Final Report:
An Investigation of Airtightness in Manitoba's Commercial Building Sector

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Important Notice

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Contents

List of Tables and Figures

Tables

Figures

Executive Summary

This report documents a research project carried out by the Sustainable Infrastructure Technology Research Group at Red River College (RRC-SITRG) in Winnipeg, Manitoba, Canada. The project had two primary objectives: to expand the knowledge base on the airtightness characteristics of commercial buildings by performing tests on a cross-section of Manitoba's commercial building stock, and to gain critical, practical experience with airtightness testing procedures for commercial buildings.

Between 2012 and 2014, a total of 26 commercial buildings in Manitoba were tested. Overall, they represented a fairly diverse sample of Manitoba's commercial construction: 18 (69%) were situated in the City of Winnipeg; they ranged in age from one to over 100 years; floor areas varied from 150 m^2 to 19,788 m^2 (1,615 ft^2 to 212,918 ft^2); and building heights ranged from one to 16 stories. Five of the structures were owned by Manitoba Hydro who also provided financial and in-kind support for the project. The rest were occupied by a variety of private and public owners. An effort was also made to include a few buildings that were undergoing, or had recently completed, a major building envelope retrofit. This report contains and discusses the airtightness results for the complete sample of 26 buildings along with separate discussions for various subsets based on their age, type or retrofit status.

To develop the project's experimental protocol, the most commonly used airtightness testing standards were reviewed along with the metrics most frequently employed for reporting results. Based on this information, it was concluded that the most appropriate methodology for the project was the *Air Leakage Test Protocol for Building Envelopes Version 3* published in 2012 by the U.S. Army Corps of Engineers and the Air Barrier Association of America USACE/ABAA). Standard practice when performing commercial building airtightness tests is to conduct separate tests with the building first depressurized and then pressurized. The final building airtightness is then calculated as the average of these two results. This practice was used on 23 of the 26 buildings in the project. The remaining three were tested using depressurization only.

A literature review was also conducted which identified related, prior studies by ASHRAE, RDH Building Engineering Ltd. and Proskiw Engineering Ltd. These provided useful comparative data to interpret this project's results.

One of the outcomes of this project was the realization by the RRC-SITRG project team that the treatment of intentional openings in the building envelope was a critical issue which had not been properly addressed by existing testing standards. Rather than the single sealing schedule currently employed by these standards, it was realized that two, separate schedules were required: an "envelope" and an "energy" sealing schedule. This information was transmitted to the technical committee reviewing the USACE/ABAA standard where it was discussed and ultimately incorporated into the revised draft of the document. Most of the buildings tested in this project used the "envelope sealing schedule" (i.e., all mechanical penetrations sealed). However, six used the "energy sealing schedule" (i.e., some, but not all, of the intentional openings sealed). One building was tested using both schedules.

To quantify airtightness, two different metrics were employed: the Normalized Leakage Rate at a pressure differential of 75 Pascals (NLR_{75}) and the air change rate at 50 Pascals (ac/hr_{50}) Using these two parameters, the NLR_{75} and ac/hr_{50} results were computed and compared to the following standards which contain recommendations on permissible air leakage rates for commercial buildings:

- 2012 International Energy Conservation Code (2.03 L/s•m^2)
- 2012 USACE/ABAA (1.27 L/s•m^2)
- 2010 National Building Code of Canada (0.10 L/s•m^2 for air barrier systems)

Examinations were also made of each building during the test to identify the most significant sources of air leakage.

The 26 buildings tested during this project displayed a wide range of airtightness rates. For example, the measured NLR_{75} values ranged from a low of 0.19 to a high of 3.44 L/s•m^2, a variation of almost 18:1 between the leakiest and tightest buildings. The mean NLR_{75} of the complete sample was 1.70 L/s•m^2, which is similar to the mean value of 1.47 L/s•m^2 reported in the recently completed ASHRAE survey of new buildings (2014). The RRC-SITRG results were surprising given that unlike the buildings surveyed by ASHRAE, only a handful were designed and constructed with any explicit concern for airtightness.

In addition to the overall sample results, the performance of various sub-categories of buildings were examined. For example, five of the 26 buildings tested were classified as new construction and were observed to perform well relative to comparable data for new buildings reported in the literature. The average NLR_{75} of the Manitoba new-builds was about two-thirds that of the 16 buildings in the ASHRAE study which, themselves, were biased towards tighter construction. Further, the Manitoba buildings displayed lower air leakage rates than those reported in the legacy literature for such construction.

While the Manitoba results for new construction appear impressive, they actually understate the true performance since one of the five new-builds was significantly leakier than the others in this category. If the results for this one building (a warehouse that exhibited disproportionally higher air leakage when pressurized than depressurized) are eliminated, the average NLR_{75} of the remaining four dropped from 0.95 L/s•m^2 to 0.36 L/s•m^2. This is less than one-third of the recommended NLR_{75} (1.27 L/s•m^2) used by the USACE/ABAA standard.

Warehouses and light industrial buildings were another category examined. They were observed to perform surprisingly well relative to those reported in the literature. For example, the average NLR_{75} for the 11 warehouse and light industrial buildings was only 14% greater than that of the 16 mostly new buildings in the ASHRAE sample, even though the Manitoba buildings were predominately older structures.

Four schools were also included in the RRC-SITRG sample. Although the sample size was small, the most surprising observation was that the NLR_{75} varied by a factor of over 10:1

between the loosest and the tightest schools. However, this was largely because the most airtight structure in the 26 building sample was a one year-old middle school which had a carefully designed, and installed, air barrier. Its measured NLR_{75} was only 0.19 L/s•m^2, making it one of the tightest buildings of its size ever tested anywhere in the world.

The seven office buildings in the sample were the most geographically dispersed sub-category in the project. Their mean NLR_{75} was only about 7% greater than the 16 new buildings reported in the ASHRAE sample, despite the seven having an average age of over 50 years.

Two Winnipeg churches were included in the sample and these were both large, architecturally unique structures with many complex details. Testing revealed that they were comparatively leaky with only one other building sub-category (greenhouses) displaying a higher mean NLR_{75} value. For example, the mean NLR_{75} of the two churches was about 60% higher than the corresponding NLR_{75} in the ASHRAE study. Given the age of the buildings and the fact that the sample size was so small, it is unclear how representative these results are of typical churches, especially since both displayed unique air leakage behaviour patterns.

Two greenhouses, both located on the RRC campus, were also included in the sample. One used a conventional greenhouse design while the other was classified as a passive solar greenhouse. Despite the latter being specifically designed to reduce energy use, their measured airtightness results were almost identical. Further, the two greenhouses were among the leakiest of all the buildings tested in this project with NLR_{75} values of 2.88 and 2.94 L/s•m^2 respectively.

The project also studied the impact of air leakage sealing on three of the 26 buildings which were, or had been, recently retrofitted (two offices and one school). These retrofits produced absolute reductions in the NLR_{75} which were surprisingly consistent, ranging from 0.16 L/s·m^2 to 0.21 L/s·m^2. This represented an average reduction of 16% in the NLR_{75}. Interestingly, the two buildings that had all or most of their glazing replaced experienced the same reduction in their NLR_{75} - 0.21 L/s·m^2.

Finally, a series of recommendations were prepared to: maximize awareness of the project's key findings; establish recommended airtightness targets and protocols suitable for Manitoba buildings; expand the database of airtightness test results (including a pilot program to encourage testing); review opportunities to increase the use of low-leakage HVAC dampers; and finally, reduce the cost of preparing a building for airtightness testing through development of a how-to-guide.

1.0 Introduction

1.1 Project Proponent and Supporters

This applied research project was undertaken by the Sustainable Infrastructure Technology Research Group at Red River College (RRC-SITRG) in Winnipeg, Canada. Established in late 2009 with a College and Community Innovation grant from the Natural Science and Engineering Research Council of Canada (NSERC), RRC-SITRG focuses on applied research and development to improve the energy performance of new and existing buildings.

Technical support for conducting the airtightness testing, interpreting the test results and preparing this report was provided to RRC-SITRG by Gary Proskiw of Proskiw Engineering Ltd. (PEL), a Winnipeg-based consultant specializing in building science with over 35 years of experience in building envelopes and airtightness testing.

Financial support for the project was provided through a grant by Manitoba Hydro's Research and Development Program. Manitoba Hydro also provided valuable in-kind support through its Customer Engineering Services staff. The many building owners and operators throughout Manitoba who participated in the project also provided additional in-kind support.

1.2 Project Background, Description and Objectives

The project's overall vision was to significantly expand the knowledge base on airtightness characteristics and testing techniques for commercial buildings at both a provincial and national level. Specific objectives of the project were to:

1. Develop practical airtightness testing protocols within the context of current standards.
2. Determine baseline airtightness rates in a sample of up to 20 commercial buildings in Manitoba that represent a range of ages and types of buildings.
3. Compare building pre- and post-retrofit airtightness rates for a subset of these buildings to determine the feasibility of cost-effective air sealing strategies.
4. Compare the baseline airtightness rates to the recommendations of the *National Building Code of Canada 2010* and *National Energy Code of Canada for Buildings 2011* to provide rationale for potential inclusion of mandatory airtightness rates in subsequent codes.
5. Provide exposure and training to engineering technology students at RRC in airtightness testing procedures and protocols.
6. Document and share the project's results with Manitoba Hydro and Manitoba's building industry.

This project is a response to a survey conducted in 2010 of 33 building science experts from Manitoba and across Canada about building-related applied research priorities for RRC-SITRG. These experts rated commercial building airtightness as the most important priority for energy-related building research in Manitoba. The reason the survey results targeted commercial building airtightness as so important can be best appreciated if the knowledge base is compared to that of residential construction. More than 30,000 houses in Manitoba have had their airtightness measured through initiatives such as the Federal Government's ecoENERGY Retrofit Homes Program and the R-2000 New Home Program. In contrast, less than ten commercial buildings had been tested for airtightness in Manitoba prior to this project and all of these were of relatively modest size. Yet, over the last two decades, hundreds of millions of dollars have been spent in this province repairing building envelopes of commercial buildings that have experienced premature failure due to excessive air leakage.

A key challenge in commercial building airtightness testing is the lack of experienced and technically proficient personnel capable of undertaking this complex task. Current standards for commercial building testing are relatively new and were largely derived from comparable residential testing standards. While the basic protocols used for airtightness testing of large and small buildings are similar, in practical terms, commercial buildings pose significantly greater challenges. For example, the air-moving requirements of the test equipment are typically an order of magnitude greater than those of houses. This requires larger, and multiple, fan units to achieve the necessary air flow rates and to provide more consistent pressure differentials across the building envelope. In addition, the calibration and coordination of a multi-fan system requires integration of complex software for data analysis. Commercial buildings also have much more complicated heating, ventilating and air-conditioning (HVAC) systems than houses and present additional testing challenges such as stack effect in multi-floor buildings and ensuring interconnectivity between floors.

Due to the limited number of commercial tests performed, testing techniques and procedures are still evolving. As a result, very little data is available on airtightness in commercial buildings. A literature search conducted in 2001 by Canada Housing and Mortgage Corporation (PEL identified airtightness data for 192 large buildings - worldwide! Of these, 62 were in Canada with the bulk situated in Central Canada (30% of these were MURBs). A wide range of airtightness rates were recorded with some measured rates being 10 to 50 times greater than recommended values.

In recent years there has been increased interest in airtightness testing of commercial buildings, primarily in the United States and also in the United Kingdom (which has established mandatory airtightness testing requirements for many types of commercial building projects). This interest is driven by both the recognition of the importance of building airtightness and the emergence of new test equipment with the capacity to measure a wide range of commercial building types.

In the U.S., the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) recently completed a study of large building airtightness. While this project underscored the importance of quantitative testing, the data is of limited value to the Canadian market, since ASHRAE's focus was on new construction (less than five years old) and included only one building in a climate typical of that found in Manitoba. There also has been a growing interest in Canada about airtightness in new and existing buildings that has been reflected in building and energy codes. For example, an air barrier system was first referenced in the *National Building Code of Canada* (NBC) in 1990. In 1995 an appendix of recommended airtightness rates was added to the NBC.

1.3 Organization of this Report

The **Introduction** (Section 1.0) introduces the research group which conducted this applied research project, along with the organizations that provided financial and/or in-kind support. A statement of the project's vision and a list of objectives are then provided followed by a background discussion about the motivation for initiating this project.

The **Building Airtightness Primer** (Section 2.0) describes the physical process of air leakage in buildings. Readers already familiar with the basic concepts and mechanisms of building air leakage may wish to skip this section.

Airtightness Test Protocols, Metrics and Standards (Section 3.0) provides context for the airtightness test protocols and metrics used in this project as well as the standards used as benchmarks for the test results presented and discussed in Section 5.0.

The **Project Methodology** (Section 4.0) lists the members of the project team and their respective roles; describes how buildings were selected for the project; explains how the airtightness tests were conducted and briefly describes the equipment that was used.

The **Airtightness Test Results and Discussion** (Section 5.0) presents and discusses the airtightness test results for the entire sample of buildings examined by the project plus the results disaggregated by building type, age and retrofit status

The **Conclusions and Recommendations** (Section 6.0) summarize the project's key findings and provide specific recommendations by the report's authors about opportunities for future research.

In addition to this report, a summary of the results for each building have been prepared and were shared with each owner on an individual basis. These building summaries have not been included in this report to avoid the possible identification of individual buildings and disclosure of their specific tests results.

2.0 Building Airtightness Primer

2.1 What Causes Building Air Leakage?

Building air leakage describes the physical process by which unintentional air movement occurs between the interior of a building and its outdoor environment. For air leakage to take place, two criterion must be met: pathways (i.e., ‘holes’) must exist across the building envelope and a pressure differential must be present across the pathways connecting the indoors and outdoors. If either is missing, no leakage occurs. In practice, all buildings contain air leakage pathways – although their size, number and locations vary dramatically. Pressure differentials, which create the necessary driving forces for air leakage, can be generated by any of three mechanisms: stack effect, wind action and the operation of mechanical systems which exhaust or supply air across the envelope.

The ‘airtightness’ of a building is simply the cumulative resistance to air flow created by the presence of the building envelope. Since no building envelope is completely free of air leakage pathways, it follows that no building is perfectly airtight. In fact, all buildings contain a multitude of air leakage pathways that range in size from microscopic to macroscopic. The resistance to air flow created by a building envelope is a collective function of the flow geometry, crack length and the entrance and exit effects as the air passes through each leakage pathway as it transits through the envelope.

It should also be appreciated that building air leakage does not occur through a single passageway, but rather through a multitude of interconnected pathways that physically extend across the envelope. These can be direct passages (such as an open or broken window) or complex, indirect pathways in which the air enters the envelope at one location, flows laterally (horizontally and/or vertically) and then exits at some other location. The distance between the entry and exit points can be very short (a few millimetres) or can extend the height or length of the building. Further, the various pathways can be, and usually are, interconnected with each other such that sealing just one entry or exit location may not eliminate – or even significantly diminish – the building's overall air leakage characteristics.

2.2 Where Does Air Leakage Occur in a Building?

A common question about airtightness is "Where do most of the leaks occur?”. While it is difficult to predict where leakage will occur in a specific building without benefit of an airtightness examination, some general observations can be offered based on airtightness tests on various types of structures over the last several decades.

First, contrary to popular opinion, doors and windows are seldom the dominant leakage locations in buildings – although greenhouses and some curtain wall structures would be notable exceptions since a majority of their envelope area can be classified as glazing or fenestration. However, for most buildings, only a modest percentage of the total leakage occurs through doors and windows. The rest takes place through the opaque portions of the envelope. While most people consider the walls, ceilings, foundations, etc. which comprise the building envelope to be solid, most of these surfaces are actually porous to airflow, albeit to varying degrees, with the notable exception of materials like glass and metal, which are airtight. However, where major envelope surfaces physically meet a discontinuity results and air leakage can occur if measures are not taken to control it. Likewise, a similar problem can occur where objects, such as mechanical ducts, pipes or electrical lines, penetrate through the air barrier. In fact, most of the air leakage that occurs in a building takes place at these three types of locations:

1. **Joints** – These are locations where major parts of building envelope join together. Some examples are joints between individual wall, ceiling or foundation sections (at a corner or within the broad expanse of the section); joints between movable and non-movable sections of individual windows; and joints between overhead doors and the floor or wall.
2. **Intersections** – These are locations where major components of the building physically meet. Examples include intersections between the exterior wall and the floor system(s); the wall and ceiling or the wall and the foundation; and the ceiling and the tops of partition walls. For example, in small commercial and residential construction, the single largest source of air leakage is usually at the floor headers since three major building components (foundation, floor system and the exterior wall) intersect, thereby creating multiple opportunities for air leakage.
3. **Penetrations** – These are locations where one part of the building envelope passes through another part. This includes mechanical or electrical systems which pass through the building envelope; penetrations for electrical lines or services, gas or water pipes, air-handling ducts, communication lines and access hatches. Window and door rough-openings are also considered penetrations.

3.0 Airtightness Test Protocols, Metrics and Standards

3.1 Airtightness Test Protocols

Numerous testing standards have been developed over the last 30 years to define the procedure for measuring a building's airtightness. While these are each targeted at slightly different applications or use slightly different approaches, they all basically follow a similar methodology:

Step One – Building Preparation: The building is first prepared for testing: all mechanical systems which move air into or out of the building are shut off, windows and exterior doors are closed, interior doors are opened and intentional openings (such as air inlets and outlets, as well as other mechanical penetrations) are sealed.

Step Two – Building Pressurization/Depressurization: Once the building preparation is complete, a high-capacity blower, or blowers, is installed in a suitable exterior doorway(s) and used to pressurize or depressurize the structure to a series of pre-defined, indoor-to-outdoor pressure differentials. These are sufficiently large that they will normally overpower the naturally induced pressure differentials that the building may be experiencing due to stack effect and wind action (there should not be any mechanically induced pressure differentials since the mechanical system is disabled). This means that all of the airflow across the envelope is in one direction and all the air being moved into or out of the building by the blowers is in the opposite direction. Further, these two flow rates must equal each other. Therefore, by measuring the airflow rate at the blower(s), the airflow rate across the envelope can be determined.

Step Three – Airflow Measurement: Once the indoor-to-outdoor pressure differential has stabilized at each test condition, the airflow rate through the blowers is measured – typically using orifice plates mounted on the blowers. This process is then repeated over a range of indoor-to-outdoor pressure differentials. Once all the flow rate and pressure differential data pairs have been recorded, along with various environmental information such as indoor and outdoor air temperatures and wind conditions, a mathematical analysis is used to develop a regression equation as shown in Eq. (1):

$$Q = C\Delta P^n \quad \textbf{(1)}$$

where:

Q = flow rate (L/s)
C = flow coefficient (L/s•Pa^n)
ΔP = indoor-to-outdoor pressure differential (Pa)
n = flow exponent (dimensionless)

Step Four – Calculation of Airtightness Results: The test results are then combined with information on the building's size (envelope area and building volume) to generate a quantified airtightness result using one, or more metrics (discussed below in Subsection 3.2).

The first airtightness testing standards targeted houses and other small buildings since the test equipment then available had limited airflow capacity. As equipment capacity grew and field experiences with airtightness testing expanded, standards were also developed for testing larger commercial, institutional and multi-family buildings.

Some of the more significant standards commonly used for performing building airtightness tests are briefly described below. The following discussion and referenced standards are far from a complete overview of the subject since there are several other standards that address specific aspects of building airtightness testing. Those discussed below are mentioned because they are the most widely used standards in North America and were also instrumental in selection of the final testing protocol used for this project.

CAN/CGSB-149.10-M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method – First published in 1986, CGSB 149.10 has been used to test hundreds of thousands of Canadian houses (CGSB, 1986). It has also been used for larger buildings although its primary target is low-rise residential construction. The test anticipates use of either a single large blower or multiple smaller blowers to depressurize (only) the building in increments of 5 Pa, starting at a 50 Pa and working down to 15 Pa. The standard provides guidance on sealing intentional openings to achieve representative results, and how to measure the reference exterior pressure using multiple pressure taps. It recommends that tests not be conducted when the wind is greater than 20 km/hr (5.6 m/s). It is important to note that CGSB 149.10 only describes the procedure to be used for airtightness testing – it does not contain any recommended or mandatory airtightness targets.

ASTM E779-10 Standard Method for Determining Air Leakage Rate by Fan Pressurization – This standard uses a similar methodology to that of CGSB 149.10 with two exceptions: the test is conducted under both pressurization and depressurization conditions, and the range of pressure differentials varies from 10 Pa to 60 Pa in increments of 5 Pa to 10 Pa (ASTM, 1992). This is the most widely used airtightness testing standard in the United States and has also been used to conduct hundreds of thousands of tests – predominately on houses. Like CGSB 149.10, ASTM E779 does not contain any airtightness targets.

U.S. Army Corps of Engineers Air Leakage Test Protocol for Measuring Air Leakage in Buildings – In 2009, the U.S. Army Corps of Engineers (USACE) published an airtightness testing protocol specifically aimed at larger, commercial-style buildings as part of their program to meet energy saving targets (USACE, 2009). It was based on ASTM E779, but contained modifications to make it more applicable to larger and taller buildings which have increased wind exposure and stack effect. The primary change is that the USACE procedure specifies testing at higher pressure differentials (25 Pa to 75 Pa) with at least 10 data points in this range. Also, the standard requires that the test be conducted under both pressurized and depressurized conditions to better account for any bias. Like CGSB 149.10 and ASTM E779, the original version of the USACE standard only described the testing protocol but did not contain any airtightness targets.

Based on the experiences gained with the original 2009 version of the document, an updated version was released in 2011 (Version 2). However, reflecting the evolving understanding of testing larger buildings, the USACE recognized that an even newer version of their standard was required. Since much of this knowledge existed in the private sector – among private consultants, equipment manufacturers, testing firms, etc. – the USACE decided to develop this updated version in conjunction with the Air Barrier Association of America (ABAA) – see below.

U.S. Army Corps of Engineers/Air Barrier Association of America – The USACE, working with ABAA, a private sector industry organization, published Version 3 of the USACE standard with the slightly modified title *Air Leakage Test Protocol for Building Envelopes* (USACE, 2012). This was published in 2012 although the USACE and ABAA continued development of the test standard given that new information continued to appear which had not found a place in the document. One goal of this on-going process has been to develop the standard into a form which would permit it to be published by the American Society for Testing and Materials (ASTM) since ASTM publishes hundreds of standards pertaining to construction, many of which are referenced in American, Canadian and international building codes. As of the writing of this report, this process is still underway.

Unlike CGSB 149.10 and ASTM E779, the USACE/ABAA standard not only describes the testing procedure, it also contains an airtightness target. Specifically, this target is a Normalized Leakage Rate (NLR_{75}) of 1.27 $L/s•m^2$ (0.25 cfm/ft^2), discussed further below. Although no final decision has been made, it is anticipated that this target will eventually be reduced to 0.76 $L/s•m^2$ (0.15 cfm/ft^2).

3.2 Metrics for Reporting Airtightness Test Results

As described earlier, an airtightness test is used to measure the building's airtightness rate at a series of pre-defined, indoor-to-outdoor pressure differentials. This data is mathematically combined to produce a regression curve of the form described in Eq. (1) on page 6, sometimes referred to as the 'Power Law Function'.

Notice that Eq. (1)`s an empirical relationship that has to be measured on the actual building; it cannot be calculated or otherwise predicted with any degree of confidence using construction drawings, on-site inspections, computer modelling or any other means. While this statement applies to all buildings, it is particularly relevant when discussing larger commercial structures of the type investigated in this study.

One of the problems encountered with discussions of air leakage is that several different metrics are commonly used for reporting building airtightness data. The most basic approach is to report the overall air leakage at some specified pressure differential (e.g., "X" litres per second at a building pressure differential of 75 Pa). The primary limitation of this approach is that building size is not factored into the equation. A leakage rate of 1000 L/s in a large, commercial building could indicate a very tight structure whereas the same leakage rate in a small house would indicate a very loose building. Building size is normally introduced into airtightness metrics using either the building volume or the envelope surface area. For example, residential airtightness tests are commonly reported using the "air change rate per hour at an indoor-to-outdoor pressure differential of 50 Pascals", as shown below in Eq. (2). This is a volume-based metric and has been used extensively since the earliest days of airtightness testing.

Air change rate at 50 Pascals:

$$ac/hr_{50} = \frac{\text{Total Leakage Rate at 50 Pa (expressed in building volumes)}}{\text{Building Volume}} \qquad \textbf{(2)}$$

For larger, commercial building tests (such as those used in this study), the most common method of expressing results is to use the "Normalized Leakage Rate at 75 Pa" (NLR_{75}), which is a building envelope, area-based metric as defined by Eq. (3) below.

Normalized leakage rate at 75 Pascals:

$$NLR_{75} = \frac{\text{(Total Leakage Rate at 75 Pa)}}{\text{Envelope Area}} \qquad \textbf{(3)}$$

In North America, the ‘Envelope Area’ in Eq. (3) is defined to include both the above-grade and below-grade portions of the building envelope. In Europe (or at least some of its constituent countries), only the above-grade portions of the envelope are included in the term. In all cases however, the dimensions used to calculate the envelope area are based on the building's interior, not exterior, dimensions. This is noted because it is contrary to common practice in the real estate industry which often uses exterior dimensions to describe a building's size.

Various other metrics, and various other pressure differentials, are also used to express airtightness. However, the NLR_{75} and ac/hr_{50} are by far the most common and, for that reason, are used in this report.

One point seldom recognized about airtightness testing metrics is:

> *Volume-based metrics (such as ac/hr_{50}) provide a commentary on the energy load which air leakage creates in the building since it describes the volumetric flow rate that the building experiences and the volumetric flow rate defines how much air has to be heated or cooled. In contrast, area-based metrics (such as the NLR_{75}) provide a commentary on the threat posed to the building envelope by air leakage-induced moisture deposition, since it is the moisture loading per unit area of building envelope which has to be controlled if building durability is to be safeguarded (Proskiw Engineering Ltd., 2004).*

Of course, since both metrics are basically describing the same thing (how leaky is the building), it should come as no surprise that both the NLR_{75} and ac/hr_{50} tend to generally behave in a similar – although not exact – fashion.

Obviously, both energy performance and envelope durability are of concern for buildings. However, observing the respective metrics used to describe residential versus commercial building leakage, it is apparent that residential airtightness results are designed (intentionally or otherwise) to emphasize energy conservation whereas commercial airtightness results focus on envelope protection and durability.

In this report, airtightness data is primarily reported using the Normalized Leakage Rate at an indoor-to-outdoor pressure differential of 75 Pascals (i.e. Eq. 3) since this is standard practice in the literature. Since the NLR_{75} is commonly reported using both metric and imperial units, both are shown in this report with metric results reported first followed by the equivalent imperial units. In addition, the results are presented using the air change rate at 50 Pascals (ac/hr_{50}). While this metric is most commonly used for residential buildings, it is also reported herein because of the commentary it provides for energy purposes.

3.3 Airtightness Standards

3.3.1 Airtightness Standards for Houses

Before considering commercial building airtightness standards, it is worthwhile to briefly review parallel activities in the low-rise housing sector – given the latter's longer development history and practical application in the field.

Numerous airtightness standards have been developed both in Canada and internationally for low-rise residential construction (i.e., detached, semi-detached and row houses). In Canada, the tradition of airtightness testing complete with formal, quantitative requirements dates back more than 30 years with introduction of the R-2000 Program, now the *R-2000 Standard* (NRCan, 2012). This Standard specified that an airtightness test had to be performed on every R-2000 house and the measured leakage rate could not exceed 1.5 air changes per hour at a pressure differential of 50 Pascals (or have an Normalized Leakage Area at 10 Pa which does not exceed 0.7 cm^2/m^2) when tested in accordance with *CAN/CGSB 149.10 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method*.

Recently, the *National Building Code of Canada 2010* (NBC) was modified with the addition of *Section 9.36 Energy Efficiency* that describes prescriptive design features for airtightness that, it is anticipated, will result in an air change rate that does not exceed 2.5 ac/hr_{50} at 50 Pascals, although this target is not explicitly stated in the document (NRC, 2012). However, there is no requirement for actual testing of the dwelling nor is this target specified as a requirement which has to be met.

3.3.2 Airtightness Standards for Commercial Buildings

At present, there are no mandatory or voluntary airtightness requirements in Canada for commercial buildings of the type studied in this project. The 2010 NBC and the *National Energy Code of Canada for Buildings 2011* (NECB) provide some general requirements on air barrier continuity although these are more qualitative than quantitative (NRC, 2010 and 2011). For example, the 2011 NECB states that "*the building envelope shall be designed and constructed with a continuous air barrier system comprised of air barrier assemblies to control air leakage into and out of the conditioned space*" and that "*all opaque building assemblies that act as environmental separators shall include an air barrier assembly*".

Further, materials used as part of the air barrier assembly must have a measured leakage rate that does not exceed 0.02 L/s•m^2 at a pressure differential of 75 Pascals. However, it should be noted that (at the time of writing) consideration was being given to the possible inclusion of quantitative airtightness requirements for commercial buildings in a future edition of the NECB.

In the United States, the most widely used energy code is the *International Energy Conservation Code* (IECC) (IECC, 2012). The 2012 edition introduced requirements for commercial building airtightness that can be met by using either materials or assemblies which have demonstrated low leakage characteristics or by testing the completed building. If the test option was selected, the maximum measured NLR_{75} could not exceed 2.03 L/s•m^2 (0.40 cfm/ft^2).

Perhaps the most aggressive promotion of commercial building airtightness requirements has been provided by the U.S. Army Corps of Engineers (USACE) who are responsible for establishing building standards for U.S. military construction. As previously discussed, in 2012 they introduced a NLR_{75} airtightness requirement of 1.27 L/s•m^2 (0.25 cfm/ft^2) at 75 Pa for all new construction. Further, it is believed that they are considering lowering this target to 0.76 L/s•m^2 (0.15 cfm/ft^2), see Table 1.

Table 1 – Current Airtightness Performance Standards for Commercial Buildings

Airtightness Requirement	**Maximum Permitted NLR_{75}**	
	Metric (L/s•m^2)	**Imperial (cfm/ft^2)**
2012 International Energy Conservation Code	2.03	0.40
2012 USACE/ABAA Air Leakage Test Protocol for Building Envelopes Version 3 – May 11, 2012	1.27	0.25
Proposed USACE/ABAA Air Leakage Test Protocol for Building Envelopes	0.76	0.15

3.3.3 Airtightness Standards – Commercial Building Air Barrier Systems

While the 2010 NBC does not contain any whole building airtightness requirements for commercial structures, it does contain recommendations for commercial building air barrier systems (NRC, 2010). The NBC describes an air barrier system as those portions of the building envelope which are opaque and insulated (i.e., this includes walls, ceilings, foundations, etc. but excludes windows and doors and other openings). The recommendations are shown in Table 2 and illustrate how the system requirements vary depending on the anticipated indoor relative humidity – as the relative humidity increases, the maximum recommended system air leakage decreases, thereby providing additional protection against moisture transport through the building envelope.

Table 2 – NBC Recommended Maximum Air Leakage Rates for Air Barrier Systems

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

Comparing the recommendations for air barrier systems to those shown in Table 1 on page 11 for whole buildings, it is apparent that the system recommendations are far more rigorous than those for the entire building. This is to be expected since, as previously discussed, most of the air leakage in a building does not occur through the large expanses of the walls, ceilings or foundations, but rather through the joints, intersections and penetrations which interrupt these surfaces.

'System' recommendations basically define airtightness performance requirements for the major components that make up the building envelope while 'whole building' requirements address how effectively these components are assembled into a complete structure. This is analogous to how the Carnot efficiency is used in thermodynamics to describe the most theoretically efficient cycle for converting a given amount of thermal energy into work. If a building could be constructed such that there was no leakage through the joints, intersections and penetrations, then the system recommendations in Table 2 could theoretically be achieved for the whole building. Of course, this never occurs in reality but since the system recommendations represent the best possible scenario for building envelope components, they also represent the best possible airtightness performance for a structure constructed from systems that meet the NBC recommendations.

Most Canadian buildings operate with indoor relative humidity levels in the middle range of Table 2 (i.e., 27% to 55% RH) during the heating season and, for that reason, a system leakage value of 0.10 (L/s•m^2) is often used when discussing typical air barrier system requirements. This value will be referenced later when discussing the measured airtightness results from this project.

3.3.4 Comparative Airtightness Testing Data – Results from the Literature

An estimated 250,000 to 500,000 Canadian houses have had their airtightness measured over the last 35 years. In Manitoba, which has a long history of energy efficient construction and airtightness testing, the number of houses that have been tested is estimated to exceed 30,000. In contrast to residential construction, the number of commercial buildings that have been tested for airtightness is (at best) a few hundred. Further, prior to this project the number of commercial buildings in Manitoba that had been tested for airtightness was only a small handful, estimated at less than 10. This meant that the overall existing knowledge base on commercial building airtightness data has been very limited.

Fortunately, some commercial buildings have been tested, their results documented and reported in the literature. To provide some comparative data to interpret this project's results, three primary references were identified and used as benchmarks for interpreting the results of this study:

1. ASHRAE Project 1478-RP "*Measuring Airtightness of Mid- and High-Rise Non-Residential Buildings*", May 13, 2014. Wiss, Janney, Elstner Associates, Inc.

   This project measured the airtightness of 16 new buildings, with heights ranging from 4 to 14 stories constructed since 2000. The tested buildings were located in the United States, specifically in Climate Zones 2 through 7 of the *International Energy Conservation Code (IECC) Climate Zone Map* (WJE, 2014). (NOTE: Manitoba’s climate zones consist of 7(a), 7(b) and 8).

2. "*Air Leakage Control in Multi Unit Residential Buildings, Development of Testing and Measurement Strategies to Quantify Air Leakage in MURBS*". April 2, 2013. RDH Building Engineering Ltd.

   This literature survey, commissioned by Canada Mortgage and Housing Corporation (CMHC), was primarily interested in documented airtightness results for Multi-Unit Residential Buildings (MURBs) since that is CMHC's primary focus (RDH, 2013). The report contains results from 296 buildings in Canada and the U.S. although only 43 of these were MURB's. Most of the results (245 out of 296, or 83%) came from tests performed for the U.S. Army Corp. of Engineers on American military buildings.

3. *Air Leakage Characteristics, Test Methods and Specifications for Large Buildings*. March , 2001. Proskiw Engineering Ltd.

   This literature survey, carried out for CMHC, was a precursor to the RDH study described above. It identified airtightness results from 192 buildings in Canada (including five in Manitoba), the U.S., Great Britain and Sweden. It should be noted that some of the results in the PEL report (approximately 5% to 15%) were also referenced in the RDH report.

It is also worth noting that the first two studies (ASHRAE and RDH) were both released within the last year while the third report (PEL) is almost 14 years old.

4.0 Airtightness Test Personnel, Process and Observations

4.1 Project Team

Members of the project team, their affiliations and roles included:

Rob Spewak, Applied Research and Commercialization Manager, Red River College – Rob coordinated and provided overall responsibility for RRC's involvement in the project. He also assisted with several of building airtightness tests and the review of this report.

Ken Klassen, CARSI Research Professional, Red River College – Ken provided general assistance and guidance for the overall project and coordinated the assembly and final drafting of this report. Similar to Rob, Ken also assisted with several of the building airtightness tests.

Kevin Knight, Research Associate, Red River College – Kevin provided technical support and onsite management of the airtightness tests. This included recruiting and interfacing with building owners and operators, and supervision of the RRC students who assisted with most of the airtightness tests. Kevin also assisted with the drafting and review of this report.

Cory Carson, SITRG Mechanical Engineering Research Associate, Red River College – Cory coordinated the logistics for each airtightness test including securing supplies and rental equipment. He also led the set-up and operation of the airtightness testing equipment for each building.

Harry Schroeder, Customer Engineering Services, Manitoba Hydro – Harry served as Manitoba Hydro primary contact with RRC-SITG and Proskiw Engineering for the development and implementation of this project. He also helped with the selection of buildings for testing (including several from Manitoba Hydro) and, similar to Rob and Ken, also assisted with several of the airtightness tests.

Gary Proskiw, Proskiw Engineering Ltd. – Gary provided overall guidance for the technical aspects of choosing the airtightness testing protocol, training of RRC students employed by the project and the onsite testing of each building in the project. In addition, Gary also played a major role interpreting the test results and contributing to the drafting and review of this report.

Architectural & Engineering and Mechanical Engineering Technology Students – Using funding from the Natural Sciences and Engineering Research Council (NSERC), RRC hired several students enrolled in the college's Architectural & Engineering and Mechanical Engineering Programs to assist with the testing (i.e., equipment set-up and tear-down, building preparation, etc.).

4.2 Building Selection

The original goal for the project was "*to determine baseline airtightness rates in a sample of up to 20 commercial buildings in Manitoba that represent a range of ages and types of buildings*." A minimum of three of these buildings were to be facilities owned and operated by Manitoba Hydro to reflect their financial and in-kind support for this project.

This goal was exceeded with 26 buildings eventually selected and tested, five of which were Manitoba Hydro facilities.

Suitable buildings tested under this project were identified by project team members through their networks of personal contacts. An effort was made to identify at least a few buildings that were scheduled to receive, or recently had, a major building envelope retrofit.

Although most of the buildings eventually selected for testing were in the Winnipeg Capital Region, an effort was made to also test at least two buildings in Western Manitoba and two in Northern Manitoba. This mix of buildings and locations was intended to provide a reasonably representative database of airtightness rates from across the province. Refer to Section 5.0 and Table 3 for additional detail about the various subsets of buildings tested by the project based on their age, type or retrofit status.

(NOTE: For the purposes of this project, 'commercial' buildings were deemed to be residential and non-residential buildings from both the private and public sector. This included institutional buildings such as schools, churches and light industrial buildings, especially those that included other uses such as an office component).

4.3 Diagnostic Test Equipment

Equipment and software used to test the buildings under this project was provided by RRC-SITRG. With the assistance of a NSERC Applied Research Tools and Instruments (ARTI) grant, RRC-SITRG has acquired a high performance, multi-fan blower door system from Retrotec Inc. that is capable of testing a wide range of commercial buildings (see Figure 1).

During the project when weather and timing permitted, this multi-fan blower door system was supplemented by other diagnostic tools (i.e., a thermal imaging camera and a video boroscope) for assessing building envelope performance acquired by RRC-SITRG through its ARTI grant.

Figure 1 – Multi-Fan Blower Door System Used for Airtightness Testing

4.4 Selection of an Airtightness Test Protocol

Sub-section 3.3 briefly reviewed the evolution of airtightness testing standards, particularly those intended for larger, commercial buildings. Based on this information, it was decided that the most appropriate methodology for the project described in this report was the USACE/ABAA standard, Version 3 published in 2012. However, as mentioned, this document was under active review by its technical committee when the selection was made for this project by RRC-SITRG. Further, three of the team members who worked on the RRC project described in this report were also actively participating in the review process.

In some respects, the RRC-SITRG project was used as a test bed for possible changes to the USACE/ABAA document. One of these issues, the treatment of intentional openings, had great significance to the current project and needs to be discussed separately (see Sub-section 4.5 below) since it impacted the testing protocol eventually used in this project.

It is also standard practice to perform commercial building airtightness tests by conducting separate tests with the building depressurized and then pressurized. The final building airtightness is then calculated as the average of these two sets of results. This practice was used on 23 of the 26 buildings tested in this project. The remaining three were tested under depressurization conditions only.

4.5 Treatment of Intentional Openings

Intentional openings in the building envelope are those openings deliberately introduced as part of the design process and typically include air intake or exhaust louvers, make-up air intakes, pressure relief dampers or louvers, dryer and exhaust vent dampers and any other intentional hole that is not included in the air barrier design or construction. In most cases, these are simply entry or exit points for the mechanical system. For example, the relevant portion of the USACE/ABAA standard, Version 3, Section 4.8.2 which discusses the building preparation states:

> *The following requirements pertain to masking HVAC openings other than flues:*
>
> a. *The test is conducted with ventilation fans and exhaust fans turned off and the outdoor air inlets and exhaust outlets sealed (by dampers and/or masking),*
> b. *Motorized dampers must be closed and may be tested masked or unmasked,*
> c. *Undampered HVAC openings must be masked during testing, and*
> d. *Gravity dampers shall be prevented from moving or can be masked*.

To understand the rationale for this sealing schedule it is necessary to briefly delve into the history of airtightness testing. As far as can be determined, the concept of sealing intentional openings is believed to date back to the mid-1980s when CGSB 149.10 was developed. This contained a sealing schedule believed to have been predicated on the notion that the purpose of an airtightness test was to generate a number that could be used, in some form, as part of a building energy simulation. Thus, intentional holes should be sealed if their leakage was accounted for in some other energy modelling input. For example, a naturally aspirated furnace vent would be sealed since the inefficiency caused by air leakage through the vent was already accounted for in the furnace efficiency.

However, for commercial buildings, this logic may not be appropriate. To illustrate, if a building owner has spent a million dollars to install a (ostensibly) high performance air barrier on a new building, then the owner will presumably want the airtightness test to provide some indication of how well the air barrier has been installed by comparing the measured leakage to some standard or contract requirement. Since air leakage through intentional openings would not be the issue in such a situation, the building's intentional openings would be sealed.

Conversely, if the concern is energy performance then air leakage through both the building envelope and mechanical penetrations (including that which occurs through leaky dampers) is of interest. For example, consider the sealing schedule in the USACE/ABAA standard. Some of the buildings encountered in this project used simple gravity dampers on large exhaust air fans which open to allow air to be exhausted but then, under depressurization conditions, close and prevent air from leaking into the building. According to the USACE/ABAA standard, these should be sealed. However, if energy is the issue, this may not be appropriate. What if the fan is off, but located on the leeward side of the building? Under such a condition, air would be free to leak out through the dampers thereby adding to the energy load. Presumably then, the exhaust fan/dampers should not be sealed for an airtightness test – contrary to conventional practice for the treatment of intentional openings.

This realization, that there should be two sealing schedules employed for intentional openings on commercial buildings, was recognized by the RRC-SITRG project team during the field testing phase of this project. This information was transmitted back to the USACE/ABAA technical committee where it was discussed and ultimately incorporated into the draft standard. This is believed to be the first North American building airtightness testing standard that will recognize this distinction. It is worth noting that this observation was a direct by-product of the RRC project.

Depending on the building, leakage through unsealed intentional openings can exceed that through the rest of the building envelope. For example, Building #18 in this RRC-SITRG project was tested using both sealing schedules. In the 'envelope' configuration, the measured NLR_{75} (discussed below) was 1.20 L/s•m^2 (0.24 cfm/ft^2), whereas in the 'energy' condition, this increased by 37% to 1.62 L/s•m^2 (0.32 cfm/ft^2).

For these reasons, most of the buildings tested in this project used (what has become known as) the 'envelope sealing schedule' (i.e., all mechanical penetrations were sealed). However, six of the buildings used the 'energy sealing schedule' (i.e., only some of the intentional openings were sealed and one (Building #18) used both. This is not a minor technical issue, since on some buildings use of the 'energy sealing schedule' significantly increased the measured air leakage rates. While this is undesirable from a consistency perspective, it should be appreciated that the 'energy' air leakage rate will always be greater than the 'envelope' air leakage rate. Therefore, even though both sealing schedules were used in this project, the 'energy' results represent the worst-case scenario. A building which was sealed according to the ‘energy’ schedule would always have a higher air leakage rate if tested according to the ‘envelope’ schedule.

5.0 Airtightness Test Results and Discussion

5.1 Presentation of Results

This section reviews the airtightness results from the 26 buildings tested during the project. Results from the complete sample of 26 are discussed first, followed by separate discussions on various subsets of buildings based on their age, type or retrofit status, as summarized in Table 3. (NOTE: Results for some buildings appear in more than one category.)

Table 3 – Categorization of Buildings Tested

Category	Number of Buildings
Complete sample	26
New construction	5
Warehouses/light industrial	11
Office buildings	7
Schools	4
Churches	2
Greenhouses	2
Retrofits	3

Each of the building categories shown in Table 3 is discussed below using the following format to present the results:

Summary of Airtightness Test Results – This summarizes both the mean and the range of the measured NLR_{75} and ac/hr_{50} values for each subset of buildings. In addition, the most significant air leakage locations observed during the field tests are listed.

Comparative Results – Applicable data from the three primary references (i.e., ASHRAE, RDH and PEL reports – see page 13) are provided to serve as benchmarks against which the results of this report can be compared.

Airtightness Results **–** This provides a more detailed summary of the measured results and is expressed in separate tables for metric and imperial units. In each table, which can be found in Appendix A, there are three columns of results: (1) those obtained during the depressurization portion of the airtightness test, (2) those from the pressurization portion of the test; and finally (3) the average (mean) results from the two tests. The mean results are the most important and should be used for comparisons to other airtightness data in the literature.

These tables also summarize the buildings' critical geometric data (envelope surface area and volume) as well as the mean:

- Flow coefficient (C)
- Flow exponent (n)
- Normalized Leakage Rate at 75 Pa (NLR_{75})
- Air change rate at 50 Pa (ac/hr_{50}) and
- Flow rate at 75 Pascals (useful for determining fan capacity required to perform the test).

For each of these parameters, the results show the: arithmetic mean value, standard deviation, range and the number of buildings in that particular subset.

The results are also shown graphically for each building category (see Figure 2 on page 20) along with the following reference airtightness targets (discussed above):

- 2012 IECC (2.03 L/s•m^2)
- 2012 USACE/ABAA (1.27 L/s•m^2)
- 2010 NBC Air Barrier System Recommendation (0.10 L/s•m^2)

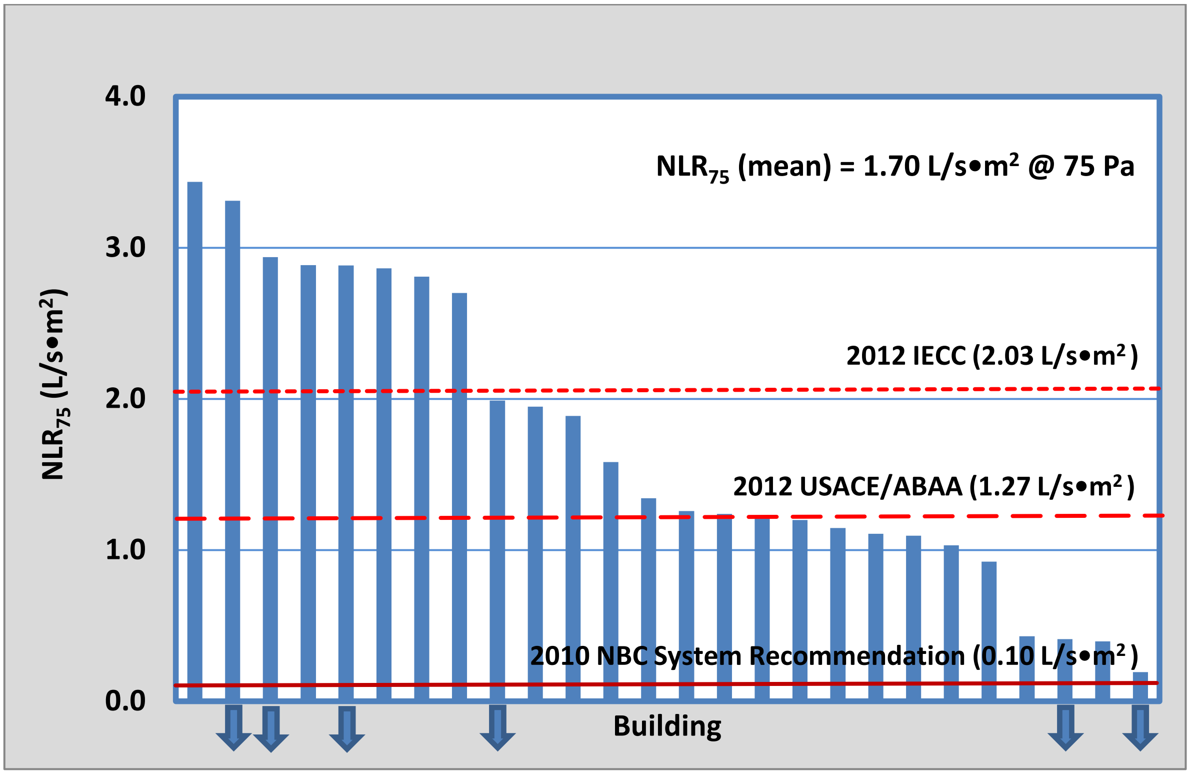
These targets are not presented as definitive, reasonable or even desirable goals, but rather as indications of what others have suggested or proposed as being appropriate. Further, it should be appreciated that that the two building targets (2.03 and 1.27 L/s•m^2) are American standards developed largely on American experiences and their current air barrier technology. Canadian experiences and knowledge are generally more advanced in this field than those in the U.S., so the appropriateness of the American targets has yet to be vetted against Canadian capabilities. Finally, it is important to recall that the final target shown, 0.10 L/s•m^2, is a recommended (not mandatory) *system* requirement, and is not a whole building target. As described in Section 3.0, it is used here to represent a theoretical, even ultimate, airtightness target.

In each graphical summary of a building subset, such as “New Construction” or “Schools”, the results from the entire 26 building sample are displayed, but with the buildings in the designated subset identified in yellow as follows:

Finally, the six buildings tested using the "energy" sealing protocol are identified by the following downward facing, blue arrows positioned on the graph's x-axis:

As described earlier, when a building is tested using the ‘energy’ sealing protocol, the leakage will always be higher than if it had been sealed using the ‘envelope’ protocol. So, for the six buildings tested using the "energy" protocol, the leakage rates shown on the graphical summaries represent the maximum possible leakage. Had these tests been conducted using the ‘envelope’ sealing protocol, the measured leakage would have been *lower* than that shown.

Figure 2 – Reference Airtightness Standards Used in This Report



5.2 Complete Sample (26 Buildings)

5.2.1 Description of Buildings

The 26 buildings in the overall sample were located across Manitoba with 18 (69%) situated in the greater Winnipeg area. They ranged in age from one to over 100 years.

In terms of size, their floor areas ranged from 150 m^2 to 19,788 m^2 (1,615 ft^2 to 212,918 ft^2), a variation of 132:1 between the largest and the smallest. (NOTE: In this report building floor areas are reported using interior dimensions as opposed to using exterior dimensions). Volumes varied from 587 m^3 to 66,304 m^3 (20,710 ft^3 to 2,340,079 ft^3).

Building height ranged from one to 16 stories (approximately 58 m or 189 ft.). Manitoba Hydro owned five of the buildings while the remainder were occupied by a variety of private and public owners.

5.2.2 Airtightness Test Results and Summary

Table 4 – Summary of Airtightness Test Results for Compete Sample of All Buildings

	No. of Buildings	NLR_{75} (mean and range)		ac/hr_{50}
		L/s•m^2	ft^3/min•ft^2	
Complete Sample	26	1.70 (0.19 - 3.44)	0.34 (0.04 - 0.68)	2.33 (0.19 - 5.92)

Table 5 – Comparative Results for Complete Sample of All Buildings

	No. of Buildings	NLR_{75} (mean and range)		Notes
		L/s•m^2	ft^3/min•ft^2	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	40	3.96 (0.81 - 10.00)	0.78 (0.16 - 1.97)	MURB's only
PEL (literature survey)	41	2.12 (0.23 - 6.37)	0.42 (0.05 - 1.26)	Canadian buildings only

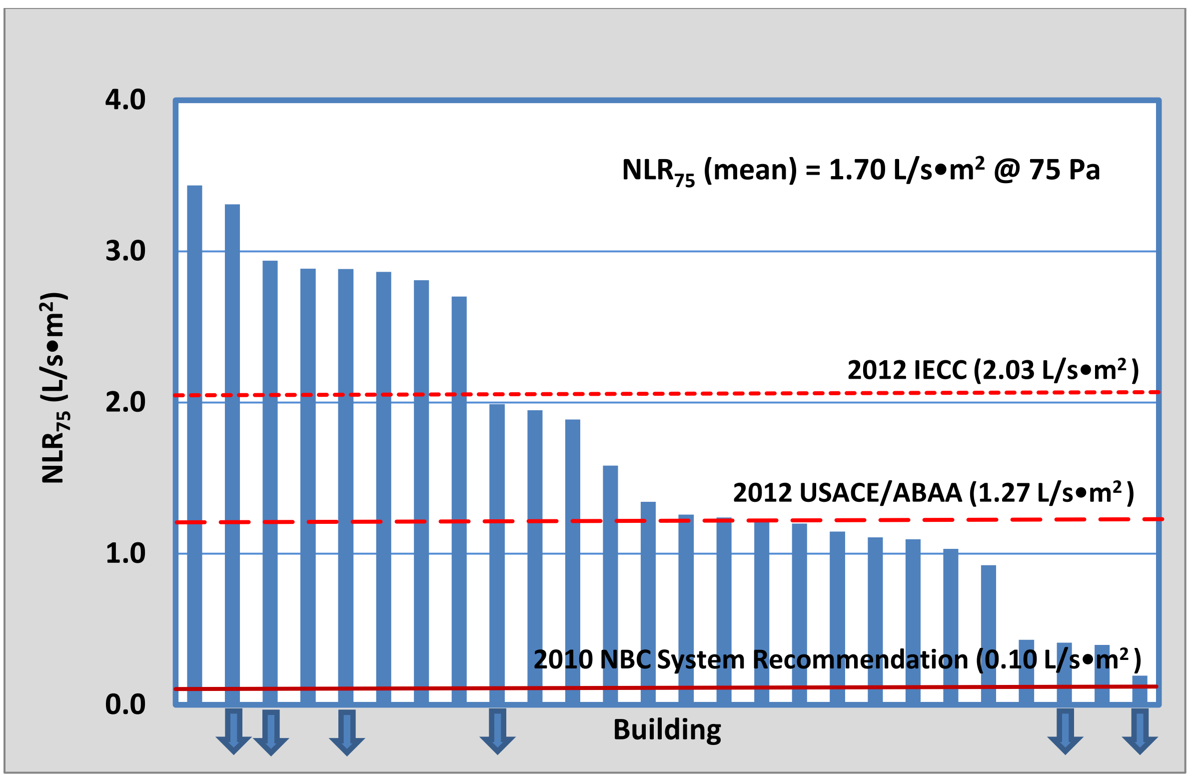
5.2.3 Discussion

The complete sample of 26 buildings tested for airtightness in this project displayed a wide variation in all relevant factors that can influence airtightness (e.g., age, year of construction, building height, wall construction, etc.).

The measured NLR_{75} values ranged from 0.19 to 3.44 L/s•m^2, a variation of almost 18:1 between the leakiest and tightest buildings tested. The mean NLR_{75} of the entire sample was 1.70 L/s•m^2, which is surprisingly similar to the mean value reported in the ASHRAE survey of new buildings (1.47 L/s•m^2), even though most of the buildings in the ASHRAE study were designed and built to comply with some voluntary standard such as LEED. Only a handful of the buildings in the RRC study were designed and constructed with any explicit concern for airtightness.

Further, the Manitoba buildings tested for this project performed significantly better than those identified in the previous literature reviews by RDH or PEL.

Figure 3 – Normalized Leakage Rate for Complete Sample of 26 Buildings Tested



5.3 New Construction (5 Buildings)

5.3.1 Description of Buildings

Five of the tested buildings were classified as new construction for the purposes of this project (i.e., they were less than five years old at the time of the test). They consisted of two warehouse-type structures (one of which was the CARSI building at Red River College), one school, one recreational structure and one school office building.

5.3.2 Airtightness Test Results and Summary

Table 6 – Summary of Airtightness Test Results for New Buildings

	No. of Buildings	NLR_{75} (mean and range)		ac/hr_{50}
		$L/s\bullet m^2$	$ft^3/min\bullet ft^2$	
New construction (less than 5 years old)	5	0.95 (0.19 - 3.31)	0.19 (0.04 - 0.65)	1.09 (0.19 - 3.20)
Major Air Leakage Locations				
• Exhaust and make-up air fans with one-way dampers • Roof wall intersections; especially on walls running perpendicular to roof deck flutes • Overhead doors				

Table 7 – Comparative Results for New Buildings

	Number	NLR_{75} (mean and range)		Notes
		$L/s\bullet m^2$	$ft^3/min\bullet ft^2$	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	See Text			
PEL (literature survey)	34	4.52 (0.23 - 12.72)	0.89 (0.05 - 2.51)	Canadian, U.S. & U.K. buildings
PEL (literature survey)	20	2.45 (0.23 – 4.01)	0.48 (0.05 – 0.79)	Canadian buildings only

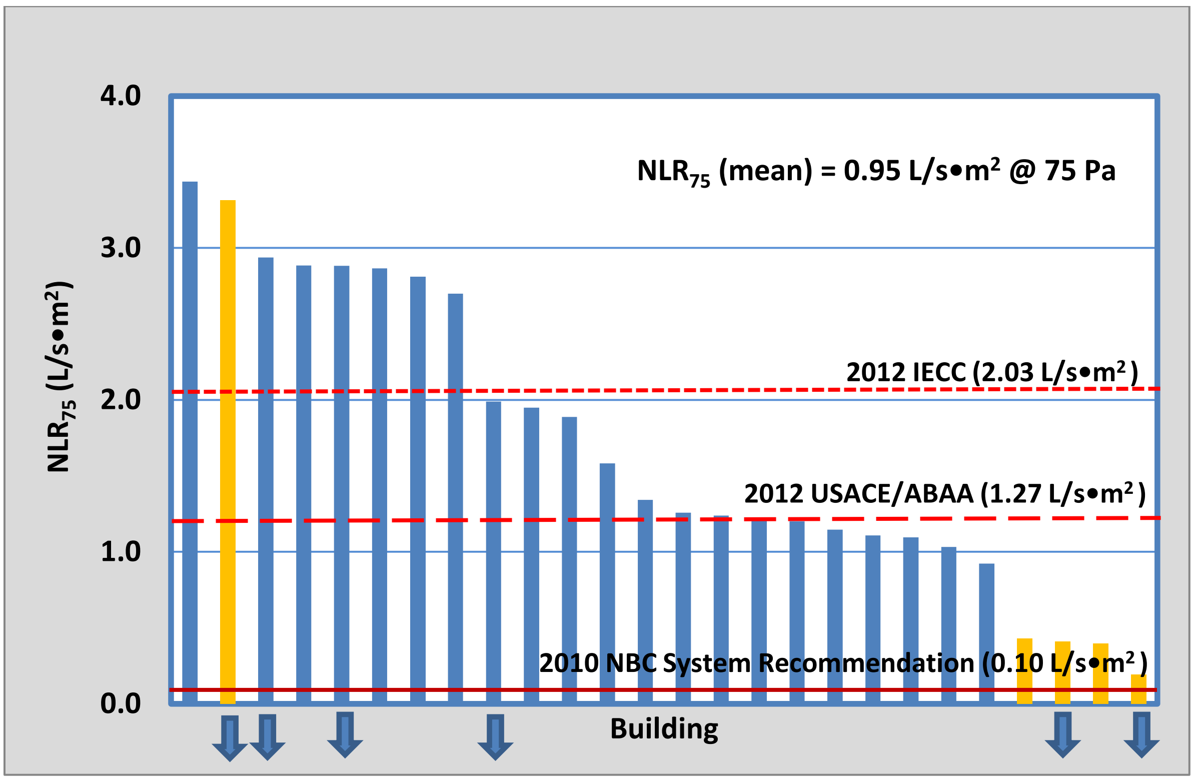
5.3.3 Discussion

Although the sample size of five buildings was not large, it did provide a solid glimpse into the airtightness characteristics of new construction in Manitoba. And, as discussed below, it demonstrated what can be achieved using existing technology, skills and products currently possessed by the local construction industry.

Examining the results, the airtightness of the five Manitoba buildings was surprisingly good. For example, the mean NLR_{75} of the five Manitoba new-builds was only about two-thirds that measured during the recently completed ASHRAE project (which was restricted to new construction).

The Manitoba results become more impressive when it is recognized that 12 of the 16 buildings in the ASHRAE project participated in an environmental labelling program (such as LEED) in which deliberate efforts were often made to achieve a higher quality building envelope and tighter air barrier system. Also, the report's authors state that the "*data set is biased towards tighter buildings due to self-selection and volunteerism by owners and architects*". However, this must be tempered with the knowledge that all of the 16 buildings were constructed in the United States, which lags somewhat behind Canadian expertise in achieving airtightness in commercial construction.

Figure 4 – Normalized Leakage Rate for New Buildings (yellow bars)



The RDH report did not provide an explicit tabular summary of results for new construction, but examination of some of the graphical results suggests about 20 buildings were included (including several which were first documented in the PEL study discussed below). Based solely on the graphical evidence, the NLR_{75} values in the RDH report ranged from about 1.8 to 5.0 L/s•m^2 for the new buildings in the RDH study.

The PEL report did not include a breakdown of the average airtightness for newly constructed buildings, so the original data from that project was re-examined to provide the relevant results.

This showed that 34 buildings were classified as new construction. However, the PEL report preceded the other two primary references by about 12 years which means it was reporting on older construction – in some cases on buildings constructed as early as 1970. Also, American and U.K. buildings were included in the original group of 34. Therefore, the original group was edited to eliminate the American and U.K. entries, thereby producing data for 20 (then) new, Canadian buildings. Comparing these results, the average NLR_{75} of the five new buildings in the present study was 0.95 L/s•m^2 versus 4.52 L/s•m^2 for the 34 Canadian, American and U.K. buildings, and 2.45 L/s•m^2 for the Canadian-only buildings in the PEL report.

Overall, the five new Manitoba buildings performed quite well compared to other new buildings reported in the literature. As noted, their average NLR_{75} of the Manitoba new-builds was about two-thirds that of the 16 buildings in the ASHRAE study which, themselves, were biased towards tighter construction. Further, the Manitoba results were well below those reported in the legacy literature for airtightness of comparable buildings.

Figure 5 – Exhaust Fan with Backdraft Dampers

While the Manitoba results for new construction appear impressive, they actually understate the true performance. Closer examination of the test results revealed a discrepancy between the depressurization and pressurization results for Building #1, a newly constructed warehouse. The measured NLR_{75} in the depressurization portion of the test was 1.85 L/s•m^2, while during the pressurization test it was 4.78 L/s•m^2. This difference in results is far outside the normal variation that occurs during airtightness tests. However, examining Figure 5, the reason for this difference becomes clear. The building contained a number of large capacity exhaust fans equipped with gravity-operated backdraft dampers which were held shut during the depressurization test but opened fully during the pressurization test, thereby significantly increasing the overall leakage rate of the building. As discussed below, these fans were not sealed in Building #1 during either the depressurization or pressurization tests.

If the results for Building #1 are removed, the average NLR_{75} for the remaining four structures dropped from 0.95 L/s•m^2 to 0.36 L/s•m^2, a reduction of 62%. This is less than one-third of the recommended whole building airtightness (1.27 L/s•m^2) used by the USACE. These results are particularly interesting since Building #1 was architecturally one of the most basic buildings of the five. For example, the other new buildings included: a school with a complex floor plan and layout, multiple roof levels and dozens of mechanical penetrations of the building envelope; and a recreational complex which also used a non-standard layout, multiple roof levels and mechanical penetrations. In contrast, Building #1 was a simple rectangular structure with a single roof level, yet it was the second leakiest structure in the entire 26 building sample.

Overall, these findings indicate that designing and constructing commercial buildings with low levels of natural air leakage is achievable using knowledge and technology which now exists within the Manitoba design and construction industries. Further, these results demonstrate that very low air leakage rates can be attained even if the building is architecturally complex.

Damper Leakage – One of the major lessons from this project was the recognition that the sealing schedule used for airtightness testing must be selected based on what the test is designed to measure.

Fundamentally, all airtightness test protocols require that intentional openings in the building envelope – primarily those for the mechanical system – should be sealed during the test. The logic behind this is that while these constitute a 'hole', air which moves through them is accounted for, from an energy perspective, in either the efficiency of the mechanical device for which the hole has been made (such as a combustion heating device) or directly through calculation based on how much air is mechanically moved through the hole (such as operation of an exhaust fan, air intake or similar device). However, this logic fails to recognize that some types of mechanical devices, such as exhaust fans equipped with gravity-operated backdraft dampers, can leak significant quantities of air when the fan is off, the dampers should be closed, but wind action, stack effect or other mechanical devices create a suitable pressure differential at the fan face causing the dampers to open. This constitutes real and potentially significant air leakage which would not be identified if the sealing schedule required such openings to be sealed during the airtightness test.

While the pressurization results for Building #1 were disappointing, it must be recognized that the simple replacement of the gravity-activated damper with a power-operated unit would have reduced the building's measured leakage rate substantially – at a fairly modest cost. However, more importantly, this raises an important issue regarding mechanical dampers used in the mechanical systems of commercial buildings. Virtually all modern commercial buildings use some type of mechanical ventilation system to exhaust stale air and to introduce and distribute fresh air around the structure. In these systems, mechanical dampers are used to regulate airflow, both into and out of the system, as well as within the system itself. However, it is the dampers which control air movement directly at the face of the building envelope which are of prime importance since they (along with their exhaust, supply or recirculation fans) determine how much air is mechanically moved across the envelope.

Historically, airtightness testing protocols have required the mechanical inlets and outlets to be sealed for testing. However, this does not reflect how they are actually used or operated. Most commercial buildings are occupied for only a fraction of the time. For example, office buildings and commercial structures are usually unoccupied at night, on weekends and on holidays. During these periods, the HVAC system usually closes the dampers located at the air inlets and outlets. This means that the only significant resistance to air leakage through the inlets and outlets is that provided by the dampers.

Even if the HVAC fans are turned off, significant air leakage can still occur through the dampers if they do not seal tightly. Also, many buildings have their primary air inlets and outlets located at either the top or bottom (or both) of the building since that is where most of the mechanical system is located. However, these locations also experience the strongest stack effect which means that the dampers will be exposed to the most pronounced pressure differentials which the building normally experiences. In most cases, this will contribute (perhaps significantly) to the building's energy load although it should have minimal impact on the performance and durability of the building envelope since any air leakage past the dampers enters the ductwork and eventually the conditioned space within the building. This air does not normally transit through the insulated portions of the building envelope and should not pose a threat to the envelope.

While damper leakage can be a potentially serious issue, it should also be appreciated that any air leakage will also encounter additional flow resistances before it enters the occupied portion of the building such as that created by heating and cooling coils located in the ductwork, air filters, the ductwork itself, etc. Collectively, these can produce a high pressure drop so their resistance will mitigate damper leakage somewhat. However, the same can be said for air leakage that occurs through cracks, openings or discontinuities in the insulated portion of the envelope. For example, leakage which occurs across a wall may also encounter flow resistances caused by interior partitions, closed doors, etc. This phenomenon is described by the ‘thermal draft coefficient’ (TDC) which relates the actual pressure differential at any point on the building envelope divided by the theoretical pressure differential which would exist if there were no internal flow resistance inside the building.

While the damper air leakage issue poses a potential energy liability to the building, it is also a possible opportunity for improving building energy performance in both new and existing structures. It is therefore recommended that a review should be conducted to identify potential opportunities that would arise from using improved low-leakage HVAC dampers in commercial construction. This does not have to apply to every damper in the building’s mechanical system, only to those that regulate airflow directly across the building envelope. Manitoba Hydro may wish to explore this as a potential Power Smart program for both new and existing construction.

5.4 Warehouses and Light Industrial (11 Buildings)

5.4.1 Description of Buildings

The 11 structures in this subset consisted of a variety of small-to-medium sized warehouse-style and light industrial buildings. These structures included a retail outlet, office building, college test and research facility, town hall/fire station and a military office/construction building. Their ages ranged from less than one year to over 100 years. Five of the warehouses were owned by Manitoba Hydro; four in Winnipeg and one in Thompson. Two of the buildings were classified as new – less than five years old. This was also the largest subset of the 26 buildings tested by this project.

5.4.2 Airtightness Test Results and Summary

Table 8 – Summary of Airtightness Test Results for Warehouse/Light Industrial Buildings

	No. of buildings	NLR_{75} (mean and range)		ac/hr_{50}
		$L/s{\bullet}m^2$	$ft^3/min{\bullet}ft^2$	
Warehouses/ Light Industrial	11	1.68 (0.4 - 3.44)	0.33 (0.08 - 0.68)	2.25 (0.55 - 4.55)
Subset of Manitoba Hydro Buildings	5	1.47 (0.92 -2.89)	0.29 (0.18 – 0.57)	2.36 (1.17 – 4.55)
Major Air Leakage Locations				
• Exhaust and make-up air fans with one-way dampers • Broken/old windows • Man doors (especially at sills) • Wall (CMU)/floor slab intersections • Paint booth/dust collection systems • Overhead doors (mainly at base & sides, not between individual door panels) • Holes in walls • Unsealed walls above ceiling line • Ductwork and pipe penetrations • 1.2 m x 1.2 m (4'x4') cargo doors • Wall/roof intersection through roof flutes • Wall, floor or slab intersection				

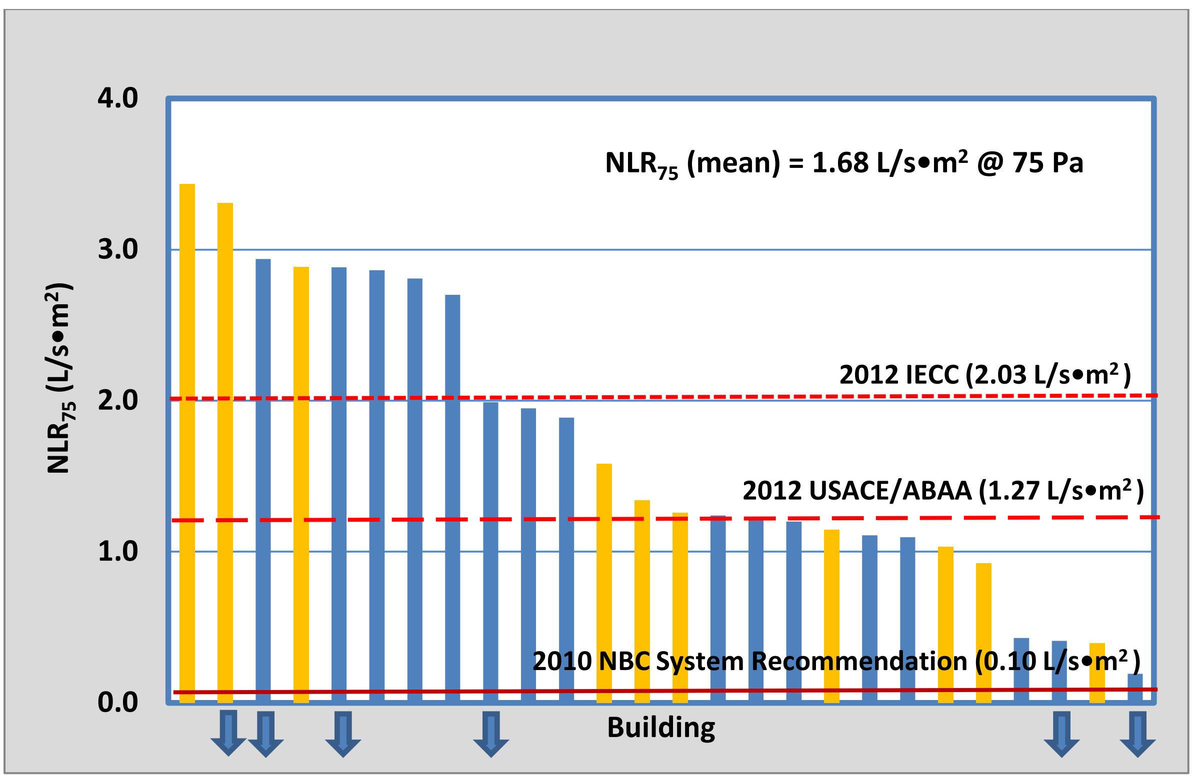
Table 9 – Comparative Results for Warehouse/Light Industrial Buildings

	No. of buildings	NLR$_{75}$ (mean and range)		Notes
		L/s•m^2	ft^3/min•ft^2	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	See Text			
PEL (literature survey)	8	1.35 (0.23 - 2.14)	0.27 (0.05 – 0.42)	Canadian buildings
PEL (literature survey)	68	6.18 (0.73 – 24.56)	1.22 (0.14 – 4.84)	U.S. buildings

5.4.3 Discussion

Overall, the 11 warehouse-style and light industrial buildings in this large subset performed surprisingly well relative to those reported in the three comparative references. For example, the average NLR$_{75}$ for these 11 buildings was only 14% greater than that of the 16 mostly new buildings in the ASHRAE sample.

Figure 6 – Normalized Leakage Rate for Warehouse/Light Industrial Buildings (yellow bars)



Further, 75% of the ASHRAE sample buildings were designed to comply with some form of environmental labelling program that include measures to achieve a high quality air barrier. Also, recall that the ASHRAE sample consisted of buildings less than five years old, whereas the average age of the warehouses/office buildings subset was about 40 years.

The RDH report did not contain any relevant data. The PEL report contained data on eight Canadian and 68 commercial buildings described as those devoted to mercantile activities (or equivalent) and which the public could access on a regular basis. The Canadian buildings included supermarkets, a post office, courthouse, library, radio station, etc. Their age ranged from new to 70 years with an average of 19 years. Physically, these were relatively low-rise structures (estimated at 3 stories or less), constructed using masonry or concrete panels, although complete data was not available in all cases. Their interior 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.

Although the 11 buildings warehouse/light industrial buildings tested by this project are not a perfect match to either the Canadian or U.S. samples, there are some parallels in terms of construction, size and function. It is interesting to note that the mean NLR_{75} value for the eight Canadian buildings in the PEL study, 1.35 L/s•m^2, was lower than both the RRC sample and the ASHRAE study of new buildings. And recall that the data from the PEL report predates this report and the ASHRAE study by 12 years. In contrast, the mean NLR_{75} for the 68 American (Florida) buildings, 6.18 L/s•m^2, was dramatically higher than any of the other sample groups. Given that all these structures were designed for a climate that is quite different from that of Manitoba, or Canada, perhaps not too much emphasis should be attached to these results.

Table 9 also contains a subset of the five Manitoba Hydro warehouse/office buildings within the larger group of 11. These five structures were constructed predominately with masonry or various types of insulated steel wall construction and ranged in age from about 12 to 40 years. The floor areas of these five buildings (calculated using interior, not exterior dimensions) ranged from 532 m^2 to 3781 m^2 (5719 ft^2 to 40,687 ft^2).

The results for the five Manitoba Hydro buildings were strangely interesting. Overall, they were slightly more airtight than the larger sample of 11 similar buildings (mean NLR_{75} values: 1.47 vs. 1.68 L/s•m^2). However, the mean NLR_{75} value for the five Manitoba Hydro buildings, with an average age of several decades, was exactly the same as the mean NLR_{75} for the 16 new buildings in the ASHRAE study, 75% of which had been designed with special attention to their air barrier.

5.5 Schools (4 Buildings)

5.5.1 Description of Buildings

Four schools were included in the 26 building sample, one in each of Winnipeg, Steinbach, St. Pierre and Swan Lake First Nations. They ranged in age from one year to over a century. The Winnipeg school, which was also one of the oldest structures in the overall sample was retrofitted during the course of the project (see sub-section 5.9 for the before and after results); the airtightness results reported below are for the "before" test.

Two of the schools had also been retrofitted with additions at one or more times during their history; the ages reported refer to the original construction. Methods of construction were varied, both between schools and within individual schools primarily because additions often used alternate methods of construction from the original structures. Older buildings generally used masonry construction which shifted to insulated wood or metal framing systems with newer schools (or additions).

5.5.2 Airtightness Test Results and Summary

Table 10 – Summary of Airtightness Test Results for Schools

	No. of buildings	NLR_{75} (mean and range)		ac/hr_{50}
		$L/s \cdot m^2$	$ft^3/min \cdot ft^2$	
Schools	4	1.12 (0.19 - 1.98)	0.22 (0.038 - 0.39)	2.13 (0.19 - 3.24)
Major Air Leakage Locations				
• Overhead doors • Wall/roof intersection (significant) • Windows and exterior doors • Electrical outlets in exterior walls				

Table 11 – Comparative Results for Schools

	No. of buildings	NLR_{75} (mean and range)		Notes
		$L/s \cdot m^2$	$ft^3/min \cdot ft^2$	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	See Text			
PEL (literature survey)	11	1.48 (0.74 - 2.11)	0.29 (0.15 – 0.42)	Canadian (Ottawa) schools

5.5.3 Discussion

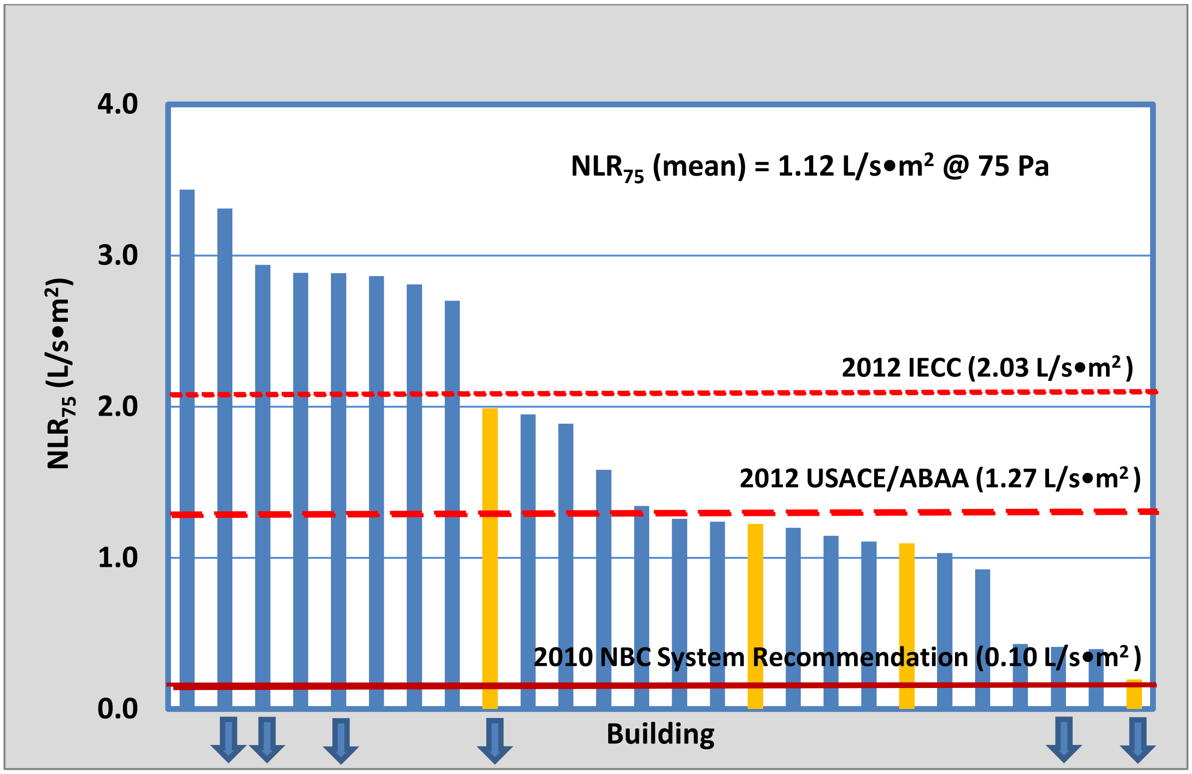
Although the sample size was not large, the results were quite interesting. Perhaps the most surprising observation is that the NLR_{75} values ranged by a factor of over 10:1 between the loosest and the tightest schools. This is largely because the most airtight structure in the 26 building sample was one of the schools in this subset – a one year old middle school which had been intentionally designed to achieve a high level of airtightness using a carefully installed air barrier. With a measured NLR_{75} of 0.19 L/s•m^2, it is obvious that they succeeded. These results are particularly encouraging because this was architecturally one of the more complex buildings in the overall sample. It contained two floor levels, multiple wall heights and roof levels, a modern integrated mechanical system with multiple penetrations through the building envelope, a powerful dust collection system that penetrated the envelope, and a very "non-rectangular" floor plan. The latter point is mentioned because buildings become significantly more complex to make airtight as their architectural design and layout becomes more intricate.

The easiest type of structure to make airtight, regardless of whether it is a commercial, residential or other type of building, is a simple rectangular shape. The more deviations which occur from this ideal, the more likely significant leakage issues will arise. The fact that this school, despite containing all these potential air leakage 'problems' could still achieve such an impressive level of airtightness is very encouraging and illustrates what can be achieved by Manitoba's design and construction industries. Also, this building was tested using the 'energy sealing schedule' for intentional openings, which means that most of the air intakes were unsealed during testing.

One of the more interesting aspects of this school was that the HVAC system dampers located at the building envelope (such as the air inlets and outlets which were controlled by motorized dampers) were surprisingly airtight. During one of the airtightness tests, a team member was "installed" inside one of the primary air-handling ducts directly behind the motorized dampers (which were located at the building envelope and thus constituted part of the air barrier) so that damper leakage could be identified with the aid of smoke wands. However, even when the building was pressurized or depressurized to the maximum pressure differential used (75 Pascals), very little air leakage could be detected over the face of the unsealed dampers. Given that the damper area was roughly 8 m^2 (85 ft^2), this is quite impressive since the dampers have to be able to tightly seal over this entire area.

Examining the ASHRAE data, the four Manitoba schools displayed an average NLR_{75} which was lower than the average value reported in the ASHRAE study – even though all of the ASHRAE buildings were less than five years old and most had been explicitly designed to achieve a high level of airtightness. In contrast, the Manitoba schools had an average age of about 50 years and only one had been designed with any concern for airtightness.

Figure 7 – Normalized Leakage Rate for Schools



The RDH report did not contain any relevant data on schools.

The PEL report contained data on 11 schools which had been tested - all located in Ottawa. Their age at the time of the test ranged from 3 to 28 years with an average of 12 years. Also, recall that the PEL report was written 12 years prior to this report. All of the Ottawa schools were single-storey, masonry structures. Overall, the measured NLR_{75} for the four Manitoba schools were similar to the 11 Ottawa schools: 1.12 L/s•m^2 vs. 1.48 L/s•m^2, although there was far more variation in the Manitoba results, as well as their type of construction and their ages.

5.6 Offices (4 Buildings)

5.6.1 Description of Buildings

The seven buildings in this category were the most geographically dispersed sub-category in the entire building sample. They were located in Winnipeg, Selkirk, Dauphin, Thompson and the Swan Lake First Nation. Several were also contained in other sub-categories. The seven buildings ranged in age from 36 to 104 years and were owned by various private and public bodies. Their heights ranged from single storey to a 16-storey office tower in downtown Winnipeg. One of the buildings was unoccupied at the time of the test and was in the process of being converted into an office building from its prior incarnation as a restaurant. Methods of construction varied, mainly reflecting their period of construction with masonry being most common in the older structures and then transitioning to metal or wood frame construction as well as one curtain wall structure.

5.6.2 Airtightness Test Results and Summary

Table 12 – Summary of Airtightness Test Results for Office Buildings

	No. of Buildings	NLR_{75} (mean and range)		ac/hr_{50}
		L/s•m^2	ft^3/min•ft^2	
Office Buildings	7	1.57 (0.41 - 2.71)	0.31 (0.08 - 0.53)	1.72 (0.49 - 3.26)
Major Air Leakage Locations				
• Underground steam lines running between buildings • Area above the ceiling line on the top floor; corners, structural steel penetrations into the envelope • Windows (old), at rough-opening and glazed unit • Window/wall (brick) intersection • Concrete window sill/wall (brick) intersection • Wall (CMU)/floor slab intersection • Paint booth/dust collection system				

Table 13 – Comparative Results for Office Buildings

	No of buildings	NLR_{75} (mean and range)		Notes
		L/s•m^2	ft^3/min•ft^2	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	See Text			
PEL (literature survey)	8	2.48 (1.44 - 4.01)	0.49 (0.28 – 0.79)	Canadian (Ottawa) offices

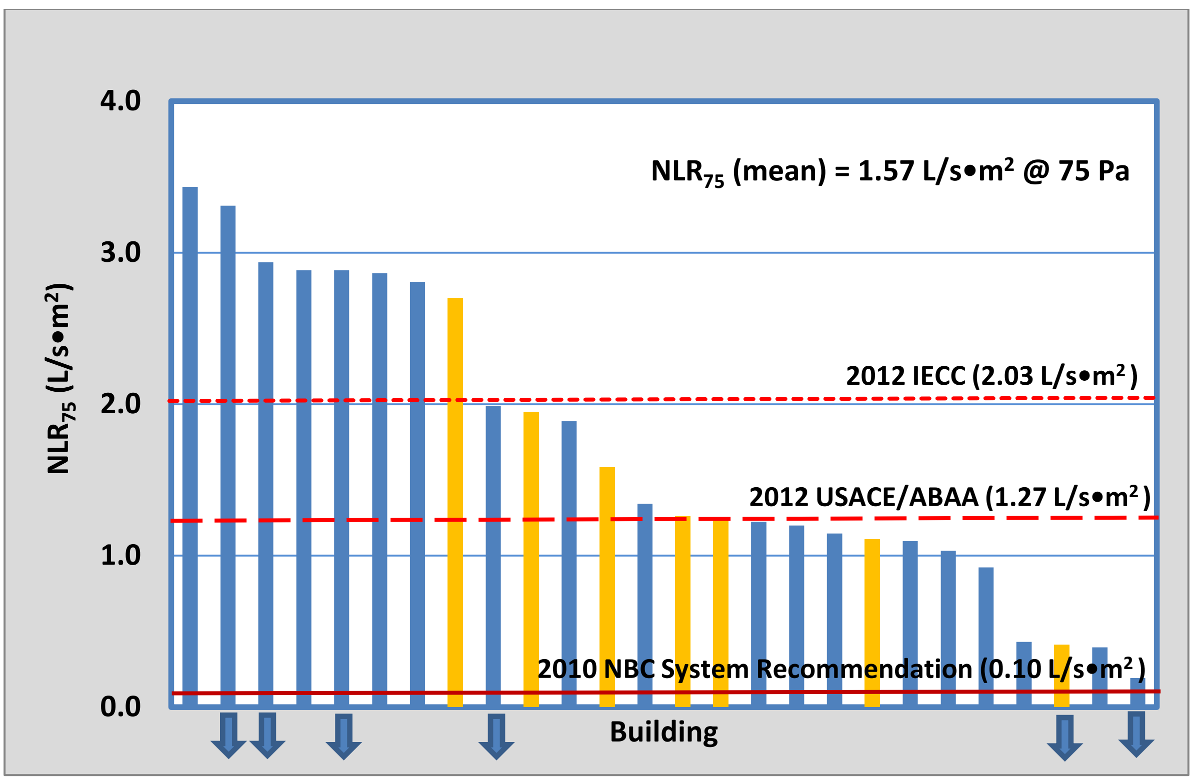
5.6.3 Discussion

The mean NLR_{75} of the seven office buildings, with an average age of over 50 years, was only about 7% greater than the 16 new buildings in the ASHRAE sample, despite the fact that most of the buildings in the latter group were designed with an explicit goal of achieving good airtightness performance. In contrast, only one (perhaps) of the buildings in the RRC sample was constructed with airtightness as a design goal.

The RDH report did not contain any useful data on office buildings.

The eight buildings referenced in the PEL report were all tested by NRC in the period 1971 to 1974 when the average age of the buildings was two years; all (or most) are believed to have been federal government buildings. Somewhat surprisingly, the average NLR_{75} of the RRC sample was less than 2/3 of the NRC group. Although not shown in the table above, the PEL report also referenced a sample of 12 British office buildings which displayed a mean NLR_{75} of 7.55 L/s•m^2. This is dramatically higher than any of the Canadian results and most likely reflects both the age of the buildings and the fact that airtightness was not perceived as a building science or design issue when they were constructed.

Figure 8 – Normalized Leakage Rate for Office Buildings (yellow bars)



5.7 Churches (2 Buildings)

5.7.1 Description of Buildings

The two churches in the sample were both located in Winnipeg and were the two most architecturally distinctive buildings in the 26 building sample. The first, constructed in 1911, used masonry construction typical of the era while the second, built in 1980, used more contemporary steel frame construction with concrete masonry unit (CMU) infill.

From a design perspective, churches are somewhat unique compared to most other buildings in that they are usually designed around a large, open, chapel area in the core with numerous rooms and offices located around the periphery. In contrast, most other types of buildings are designed using rectilinear box shapes to form rooms, hallways and other interior spaces. Churches also tend to have more architectural "character" than other buildings which, while aesthetically pleasing, may create some very interesting design challenges form an airtightness perspective.

5.7.2 Airtightness Test Results and Summary

Table 14 – Summary of Airtightness Test Results for Churches

	No. of Buildings	NLR_{75} (mean and range)		ac/hr_{50}
		L/s•m^2	ft^3/min•ft^2	
Churches	2	2.35 (1.89 - 2.81)	0.46 (0.37 - 0.55)	2.35 (2.10 - 2.60)
Major Air Leakage Locations				
• Structural bulkheads which run from inside the building to the attic or outdoors (massive air leakage observed) • Large 0.6 m x 0.6 m opening in ceiling (massive air leakage suspected) • Windows and exterior doors				

Table 15 – Comparative Results for Churches

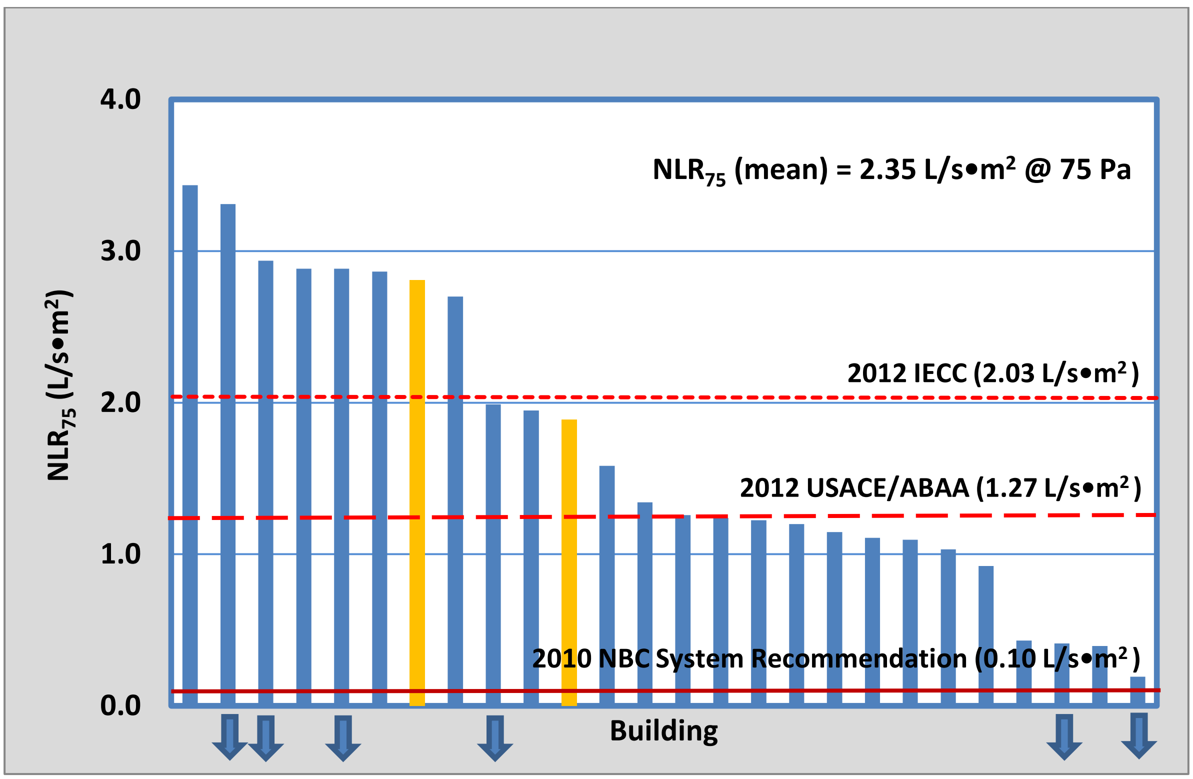
	No. of Buildings	NLR_{75} (mean and range)		Notes
		L/s•m^2	ft^3/min•ft^2	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	See Text			
PEL (literature survey)	See Text			

5.7.3 Discussion

As a sample sub-group, the two churches were comparatively leaky with only greenhouses displaying a higher mean NLR_{75} value. For example, the mean NLR_{75} of the two buildings tested was about 60% higher than the corresponding NLR_{75} in the ASHRAE study. Given the age of the buildings and the fact that the sample size was only two buildings, it is unclear how representative the results are of typical church buildings.

Both churches were large, architecturally unique structures with many complex details incorporated into the designs. And both displayed unique air leakage behaviour patterns. One, the older masonry structure, contained the usual air leakage sites but also contained a large opening in the chapel ceiling, approximately 0.8 m^2 (8 ft^2) in area, which connected the chapel to the vented attic. This permitted significant air leakage during the test and would also be a major source of air exfiltration into the attic space since the opening was located at the very top of the building where the maximum positive pressure differentials would be created by stack effect. Apparently this hole had been left open for decades - for reasons unknown.

Figure 9 – Normalized Leakage Rate for Churches (yellow bars)



The second building also had a large chapel area with a vented attic space at the top. It employed a rather unique design in that that the chapel roof was structurally supported by tilted, steel components which formed the framework for the roof. Since the steelwork was located inside the building, it was covered by a series of drywall bulkheads which formed enclosures that ran to the apex of the roof (see Figs. 9 and 10 below). Lower down, the bulkheads ran into a large horizontal bulkhead "ring", approximately 2.4 m (8 ft.) above the chapel floor. During the depressurization portion of the airtightness test, it was observed that the amount of air being exhausted by the blower doors seemed to far exceed that which could be identified entering the building at the "usual" air leakage locations.

After considerable investigation, it was discovered that the bulkheads opened into the attic space, thereby creating a series of massive air leakage channels, and also opened into the bulkhead ring surrounding the chapel. Further, the top of the bulkhead ring was anything but airtight, with many large areas completely open to the chapel space. Since the top of the ring bulkhead was not visible from ground level, there was little indication that this was a problem. Basically, air was able to leak from the chapel space, into the top of the ring bulkhead, flow horizontally to one of the sloped bulkheads which it entered and then flowed vertically into the vented attic space. Not only was this a very unique construction detail (and air leakage path), but it was also one that was very difficult to identify. Interestingly enough, the authors have subsequently encountered a very similar detail on another building (not part of this study) which caused significant moisture damage to the structure resulting in repairs costing several hundreds of thousands of dollars.

Figure 10 – Roof Structure Supported by Bulkheads that Connect to Perimeter Ring
(NOTE: Arrows indicate direction of airflow when building is pressurized)

Figure 11 – Top of Perimeter Ring Open to Interior Space
(NOTE: Openings as found indicated by red arrows)

Given that both churches had major air leakage pathways from their chapel areas into vented attics, it is interesting to note that neither showed significant evidence of moisture damage in these locations. This most likely occurred because neither building was mechanically humidified and, because they were not heavily utilized (at least in the chapel areas), other than during church services.

With a relatively low occupancy loading, moisture production would have also been relatively small resulting in low indoor relative humidity levels during the heating season. Thus, while significant air exfiltration was occurring from a heated space into the cold attics, the amount of water vapour contained in that air was relatively low. In contrast, the subsequent building (which had a similar problem) that the authors encountered was mechanically humidified and open to the public for 50 to 60 hours per week.

Neither the RDH nor PEL reports contained explicit information on churches.

5.8 Greenhouses (2 Buildings)

5.8.1 Description of Buildings

Two greenhouses, both located on the RRC campus, were included in the sample. One used a conventional greenhouse design (i.e., a symmetrical shape with equal amounts of glazing on the north and south sides of the building) while the other was a passive solar greenhouse that used a non-symmetrical shape with an insulated north wall and additional south-facing glazing. Both used single glazing and were constructed on concrete slabs-on-grade. The latter point is noted because some greenhouses use an earth floor which tends to increases air leakage. Both greenhouses were relatively new – approximately two to three years in age. However, both of these were research structures designed for and operated by RRC. Unlike some commercial greenhouses, these were very well maintained which would help to preserve their original level of airtightness.

5.8.2 Airtightness Test Results and Summary

Table 16 – Summary of Airtightness Test Results for Greenhouses

	No. of Buildings	NLR_{75} (mean and range)		ac/hr_{50}
		L/s•m^2	ft^3/min•ft^2	
Greenhouses	2	2.91 (2.88 - 2.94)	0.57 (0.57 - 0.58)	5.78 (5.63 - 5.92)
Major Air Leakage Locations				
• Greenhouse vents • Vertical walls/sloped glazing intersections • Backdraft dampers				

Table 17 – Comparative Results for Greenhouses

	No. of Buildings	NLR_{75} (mean and range)		Notes
		L/s•m^2	ft^3/min•ft^2	
ASHRAE 1478 (field tests)	16	1.47 (0.30 - 3.81)	0.29 (0.06 - 0.74)	Buildings less than 5 years old
RDH (literature survey)	See Text			
PEL (literature survey)	See Text			

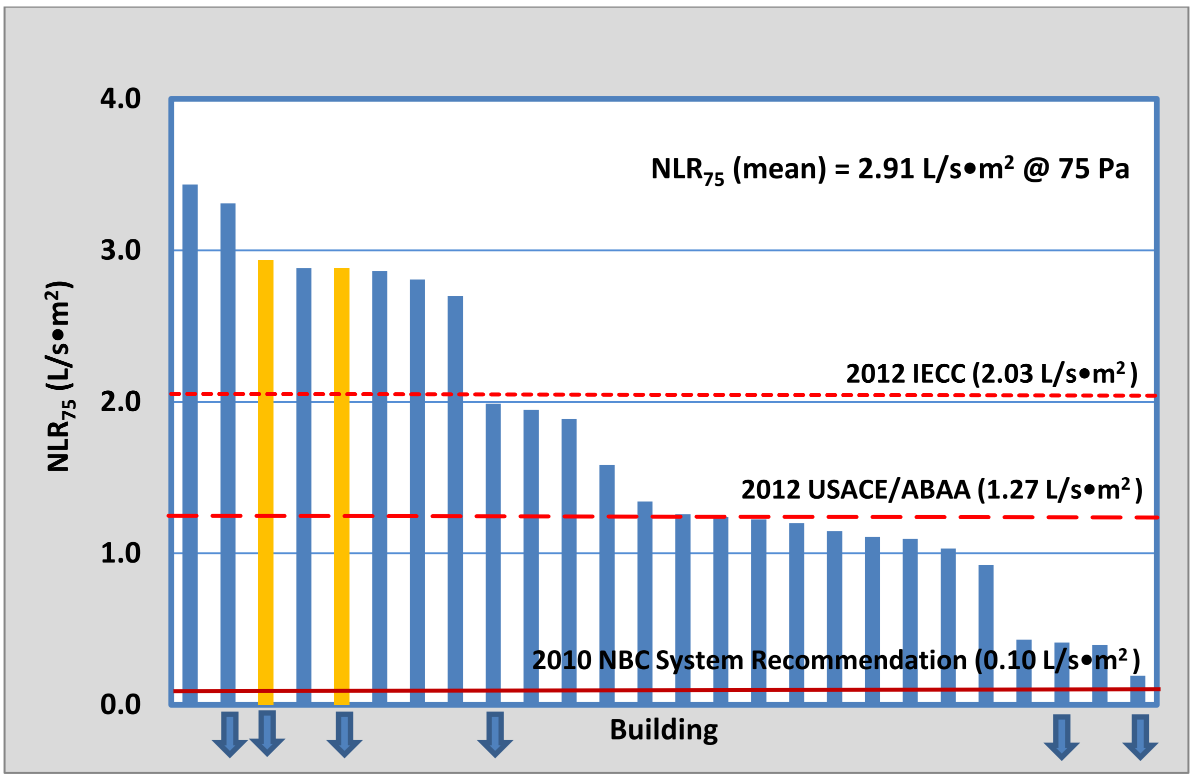
5.8.3 Discussion

The results for the two greenhouses were interesting. Despite one of the structures having being designed as a conventional greenhouse while the other was designed specifically to reduce energy use, their measured airtightness results were almost identical and the measured NLR_{75} values were within 2% of each other. Further, the two greenhouses were among the leakiest of all the buildings tested in this project with NLR_{75} values of 2.88 and 2.94 L/s•m^2. Although the results were disappointing, it is not surprising given that greenhouses are largely constructed of single panes of glass whose joints cannot be as easily sealed as is possible with more common construction materials (wood, metal, concrete). But, it also means that there is considerably more opportunity to improve airtightness in greenhouses.

Unfortunately, none of the other studies provided any data on greenhouse airtightness and a short on-line search did not reveal any useful information.

One point to note is that these two buildings were tested under depressurization mode only, no pressurization tests were performed.

Figure 12 – Normalized Leakage Rate for Greenhouses (yellow bars)



5.9 Air Leakage Retrofits (3 Buildings)

5.9.1 Description of Buildings

The impact of air leakage sealing was studied on three of the 26 buildings in the dataset that were retrofitted by their owners with various measures designed to reduce air leakage and achieve other desirable goals.

It should be appreciated that the term "air leakage sealing" does not have a specific, explicit definition when it comes to commercial buildings. It can refer to the most rudimentary attempt to reduce leakage (basic weatherstripping on select doors and windows) or can describe a complete reconstruction of the building envelope in which little, if any, of the original assembly remains intact. Both would be considered "air leakage sealing" yet their impacts would, in most cases, vary dramatically.

The three air leakage sealing retrofits studied in this project are briefly described below:

Building #3 – This is a 16-storey office tower constructed in Winnipeg in 1976 that underwent a major building envelope retrofit during the summer of 2011 to replace the existing curtain wall glazing and spandrel panels. Essentially, the building's entire wall system was re-skinned; no other air leakage control measures were included. The building also benefited from having quality control work and testing performed during the retrofit to maximize results. The building also contained a below-grade parking garage (which was not included in the test volume).

Building #4 – A 40-year old, two-storey provincial office building with a full basement, located in Selkirk and constructed with pre-cast, insulated concrete panels, this structure had about 80% of its non-operating windows (frames and insulated glazing units) replaced and some other basic measures taken to reduce air leakage.

Building #11 – This is a Winnipeg elementary school composed of three major sections: the original, masonry building constructed approximately a century ago; a single storey, wood-frame classroom addition built in the 1950's which was connected to the original structure through an above-ground link and a new, recently completed gymnasium built to contemporary standards. Only the latter part (gymnasium) was designed with any consideration for air leakage control. Crawl spaces were used throughout the building. The retrofit consisted of targeted efforts to seal doors, windows and various air leakage paths identified during the initial airtightness test and examination.

5.9.2 Airtightness Test Results and Summary

Table 18 – Summary of Airtightness Test Results for Retrofitted Buildings

	Number	Reduction in NLR_{75}	Notes
Retrofits	3	16%	One round of air leakage sealing

Table 19 – Comparative Results for Retrofitted Buildings

	No. of Buildings	Reduction in NLR_{75}	Notes
ASHRAE 1478 (field tests)	1	34%	Two rounds of air leakage sealing conducted on the building. Roughly equal reductions in leakage were obtained after each round of sealing.
RDH (literature survey)	6	31%	Single-round retrofits applied to (comparatively leaky) MURBs
PEL (literature survey)	15	17%	Single-round retrofits to MURBs, office buildings, schools and industrial buildings
PEL (literature survey)	1	92%	Single-round massive retrofit to one institutional building (swimming pool), see text

5.9.3 Discussion

The ASHRAE study included a single building that was sealed to reduce air leakage. This was identified as a four-storey educational structure with a fairly complex geometry and construction. Unlike most air sealing exercises, this building was exposed to two rounds of sealing with separate airtightness tests conducted before, during and after the work to both quantify the effects and to guide the contractors in identifying locations of air leakage. After the two rounds of sealing, the NLR_{75} was reduced by 34%, with roughly equal reductions being achieved after each round of sealing. This was also the leakiest structure in the ASHRAE sample of 16 buildings. Interestingly, the major air leakage location, and the primary area attacked during the sealing work, was the exterior wall/roof deck intersection, specifically where the fluted roof deck met the walls. This location was also identified as a major leakage area in several of the buildings in the RRC dataset.

The RDH study identified six buildings (all MURBs) that had been retrofitted to reduce air leakage, although no details were provided about the retrofits. Overall, the reported retrofits were quite successful compared to those in the RRC study; the average reported NLR_{75} reduction was 31%. However, one obvious difference between the two groups was that the buildings in the RDH study were initially very leaky; their NLR_{75} values ranged from 3.2 L/s·m² to 5.0 L/s·m^2 (0.63 cfm/ft² to 0.98 cfm/ft²). In contrast, the 26 buildings in the RRC study had NLR_{75} values which ranged from 0.19 L/s·m² to 3.4 L/s·m² (0.038 cfm/ft² to 0.68 cfm/ft²). This is significant because it is generally easier to seal leaky buildings as opposed to those with more modest leakage.

The PEL study identified 16 buildings in the literature that had been retrofitted, although only 15 of these fit into the general description of air leakage sealing (the 16th building is discussed below). The 15 buildings in the main group, which represented a mix of MURBs (3), offices (5), schools (4) and industrial (3) structures achieved an average reduction in their NLR_{75} of 17%, almost identical to that observed in this study by RRC.

The 16th building in the PEL study, a municipal swimming pool in Winnipeg, achieved a remarkable 92% reduction in its measured NLR_{75}; however this "retrofit" was more of a reconstruction of the entire wall system. The exterior walls, which used a structural steel framework with concrete masonry unit (CMU) infill, were completely removed such that the only part of the exterior wall system which remained was the steel framework. All of the CMU infill, concrete panel cladding and all interior surfaces were removed and replaced with new construction and a very carefully applied, and inspected, air barrier. In fact, its final measured NLR_{75}, 0.04 L/s•m^2 (0.008 cfm/ft^2) is one of the tightest building enclosures in the literature. For that reason, it is treated separately in this analysis.

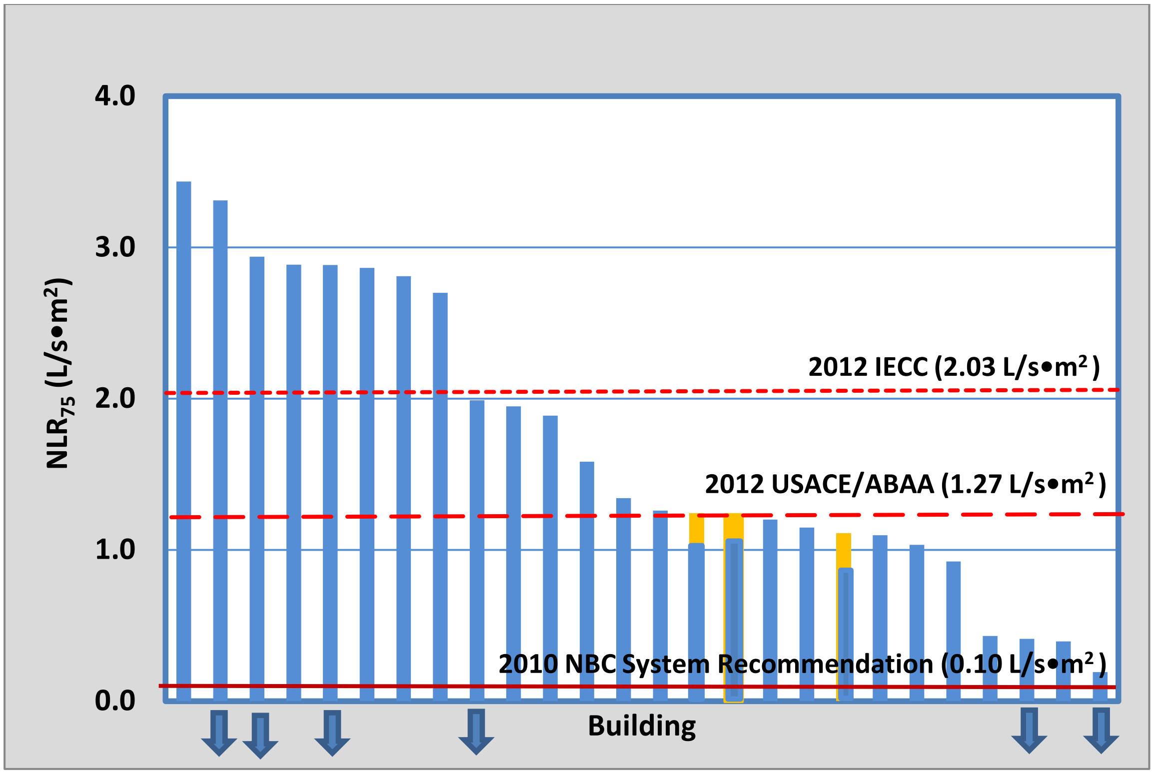
The RRC results, and the comparative data, are quite interesting. The three buildings retrofitted during this project achieved an average reduction in their NLR_{75} of 16%. The sole building retrofitted in the ASHRAE study achieved twice that level of reduction but also benefitted from two rounds of sealing with detailed airtightness/examination tests conducted before, during (after the first round) and after the tests. The 15 buildings in the PEL study that received single-round retrofits achieved comparable results to those in the RRC study, with an average reduction of 17%. The 16th building in the PEL study achieved remarkable results (92% reduction) but, as mentioned, this was a complete rebuild of the exterior wall systems. The results reported in the RDH study were more impressive (34% reduction) than those in either the ASHRAE or PEL studies, however compared to the buildings in the RRC study, these were very leaky structures and were presumably easier to seal.

It is also interesting to look at the absolute reduction in the NLR_{75} produced by the retrofits, as shown in Table 20. These were surprisingly consistent, ranging from 0.16 L/s·m^2 to 0.21 L/s·m^2 (0.032 to 0.042 cfm/ft^2). Interestingly, the two buildings that had all or most of their glazing replaced (#3 and #4) experienced the same reduction in their NLR_{75} - 0.21 L/s·m^2 (0.042 cfm/ft^2).

Table 20 – Impact of Air Leakage Sealing / Building Envelope Retrofits

Building	NLR_{75} (L/s•m^2)		Absolute Reduction	Percentage Reduction
	Pre-Retrofit	Post-Retrofit		
#3	1.24	1.03	0.21	17%
#4	1.11	0.90	0.21	19%
#11	1.22	1.06	0.16	13%

Figure 13 – Impact of Air Leakage Sealing / Building Envelope Retrofits
(Yellow bars indicate pre-retrofit NLR_{75}, Blue bars indicate post-retrofit NLR_{75})



6.0 Observations and Lessons Learned about Airtightness Testing of Commercial Buildings

This project afforded the RRC-SITRG team a rare opportunity to learn about both the airtightness of commercial buildings but also the "nuts and bolts" of conducting these types of tests. The following are various observations and findings complied during the airtightness testing program which address some of the practical aspects of commercial building testing.

6.1 Occupied vs. Non-Occupied Buildings

Whether the building's owners have or have not (yet) occupied the structure has no direct impact on the test protocol, but it does have considerable effect on the logistics and scheduling of the test. Since airtightness testing requires those performing the work to have absolute control over operation of the building for several hours (including mechanical systems, windows, doors, etc.), this can pose scheduling issues for the owner. If the building has a fairly conventional occupancy schedule (say 10 to 12 hours per day, five days a week), the testing agency can usually schedule the work during evenings, nights or weekends. Evening and night time tests also have the advantage that winds are usually lighter than during the day. However, if the building is occupied on a continuous basis, then scheduling becomes very problematic. MURB's, personal care homes and hospitals are all examples of structures which never really close. Depending on the type of business, testing of commercial buildings can usually be conducted after normal business hours. This requires the testing agency to be able to work on a 24/7 schedule. If the test includes sealing the intentional openings using the full "building envelope" schedule, days of planning and preparation may be required to efficiently execute this work in the field (and possibly in the dark).

Security is also of utmost importance and an agreed upon plan with the owner must be in place prior to the test. Environmental conditions may negatively affect the occupied space due to change in temperature when introducing cold/hot air during the test. The risk of contaminates, fumes, dust, and odours being drawn into the building must be avoided.

With new construction, it is critical that all building components which could influence airtightness must be completed. This includes all doors and windows and all of the mechanical, electrical and plumbing penetrations through the building envelope.

6.2 Time on Site and Staff Fatigue

An airtightness test on a large, complex building can easily take 8 to 12 hours (or more) to perform, even with extensive planning and preparation. This creates issues for the individuals tasked with performing the work since they will have to be on-site for extended periods of time, often performing physically challenging work, working at heights, etc. Crew fatigue has to be monitored and respected, particularly since it could create safety issues.

This was an issue on more than one occasion during the 26 building testing program, particularly for evening tests. Originally, it had been anticipated that the crew would "start" their workday at the building, so fatigue would be less of an issue. However, reality has a way of intruding upon the best-laid plans. In virtually all cases, crew members put in a normal workday and then travelled to the building to perform the test. For many individuals, this meant their workday started at 9:00 a.m. and continued non-stop till perhaps 1:00 or 2:00 the next morning. Since an airtightness test on a commercial building cannot be stopped, and then continued the next day, this can put considerable stress on fatigued crew members.

6.3 Different Forms of Occupancy

Testing agencies may have to respect restricted areas within commercial, office, workshop, warehouse, government and utility buildings due to facility management policies and security issues. For example, special conditioned spaces with restricted access, such as data, communication or archive areas, may have to be excluded from the test and be accounted for in the test calculations and reporting.

Occupied schools operate with scheduled in-service days and holidays which can often be used to perform the test. Churches are usually easier to schedule since they tend to be lightly utilized during week days and evenings. Hospitals and medical centres are extremely problematic and, in most cases, cannot be tested once the building is occupied.

One of the outcomes of RRC's research has been the recognition of the challenges involved with airtightness testing of multi-unit residential buildings (MURBs) which are unique from those encountered testing other types of large buildings. The airtightness test methods and standards are based upon the building being vacant or the testing team having control over the movement and actions of the occupants during the test (e.g., restricting entry and exit, keeping windows closed, not operating mechanical systems; etc.). This introduces a major problem with testing buildings such as MURBs, once they are occupied. As a result, airtightness testing of the over 3 million dwelling units in Canadian MURBs is rare.

This has led to a growing recognition of the need to establish performance targets for the airtightness of buildings either through regulations or voluntary programs. However, further research is needed to develop protocols that address the challenges of testing occupied multi-unit residential buildings.

6.4 Environmental Conditions

All airtightness testing standards set limits on the maximum wind speed when can be experienced during the test. For example, the proposed AABA/ASTM standard stipulates a maximum site wind speed of 20 km/hr. Exposure and building height will also influence the maximum wind speed which can be endured during the test. Generally, taller structures and those unshielded by neighbouring buildings or terrain are more vulnerable to high winds.

Rain, frost and condensation also create problems when sealing the HVAC openings. Wet, damp or icy surfaces can create major problems when sealing intentional openings since moisture and frost can cause de-bonding of the tape under sustained positive pressure differentials. The lowest temperature encountered during the 26 building test program was about -10 °C. Although tests were successfully completed at this temperature, considerable care had to be exercised to ensure that all the tape remained in place.

6.5 Safety Concerns

Safety is of upmost importance and all Workplace and Safety regulations must be followed. Some roof-top HVAC equipment (which has to be masked) may be situated in roof locations which are outside the unrestricted work area of the roof, and therefore requires fall protection. During cold weather, areas of the roof and sidewalks may be ice and snow covered which presents slip and fall hazards. Ladders and lifts are often needed and must only be used by workers who have taken appropriate safety training. An Activity Hazard Analysis may find that the building does not have adequate fall arrest equipment mounted on the building. As a result, safe preparation can be difficult to achieve. In any event, testing should not be initiated if environmental conditions make the building dangerous to work on.

6.6 Limitations of Airtightness Testing for Code Compliance and Commissioning Purposes

There has been considerable discussion of using standards such as ASTM E 779 "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization" for commissioning air barrier systems on new buildings. In our view, this is a misplaced concept since these test methods only provide a commentary on the overall building airtightness. They provide little or no insight on the leakage rates of individual components comprising the building envelope even though these components may have to meet leakage requirements stipulated by the NBC.

Continuity – NBC Subsection 5.4.1.2. Sentence 7 states that “The air barrier system shall be continuous (a) across construction, control and expansion joints, (b) across junctions between different building assemblies, and (c) around penetrations through the building assembly.”

Structural Integrity – NBC Subsection 5.4.1.2. Sentences 8 and 9 state that “*An air barrier system installed in an assembly subject to wind load, and other elements of the separator that will be subject to wind load, shall transfer that load to the structure*.” Specifically, it shall be “*designed and constructed to resist 100% of the specified wind load as determined in subsection 4.1.8.”* The air barrier system must be able to resist peak wind loads, stack pressure effects or sustained pressurization loads without exhibiting signs of detachment, rupturing or creep load failure.

Durability – NBC Subsections 5.1.4.1 and 5.1.4.2 detail the requirements for resistance to environmental loads and resistance to deterioration. The air barrier system must be durable, meaning it must be able to perform its intended function, be compatible with adjoining materials and resistant to the mechanisms of deterioration that can be reasonably expected given the nature, function and exposure of the materials, over the life of the building envelope.

All of these requirements are critical but cannot be verified by a whole building airtightness test. Therefore at all stages of the construction, testing of the materials and individual assemblies is strongly recommended. Whole building airtightness testing does not eliminate these requirements, it complements them.

6.7 Commercialization of Whole Building Airtightness Testing

Organizations who are considering whole building airtightness testing as a possible venture must appreciate the equipment cost and human resources required to undertake the work. If the building owner asks for further analysis, the role of the testing agency may expand into a consulting function which requires a licensed professional to be involved.

Based on our experiences, the testing of large, commercial buildings as a sole source of revenue is not, at present, a viable business opportunity in Manitoba. The capital outlay is high, staffing requirements dictate a diverse set of skills and the market for such services is fairly limited at present. Further, in most parts of Canada, this type of work is seasonal in nature. Given the temperature restrictions discussed above, airtightness testing becomes practical around mid-spring and continues until about mid-fall (April to November). Testing of both occupied and unoccupied buildings is further limited to periods when the weather is cooperative (low-to-moderate winds and no precipitation). The scope of work would fit well with an existing agency that has an established core of human resources, and has flexibility in staff working hours. The following summarizes the equipment costs and human resources necessary to perform this work.

Table 21 – Estimated Capital (Equipment) Costs

Item	Estimated Cost	Notes
Blower door fans	$50k	For newer, airtight buildings, only 1 to 2 blower door fans may be required; for older, leakier buildings, up to 6 fans or more may be required. This is also dependent of the size of the building.
Thermal camera	$5k	
Transportation (van)	$35k	An enclosed van is required for protecting equipment from the elements.
Miscellaneous small equipment (masking tape, utility knives, ladders, safety, etc.)	$5k	Depending on the size of the building and the number/size of intentional openings, the amount of consumables will vary from test to test.
	Total: $95K	Based on our experiences, we consider a budget of close to $100k for capital equipment (exclusive of any overhead costs) as a conservative start-up cost.

6.8 Estimated Human Resources Required

Required personnel to perform whole building air leakage tests include:

Management	1
Engineer/Architect	1
Technician	2 (1 envelope, 1 HVAC)
Labours/students	2 to 8
Total	6 to 12 individuals

Some tests require 10 or more personnel. This number may grow if there are special requirements for additional security or observation of the building during the test (HVAC masking, window and door operation, etc.). Due to scheduling restrictions imposed by the building and/or its owners, coupled with the fact that many of these tests can only be performed outside of normal working hours, the workforce will have to be flexible and capable of working effectively for extended periods of time.

6.9 Man-hour Requirements and Costing

During the testing program, detailed records were maintained on 23 of the tests to assess their man-hour requirements.

The total time required to complete one building test, including the initial site visit, pre-inspection visit and the building test ranged from 15 to 133 man-hours. In addition, reporting time ranged from 2 to 20 man-hours (calculations only, with no summary report). Administration, travel, equipment depreciation and production of a detailed summary report would be extra.

Based on the above, the average manpower requirements (exclusive of administration, travel, equipment depreciation and a detailed summary report) for the 23 buildings were:

Average test time:	54 man hours
Average reporting time:	5.5 man hours

An outline of specific knowledge and tasks with the corresponding required knowledge level is presented in Table 22.

Table 22 – Job Task Analysis

Required Knowledge, Skill and Ability, 1 (low) to 6 (high)	*1*	*2*	*3*	*4*	*5*	*6*
General						
Interaction with Owner/occupant/operators					*X*	
Building Science				*X*		
HVAC Systems				*X*		
Ability to read Architectural and Mechanical drawings				*X*		
Familiarity with test protocols						*X*
Computer Skills				*X*		
Ability to carry heavy loads (25 to 50 kg.)					*X*	
Ability to hoist loads with ropes			*X*			
Dexterity with small hand tools (screw guns, pliers, hammers, knives)				*X*		
Ability to drive trucks or vans				*X*		
Special safety concerns						
Work on ladders						*X*
Roof safety						*X*
Hand tools				*X*		
Security						
Ability to manage occupants and public					*X*	
Familiarity with building security systems					*X*	
Dealing with authorities					X	

6.9.1 Costing

Hourly charge-out rates for these tasks will range from $75.00 to $150.00, with an average billing rate of $100.00 per hour. Administration, travel, and equipment depreciation (~ 5%) would represent additional costs for all tests.

Combining this information and using some of the actual test costs incurred during the project as a guide, estimates can be made of the cost of a whole building airtightness tests for different scenarios:

Simple test with limited travel (22 man-hours) $ 2,500

Simple test with some travel (73 man-hours)
plus food, travel and accommodations $ 9,500

Complex test with no travel (143 man-hours)	$15,000
Complex test with travel	$25,000+

The costs of performing whole building airtightness tests on the project structures averaged:

Local (Winnipeg) tests	$ 8,750
Non-local tests (assuming 1,000 km round trip)	$17,250

6.10 Student learning Objectives

During the summer of 2013, students from both the Civil and Mechanical Engineering Technology Departments at Red River College were hired to assist with the project. The learning objectives for the students were that they would have performed and developed a working knowledge of the following:

- Literature studies on whole building air leakage, ASTM, Corp of Engineers protocols, and published papers;
- Attendance at lectures from senior staff on building science principles and building envelope testing methods;
- Developing organizational skills for team work, coordination with building owners;
- Performing pre-test building evaluations;
- Set up and operation of blower doors assemblies;
- Operation of computers for whole building tests;
- Preparation of the HVAC system for testing;
- Preparation of the single-zone building interior spaces for testing;
- Preparation of the multi-zone building interiors for testing;
- Understanding environmental impacts on the test;
- Assessing legitimacy of the test results and related problem solving;
- Interpreting Architectural/HVAC drawings;
- Understanding construction practices for historical buildings, walls, windows and roof types;
- Learning to define air leakage pathways;
- Performing diagnostic air leakage tests, working with smoke tracers and thermography;
- Collecting data and photographic logs; and
- Report writing.

7.0 Conclusions and Recommendations

7.1 Conclusions

Overall, the findings from this project indicate that designing and constructing commercial buildings with a high level of airtightness is achievable using knowledge and technology that currently exists within the Manitoba design and construction industries. Further, these results demonstrate that very high airtightness can be attained even if the building is architecturally complex.

From the buildings tested in Manitoba, it is also clear that there is a broad variation in airtightness. The most enlightening being one of the new school buildings that showed what is achievable when due diligence is taken during the design and construction periods. The school was constructed with a full building envelope commissioning program that incorporated a detailed design review and testing of building assemblies throughout the project. The end result was that the whole building airtightness was nearly as tight as the NBC recommendations for a *building system*. Other results indicate there is still need for improvement in the design and construction of air barriers and building envelopes.

During testing of the 26 buildings it became evident that two distinct sealing methods were required for intentional openings in the building. One method is employed for an "energy" test (mechanical system open) and one for a building "envelope" test (mechanical system sealed). These changes have been incorporated into the new USACE/ABAA standard, which is also now an ASTM Work Item 35913 that is ready for ballot to become an ASTM Standard.

It was also observed that while mechanical system damper air leakage poses a potential energy liability for commercial buildings, it also represents a possible opportunity for improving building energy performance in both new and existing structures. It is recommended that a review be conducted to identify potential opportunities from using improved low-leakage HVAC dampers in commercial construction.

One of the outcomes of this RRC's research has been the recognition of the special challenges involved with airtightness testing of Multi-Unit Residential Buildings (MURBs) which are unique from those encountered testing other types of larger buildings. The current airtightness test methods and standards are based upon the building being vacant or having control over the movement and actions of the occupants during the test (e.g., restricting entry and exit, keeping windows closed, not operating mechanical systems, etc.). This introduces a major problem with testing some types of buildings, such as MURBs, once they are occupied. As a result, airtightness testing of the over 3 million dwelling units in Canadian MURBs is rare. To address this, CMHC has engaged RRC to explore the possibilities of testing occupied buildings and developing a new test protocol for occupied MURBs.

7.2 Recommendations

Recommendation #1 – Expand efforts to share study findings

The results of this project are of significance not only for Manitoba, but also nationally. Although some actions are being taken to increase awareness (e.g., presentation at Construction Specifications Canada's 2015 national conference in Winnipeg, sharing the draft report with the NECB Building Envelope Task Group), an information transfer plan should be developed to maximize awareness of the project and its key findings.

Recommendation #2 – Establish airtightness targets and protocols for Manitoba buildings

This study has demonstrated that existing airtightness targets and protocols established by organizations based outside the province are not necessarily appropriate for Manitoba's building industry. Given that Manitoba Hydro is a trusted source of advice by its commercial customers looking to reduce the energy-related operating costs, the scope of this advice should be expanded to include Power Smart recommendations for airtightness standards and test protocols (also see Recommendation #7).

Recommendation #3 – 'Lead-by-example' with Manitoba Hydro facilities

There is an expectation that Manitoba Hydro will continue to 'lead-by-example' with respect to optimizing the performance of facilities that it owns and operates and then sharing this knowledge and experience with its customers. This commitment could by strengthened by:

- adopting an airtightness standard for its new buildings and major renovation projects, and
- testing additional Manitoba Hydro buildings for airtightness beyond the five included in this project.

Testing additional Manitoba Hydro facilities will support the recommendation to expand the database of airtightness test results (see Recommendation #4). It will also enable Manitoba Hydro to make a more informed decision about which of its buildings are the best candidates for comprehensive air leakage sealing retrofits.

Recommendation #4 – Increase the database of airtightness test results

This project has significantly expanded the knowledge base about the airtightness of commercial buildings in Manitoba, and by extension, Canada. However, increasing the number and variety of buildings to the database of test results will increase confidence in establishing reasonable airtightness targets in the commercial building sector.

An expanded database will enhance the feasibility of including an airtightness requirement in standards such as Manitoba Hydro's *Power Smart Commercial New Buildings Program*, *Power Smart Building Envelope Program*, *Green Building Policy for Government of Manitoba Funded Projects* and the next edition of the *Manitoba Energy Code for Buildings*. Recall that improved building airtightness reduces energy consumption and improves building durability. A further benefit of increasing the number of buildings tested will be to expand the local capacity for testing commercial buildings.

Recommendation #5 – Investigate feasibility of incentives for airtightness tests

Results from this project suggest that there is merit for Manitoba Hydro to investigate the feasibility of developing a pilot program to provide performance-based incentives to encourage comprehensive air leakage sealing of commercial buildings coupled with pre- and post-retrofit airtightness testing.

Recommendation #6 – Review potential opportunities for low-leakage HVAC dampers

Given the project's findings about the large impact that HVAC dampers have on the airtightness characteristics of commercial buildings, it is recommended that Manitoba Hydro examine the potential benefits of adding low-leakage dampers as a targeted measure under its *Power Smart* Commercial Buildings Optimization Program or Commercial Custom Program.

Recommendation #7 – Use two sealing schedules for future airtightness tests and standards

As explained in sub-section 4.5, the treatment of intentional openings in the building envelope (especially for HVAC equipment and systems) can have a major impact on the results and interpretation of an airtightness test on a commercial building. It is recommended that Manitoba Hydro promote the awareness of the pros and cons of two sealing schedules that can be used for the building envelope, an "energy sealing schedule" and a "building envelope schedule".

Recommendation #8 – Develop how-to-guide for preparing a building for an airtightness test

One of the largest barriers to the expanded use of airtightness testing in the commercial building sector is cost, especially the time that it takes to prepare the building for the test. As the number of building tests increased, the project team became more proficient at preparing the building, especially its intentional openings, for an airtightness test. This knowledge should be captured in a 'how-to-guide' and shared with industry and other research teams.

Recommendation #9 – Consider mandatory airtightness testing in the NBC/MBC of buildings with high-threat indoor environments or those which cannot be tested after they are occupied

A final recommendation from this project deals with the possible adoption of mandatory airtightness testing requirements for commercial buildings in the National Building Code of Canada or the Manitoba Building Code. At present, this issue is being discussed by the Task Group on Building Envelope for consideration in the 2020 NBC. While the RRC-SITRG project has helped to identify some of the issues associated with such a code change, it should also be clear that this is not a simple matter and the Task Group will need to consider a variety of factors including cost, availability of testing agencies and trained personnel, scheduling implications for the normal construction process, weather and climate related issues, etc., etc. However, one recommendation which can be offered addresses the types of buildings which should given first priority for possible mandatory airtightness testing. Based on our experiences with this project, we believe there are two types of buildings which should be considered as prime candidates. The first would be those buildings which, from a moisture perspective, are exposed to severe indoor environments. This would include structures such as indoor swimming pools in which the indoor relative humidity is considerably and consistently higher than normally encountered in most commercial buildings. Referring to Table 2 – NBC Recommended Maximum Air Leakage Rates for Air Barrier Systems, these can be defined as buildings which operate with high indoor relative humidity levels, i.e. those with relative humidity levels greater than 55%. This would apply to both new construction and to those buildings undergoing significant building envelope retrofits.

The second type of building which should be considered as a prime candidate for airtightness testing is those which, once occupied, cannot realistically be considered for future testing due to their occupancy or use. Hospitals and personal care homes (PCH's) are prime examples. Once they are occupied, they never close, they are never unoccupied, their mechanical systems can never be shut down and in most cases, they can never be surrendered to an airtightness testing organization for the six to twelve hours necessary to complete a test. If they are not tested at the completion of construction, it is unlikely they can ever be tested.

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Appendix A – Detailed Airtightness Results

Table A-1a) – Detailed Airtightness Results for Complete Sample (Metric Units)

	Metric Units		
	Depressurization	Pressurization	Mean
Envelope surface area, m^2			
Mean	4773		
Standard Deviation	3692		
Range	402 – 15,823		
Number of Buildings	26		
Volume, m^3			
Mean	12,840		
Standard Deviation	14,569		
Range	587 – 66,304		
Number of Buildings	26		
Flow Coefficient ©, $L/s \cdot Pa^n$			
Mean	552	526	
Standard Deviation	543	397	
Range	44 – 2430	37 – 1450	
Number of Buildings	26	23	
Flow Exponent (n), dimensionless			
Mean	0.5950	0.6181	
Standard Deviation	0.0837	0.1078	
Range	0.4779 – 0.8584	0.4378 – 0.9410	
Number of Buildings	26	23	
NLR_{75}, $L/s \cdot m^2$			
Mean	1.64	1.69	1.70
Standard Deviation	0.95	1.11	0.92
Range	0.20 – 3.47	0.19 – 4.78	0.19 – 3.44
Number of Buildings	26	23	26
ac/hr_{50}			
Mean	2.27	2.17	2.33
Standard Deviation	1.50	1.19	1.49
Range	0.19 – 5.92	0.19 – 4.44	0.19 – 5.92
Number of Buildings	26	23	26
$Flow_{75}$, L/s			
Mean	6604	7008	
Standard Deviation	4950	4704	
Range	746 – 19,066	849 – 19,490	
Number of Buildings	26	23	

Table A-1b) – Detailed Airtightness Results for Complete Sample (Imperial Units)

	Imperial Units		
	Depressurization	Pressurization	Mean
Envelope surface area, ft^2			
Mean	51,354		
Standard Deviation	39,722		
Range	4323 - 170,256		
Number of Buildings	26		
Volume, ft^3			
Mean	453,107		
Standard Deviation	514,165		
Range	20,710 - 2,340,079		
Number of Buildings	26		
Flow Coefficient (C), $ft^3/min{\bullet}Pa^n$			
Mean	1173	1115	
Standard Deviation	1149	841	
Range	92 - 5150	79 - 3075	
Number of Buildings	26	23	
Flow Exponent (n), dimensionless			
Mean	0.5950	0.6181	
Standard Deviation	0.0837	0.1078	
Range	0.4779 - 0.8584	0.4378 - 0.9410	
Number of Buildings	26	23	
NLR_{75}, $ft^3/min{\bullet}ft^2$			
Mean	0.32	0.33	0.34
Standard Deviation	0.19	0.22	0.19
Range	0.04 - 0.68	0.04 - 0.94	0.04 - 0.68
Number of Buildings	26	23	26
ac/hr_{50}			
Mean	2.27	2.17	2.33
Standard Deviation	1.50	1.19	1.49
Range	0.19 - 5.92	0.19 - 4.44	0.19 - 5.92
Number of Buildings	26	23	26
$Flow_{75}$, ft^3/min			
Mean	13,994	14,851	
Standard Deviation	10,489	9967	
Range	1580 - 40,400	1800 - 41,300	
Number of Buildings	26	23	

Table A-2a) – Detailed Airtightness Results for New Construction (Metric Units)

	Metric Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, m^2			
Mean	5352		
Standard Deviation	5995		
Range	1504 - 15,823		
Number of Buildings	5		
Volume, m^3			
Mean	13,381		
Standard Deviation	18,050		
Range	2387 - 45,300		
Number of Buildings	5		
Flow Coefficient (C), L/s•Pa^n			
Mean	122	134	
Standard Deviation	64	99	
Range	44 - 196	37 - 300	
Number of Buildings	5	5	
Flow Exponent (n), dimensionless			
Mean	0.6357	0.6949	
Standard Deviation	0.0420	0.1619	
Range	0.5862 - 0.6940	0.5322 - 0.9410	
Number of Buildings	5	5	
NLR_{75}, L/s•m^2			
Mean	0.64	1.26	0.95
Standard Deviation	0.68	1.97	1.32
Range	0.20 - 1.85	0.19 - 4.78	0.19 - 3.31
Number of Buildings	5	5	5
ac/hr_{50}			
Mean	0.82	1.36	1.09
Standard Deviation	0.69	1.74	1.21
Range	0.19 - 1.97	0.19 - 4.44	0.19 - 3.20
Number of Buildings	5	5	5
$Flow_{75}$, L/s			
Mean	1907	2901	
Standard Deviation	1037	2557	
Range	746 - 3105	849 - 7197	
Number of Buildings	5	5	

Table A-2b) – Detailed Airtightness Test Results for New Construction (Imperial Units)

	Imperial Units		
	Depressurization	Pressurization	Mean
Envelope surface area, ft^2			
Mean	57,593		
Standard Deviation	64,504		
Range	16,181 - 170,256		
Number of Buildings	5		
Volume, m^3			
Mean	472,264		
Standard Deviation	637,037		
Range	84,255 - 1,598,759		
Number of Buildings	5		
Flow Coefficient (C), $ft^3/min•Pa^n$			
Mean	259	283	
Standard Deviation	135	210	
Range	92 - 416	79 - 637	
Number of Buildings	5	5	
Flow Exponent (n), dimensionless			
Mean	0.6357	0.6949	
Standard Deviation	0.0420	0.1619	
Range	0.5862 - 0.6949	0.5322 - 0.9410	
Number of Buildings	5	5	
NLR_{75}			
Mean	0.13	0.25	0.19
Standard Deviation	0.13	0.39	0.26
Range	0.04 - 0.36	0.04 - 0.94	0.04 - 0.65
Number of Buildings	5	5	5
ac/hr_{50}			
Mean	0.82	1.36	1.09
Standard Deviation	0.69	1.74	1.21
Range	0.19 - 1.97	0.19 - 4.44	0.19 - 3.20
Number of Buildings	5	5	5
$Flow_{75}$			
Mean	4041	6147	
Standard Deviation	2197	5419	
Range	1580 - 6580	1800 - 15,250	
Number	5	5	

Table A-3a) – Detailed Airtightness Test Results for Warehouses Buildings (Metric Units)

	Metric Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, m^2			
Mean	4015		
Standard Deviation	2436		
Range	1420 - 8850		
Number of Buildings	11		
Volume, m^3			
Mean	8419		
Standard Deviation	5484		
Range	2629 - 19,510		
Number of Buildings	11		
Flow Coefficient (C), L/s•Pa^n			
Mean	478	405	
Standard Deviation	314	313	
Range	69 - 1087	98 - 1212	
Number of Buildings	11	11	
Flow Exponent (n), dimensionless			
Mean	0.5772	0.6422	
Standard Deviation	0.0621	0.1371	
Range	0.4981 - 0.6809	0.4378 - 0.9410	
Number of Buildings	11	11	
NLR_{75}, L/s•m^2			
Mean	1.53	1.83	1.68
Standard Deviation	0.91	1.30	1.03
Range	0.038 - 3.47	0.41 - 4.78	0.40 - 3.44
Number of Buildings	11	11	11
ac/hr_{50}			
Mean	2.12	2.38	2.25
Standard Deviation	1.13	1.29	1.15
Range	0.52 - 4.72	0.59 - 4.44	0.55 - 4.55
Number of Buildings	11	11	11
$Flow_{75}$, L/s			
Mean	5489	6016	
Standard Deviation	3480	3304	
Range	1038 - 13,403	1116 - 13,143	
Number of Buildings	11	11	

Table A-3b) – Detailed Airtightness Test Results for Warehouses (Imperial Units)

	Imperial Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, ft^2			
Mean	43,199		
Standard Deviation	26,213		
Range	15,276 - 95,222		
Number of Buildings	11		
Volume, ft^3			
Mean	297,118		
Standard Deviation	193,542		
Range	92,800 - 688,565		
Number of Buildings	11		
Flow Coefficient (C), $ft^3/min \cdot Pa^n$			
Mean	1014	859	
Standard Deviation	665	663	
Range	146 - 2305	208 - 2570	
Number of Buildings	11	11	
Flow Exponent (n), dimensionless			
Mean	0.5772	0.6422	
Standard Deviation	0.0621	0.1371	
Range	0.4981 - 0.6809	0.4378 - 0.9410	
Number of Buildings	11	11	
NLR_{75}, $ft^3/min \cdot ft^2$			
Mean	0.30	0.36	0.33
Standard Deviation	0.18	0.26	0.20
Range	0.08 - 0.68	0.08 - 0.94	0.08- 0.68
Number of Buildings	11	11	11
ac/hr_{50}			
Mean	2.12	2.38	2.25
Standard Deviation	1.13	1.29	1.15
Range	0.52 - 4.72	0.59 - 4.44	0.55 - 4.55
Number of Buildings	11	11	11
$Flow_{75}$, ft^3/min			
Mean	11,630	12,747	
Standard Deviation	7373	7,001	
Range	2200 - 28,400	2365 - 27,850	
Number of Buildings	11	11	

Table A-4a) – Detailed Airtightness Test Results for Schools (Metric Units)

	Metric Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, m^2			
Mean	8752		
Standard Deviation	5762		
Range	3412 - 15.823		
Number of Buildings	4		
Volume, m^3			
Mean	19,816		
Standard Deviation	17,415		
Range	8571 - 45,300		
Number of Buildings	4		
Flow Coefficient (C), L/$s \cdot Pa^n$			
Mean	564	681	
Standard Deviation	302	262	
Range	154 - 831	302 - 901	
Number of Buildings	4	4	
Flow Exponent (n), dimensionless			
Mean	0.6468	0.5742	
Standard Deviation	0.0661	0.0650	
Range	0.5574 - 0.6988	0.5067 - 0.6425	
Number of Buildings	4	4	
NLR_{75}, $L/s \cdot m^2$			
Mean	1.16	1.08	1.12
Standard Deviation	0.85	0.64	0.73
Range	0.19 - 2.27	0.19 - 1.69	0.19 - 1.98
Number of Buildings	4	4	4
ac/hr_{50}			
Mean	2.15	2.11	2.13
Standard Deviation	1.45	1.39	1.41
Range	0.19 - 3.42	0.19 - 3.43	0.19 - 3.24
Number of Buildings	4	4	4
$Flow_{75}$, L/s			
Mean	8674	8533	
Standard Deviation	3852	4121	
Range	3089 - 11,586	3006 - 12,527	
Number of Buildings	4	4	

Table A-4b) – Detailed Airtightness Test Results for Schools (Imperial Units)

	Imperial Units		
	Depressurization	Pressurization	Mean
Envelope surface area, ft^2			
Mean	94,171		
Standard Deviation	61,997		
Range	34,714 - 170,256		
Number of Buildings	4		
Volume, ft^3			
Mean	699,382		
Standard Deviation	614,640		
Range	302,504 - 1,598,759		
Number of Buildings	4		
Flow Coefficient (C), $ft^3/min•Pa^n$			
Mean	1195	1445	
Standard Deviation	639	555	
Range	326 - 1760	640 - 1910	
Number of Buildings	4	4	
Flow Exponent (n), dimensionless			
Mean	0.6468	0.5742	
Standard Deviation	0.0661	0.0650	
Range	0.5574 - 0.6988	0.5067 - 0.6425	
Number of Buildings	4	4	
NLR_{75}, $ft^3/min•ft^2$			
Mean	0.23	0.21	0.22
Standard Deviation	0.17	0.13	0.14
Range	0.04 - 0.45	0.04 - 0.33	0.04 - 0.39
Number of Buildings	4	4	4
ac/hr_{50}			
Mean	2.15	2.11	2.13
Standard Deviation	1.45	1.39	1.41
Range	0.19 - 3.42	0.19 -3.43	0.19 - 3.24
Number of Buildings	4	4	4
$Flow_{75}$, ft^3/min			
Mean	18,380	18,081	
Standard Deviation	8162	8732	
Range	6545 - 24,550	6370 - 26,550	
Number of Buildings	4	4	

Table A-5a) – Detailed Airtightness Test Results for Office Buildings (Metric Units)

	Metric Units		
	Depressurization	Pressurization	Mean
Envelope surface area, m^2			
Mean	4312		
Standard Deviation	3160		
Range	1600 - 10,436		
Number of Buildings	7		
Volume, m^3			
Mean	16,922		
Standard Deviation	22,914		
Range	2387 - 66,304		
Number of Buildings	7		
Flow Coefficient (C), L/s•Pa^n			
Mean	390	354	
Standard Deviation	268	284	
Range	43 - 835	38 - 882	
Number of Buildings	7	6	
Flow Exponent (n), dimensionless			
Mean	0.6361	0.6498	
Standard Deviation	0.1138	0.1094	
Range	0.5093 - 0.8584	0.5109 - 0.8240	
Number of Buildings	7	6	
NLR_{75}, L/s•m^2			
Mean	1.54	1.65	1.57
Standard Deviation	0.80	0.84	0.79
Range	0.38 - 2.65	0.44 - 2.76	0.41 - 2.71
Number of Buildings	7	6	7
ac/hr_{50}			
Mean	1.69	1.95	1.72
Standard Deviation	1.03	0.95	1.03
Range	0.49 - 3.22	0.97 - 3.30	0.49 - 3.26
Number of Buildings	7	6	7
$Flow_{75}$, L/s			
Mean	6246	5362	
Standard Deviation	4396	3628	
Range	734 - 12,983	859 - 11,442	
Number of Buildings	7	6	

Table A-5b) – Detailed Airtightness Test Results for Office Buildings (Imperial Units)

	Imperial Units		
	Depressurization	Pressurization	Mean
Envelope surface area, ft^2			
Mean	46,397		
Standard Deviation	34,004		
Range	17,221 - 112,291		
Number of Buildings	7		
Volume, ft^3			
Mean	597,212		
Standard Deviation	808,707		
Range	84,225 - 2,340,079		
Number of Buildings	7		
Flow Coefficient (C), $ft^3/min \cdot Pa^n$			
Mean	840	752	
Standard Deviation	565	602	
Range	91 - 1770	80 - 1870	
Number of Buildings	7	6	
Flow Exponent (n), dimensionless			
Mean	0.6361	0.6498	
Standard Deviation	0.1138	0.1094	
Range	0.5093 - 0.8584	0.5109 - 0.8240	
Number of Buildings	7	6	
NLR_{75}, $ft^3/min \cdot ft^2$			
Mean	0.30	0.33	0.31
Standard Deviation	0.16	0.17	0.16
Range	0.08 - 0.52	0.09 - 0.54	0.08 - 0.53
Number of Buildings	7	6	7
ac/hr_{50}			
Mean	1.69	1.95	1.72
Standard Deviation	1.03	0.95	1.03
Range	0.49 - 3.22	0.97 - 3.30	0.49 - 3.26
Number of Buildings	7	6	7
$Flow_{75}$, ft^3/min			
Mean	13,236	11,363	
Standard Deviation	9315	7689	
Range	1555 - 27,511	1820 - 24,250	
Number of Buildings	7	6	

Table A-6a) – Detailed Airtightness Test Results for Churches (Metric Units)

	Metric Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, m^2			
Mean	7234		
Standard Deviation	520		
Range	6867 - 7602		
Number of Buildings	2		
Volume, m^3			
Mean	20,738		
Standard Deviation	1128		
Range	19,941 - 21,536		
Number of Buildings	2		
Flow Coefficient (C), L/s•Pa^n			
Mean	2097	1363	
Standard Deviation	472	123	
Range	1763 - 2430	1276 - 1450	
Number of Buildings	2	2	
Flow Exponent (n), dimensionless			
Mean	0.4849	0.5775	
Standard Deviation	0.0098	0.0343	
Range	0.4779 - 0.4918	0.5532 - 0.6017	
Number of Buildings	2	2	
NLR_{75}, L/s•m^2			
Mean	2.36	2.33	2.35
Standard Deviation	0.59	0.71	0.35
Range	1.94 - 2.78	1.83 - 2.84	2.10 - 2.60
Number of Buildings	2	2	2
ac/hr_{50}			
Mean	2.41	2.28	2.35
Standard Deviation	0.32	0.38	0.35
Range	2.18 - 2.64	2.01 - 2.56	2.10 - 2.60
Number of Buildings	2	2	2
$Flow_{75}$, L/s			
Mean	16,930	16,718	
Standard Deviation	3020	3921	
Range	14,795 - 19,066	13,945 - 19,490	
Number of Buildings	2	2	

Table A-6b) – Detailed Airtightness Test Results for Churches (Imperial Units)

	Imperial Units		
	Depressurization	Pressurization	Mean
Envelope surface area, ft^2			
Mean	77,842		
Standard Deviation	5594		
Range	73,887 - 81,798		
Number of Buildings	2		
Volume, ft^3			
Mean	731,380		
Standard Deviation	40,559		
Range	702,701 - 760,060		
Number of Buildings	2		
Flow Coefficient (C), $ft^3/min \cdot Pa^n$			
Mean	4443	2890	
Standard Deviation	1001	262	
Range	3735 - 5150	2705 - 3075	
Number of Buildings	2	2	
Flow Exponent (n), dimensionless			
Mean	0.4849	0.5775	
Standard Deviation	0.0098	0.0343	
Range	0.4779 - 0.4918	0.5532 - 0.6017	
Number of Buildings	2	2	
NLR_{75}, $ft^3/min \cdot ft^2$			
Mean	0.47	0.46	0.46
Standard Deviation	0.12	0.14	0.13
Range	0.38 - 0.55	0.36 - 0.56	0.37 - 0.55
Number of Buildings	2	2	2
ac/hr_{50}			
Mean	2.41	2.28	2.35
Standard Deviation	0.32	0.38	0.35
Range	2.18 - 2.64	2.01 - 2.56	2.10 - 2.60
Number of Buildings	2	2	2
$Flow_{75}$, ft^3/min			
Mean	35,875	35,425	
Standard Deviation	6399	8309	
Range	31,350 - 40,400	29,550 - 41,300	
Number of Buildings	2	2	

Table A-7a) – Detailed Airtightness Test Results for Greenhouses (Metric Units)

	Metric Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, m^2			
Mean	524		
Standard Deviation	173		
Range	402 - 646		
Number of Buildings	2		
Volume, m^3			
Mean	757		
Standard Deviation	240		
Range	587 - 927		
Number of Buildings	2		
Flow Coefficient (C), L/s•Pa^n			
Mean	148		
Standard Deviation	95		
Range	80 - 215		
Number of Buildings	2		
Flow Exponent (n), dimensionless			
Mean	0.5610		
Standard Deviation	0.0865		
Range	0.4998 - 0.6222		
Number of Buildings	2		
NLR_{75}, L/s•m^2			
Mean	2.91		2.91
Standard Deviation	0.04		0.04
Range	2.88 - 2.94		2.88 - 2.94
Number of Buildings	2		2
ac/hr_{50}			
Mean	5.78		5.78
Standard Deviation	0.20		0.20
Range	5.63 - 5.92		5.63 - 5.92
Number of Buildings	2		2
$Flow_{75}$, L/s			
Mean	1523		
Standard Deviation	483		
Range	1181 - 1864		
Number of Buildings	2		

Table A-7b) – Detailed Airtightness Test Results for Greenhouses (Imperial Units)

	Imperial Units		
	Depressurization	**Pressurization**	**Mean**
Envelope surface area, ft^2			
Mean	5638		
Standard Deviation	1860		
Range	4323 - 6953		
Number of Buildings	2		
Volume, ft^3			
Mean	26,705		
Standard Deviation	8478		
Range	20,710 - 32,699		
Number of Buildings	2		
Flow Coefficient (C), $ft^3/min•Pa^n$			
Mean	314		
Standard Deviation	202		
Range	171 - 457		
Number of Buildings	2		
Flow Exponent (n), dimensionless			
Mean	0.5610		
Standard Deviation	0.0865		
Range	0.4998 - 0.6222		
Number of Buildings	2		
NLR_{75}, $ft^3/min•ft^2$			
Mean	0.57		0.57
Standard Deviation	0.01		0.01
Range	0.57 - 0.58		0.57 - 0.58
Number of Buildings	2		2
ac/hr_{50}			
Mean	5.78		5.78
Standard Deviation	0.20		0.20
Range	5.63 - 5.92		5.63 - 5.92
Number of Buildings	2		2
$Flow_{75}$, ft^3/min			
Mean	3226		
Standard Deviation	1023		
Range	2503 - 3950		
Number of Buildings	2		