg)	6853	2029	1	Masonry	1970	2000	4	A			1.16			Proskiw, 2000 (b)
173	1	Office	England	5315	1750		Masonry	1980	mid-1990s		B				3.1	Above-grade area	Perera et al, 1997
174	2	Office	England	13749	3769		Masonry	1963	mid-1990s		B				3.0	Above-grade area	Perera et al, 1997

LD	Author's Identification (If applicable)	Building Type	Location	Building Characteristics					Year Tested	Test Method	Test Class	C (l/s Pan)	n	NLR75 (l/s m2)		Alternate Area	Reference
				Volume (m3)	Envelope Area (m2)	Stories	Wall Construction	Year Built						Based on Total Envelope Area	Based on Alternate Area		
175	3	Office	England	32479	6189		Masonry	1991	mid-1990s		B				3.1	Above-grade area	Perera et al, 1997
176	4	Office	England	6254	2195		Masonry	1965	mid-1990s		B				6.3	Above-grade area	Perera et al, 1997
177	5	Office	England	2516	1105		Masonry	1987	mid-1990s		B				3.8	Above-grade area	Perera et al, 1997
178	6	Office	England	8651	2508		Masonry	1990	mid-1990s		B				5.1	Above-grade area	Perera et al, 1997
179	7	Office	England	2045	829		Masonry	1990	mid-1990s		B				8.7	Above-grade area	Perera et al, 1997
180	8	Office	England	8168	3058		Concrete panel	1971	mid-1990s		B				9.5	Above-grade area	Perera et al, 1997
181	9	Office	England	14904	4726		Masonry	1986	mid-1990s		B				10.2	Above-grade area	Perera et al, 1997
182	10	Office	England	14126	4394		Concrete panel	1985	mid-1990s		B				11.2	Above-grade area	Perera et al, 1997
183	BSRIA Building #2	Industrial	England								A			8.85			Jones & Powell, 1994
184	BSRIA Building #3	Industrial	England								A			9.37			Jones & Powell, 1994
185 (a)	Unit 40 (As-built)	Industrial	England				Steel cladding (& frame?)		early-1990s		A			5.47			Jones & Powell, 1994
185 (b)	Unit 40 (Sealed)	Industrial	England				Steel cladding (& frame?)		early-1990s		A			5.08			Jones & Powell, 1994
186 (a)	Unit 41 (As-built)	Industrial	England				Steel cladding (& frame?)		early-1990s		A			5.73			Jones & Powell, 1994
186 (b)	Unit 41 (Sealed)	Industrial	England				Steel cladding (& frame?)		early-1990s		A			5.21			Jones & Powell, 1994
187 (a)	Unit 42 (As-built)	Industrial	England				Steel cladding (& frame?)		early-1990s		A			5.34			Jones & Powell, 1994
187 (b)	Unit 42 (Sealed)	Industrial	England				Steel cladding (& frame?)		early-1990s		A			3.64			Jones & Powell, 1994
193	Conventional	Office	England	6254	2195		Steel frame		late 1980s	1	B	1388	0.51		5.72	Above-grade area	Perera et al, 1989
194	Low Energy Office (LEO)	Office	England	5315	1750		Concrete panels	1980s	late 1980s	1	B	424	0.60		3.23	Above-grade area	Perera et al, 1989
195	Marston shed	Industrial	England	4690	1400			mid-1960s	late 1980s	1	B	2041	0.64		23.11	Above-grade area	Perera & Tull, 1990
196	Industrial building	Industrial	England	4955	1694					1	B	3936	0.52		21.94	Above-grade area	Perera & Tull, 1990
197	Law-Court Building	Office	England	18000	4750					1	B	2350	0.77		13.75	Above-grade area	Perera & Tull, 1990
198	Building 1	MURB	Canada (St. John's)			7	BV/SS	1982	1991	3	C				10.0	Exterior walls of floors	Bennett, 1991
199	Building 2	MURB	Canada (St. John's)			6	BV/SS	1983	1991	3	C				5.0	Exterior walls of floors	Bennett, 1991