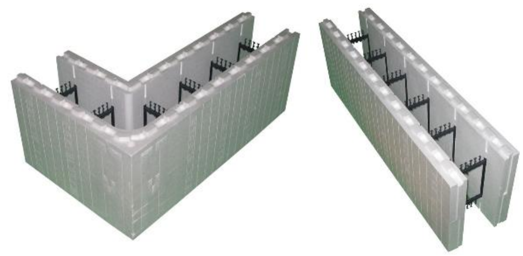
ICF Airtightness Study

Airtightness Data Analysis for Low-Rise and Mid-Rise Residential Buildings

Project 11872.000

RDH BUILDING SCIENCE LABORATORIES



To:
ICF Manufacturers Association
Ottawa, Ontario

ICFMA
INSULATING CONCRETE FORMS MANUFACTURERS ASSOCIATION

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Summary

This report provides a dataset and analysis of airtightness measurements for low-rise (1 to 3 storey) and mid-rise (4 to 6 storey) residential Insulating Concrete Form (ICF) buildings provided by ICF Manufacturers Association (ICFMA) members and published studies.

Published airtightness data indicates that typical Canadian houses are on average better than 4 ACH50 and US houses better than 5 ACH50. The average airtightness of 49 ICF houses collected from ICFMA for this study was found to be 1.26 ACH50. This is significantly better than the performance expected for typical wood frame housing.

The potential for decay of air barrier systems in modern wood framed houses has not been well studied to date. However, ICF walls are expected to have a long-term airtightness performance benefit over loose-laid house wrap air barriers in that they are rigid, strong, durable, and continuous in the field of the wall.

Several general insights on air tightness of houses are explored in this study and are useful to the ICF industry for developing air tightness strategies for energy code compliance in various climate zones within North American markets:

- Houses in cold climates are expected to be more air tight than houses in hot climates.
- Local construction quality and approaches as well as local energy efficiency programs appear to also significantly affect airtightness.
- Attached houses are expected to have greater measured air leakage than detached houses due to air leakage between units (Canadian codes suggest a 0.5 ACH50 penalty).
- There is a significant reduction in ACH50 expected for larger buildings due to form factor advantages within the calculation - linear regression analysis applied in the ICF house samples in this study shows a 0.09 ACH50 improvement in airtightness values for every additional 1000 sqft of conditioned floor area.

The airtightness of the one mid-rise residential ICF building received for this study with published results had good airtightness, and the air leakage paths in the building were similar to those reported for other mid/high rise multiunit residential building. This study also showed that ICF walls are expected to have better and more reliable airtightness than walls systems using loose laid house wrap as air barriers; however, more data is needed to draw more specific insights.

1 Introduction

The purpose of this study is to generate an understanding of the airtightness of insulating concrete form (ICF) low-rise and mid-rise residential buildings relative to typical North American wood frame construction. This report presents a collection of measured data on ICF low- and mid-rise residential buildings provided by ICFMA members and from other published studies. The datasets are further analyzed for impact of factors such as location/climate and building size on airtightness. Finally, the report concludes with a discussion of the linkages between this study and the next task, reviewing energy codes in the US and Canada.

1.1 Insulating Concrete Form (ICF) Basics

Insulating concrete form (ICF) is a system of concrete formwork made of rigid insulation that stays in place after the concrete is poured. ICF systems typically consist of light-weight expanded polystyrene (EPS) modular units that are designed to be dry stacked to create the desired above or below grade wall; interior webs maintain the distance between the inner and outer layers of EPS insulation. The ICF wall with reinforcement is filled with concrete, creating a fully insulated monolithic cast-in-place concrete core. Figure 1.1 illustrates the components of a typical ICF wall.

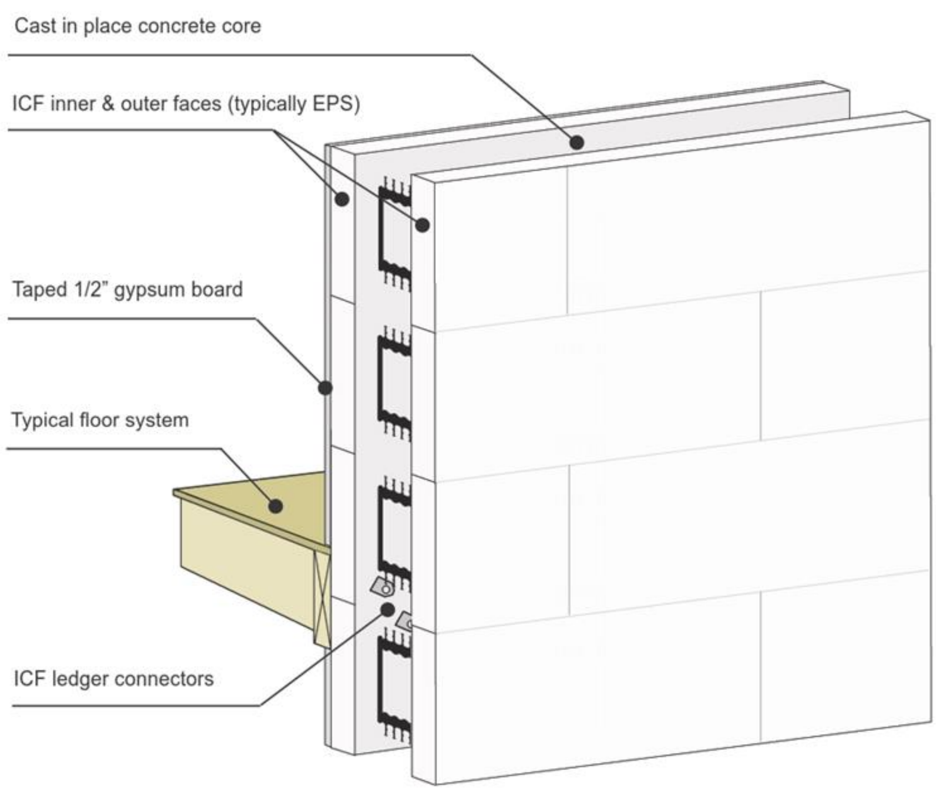
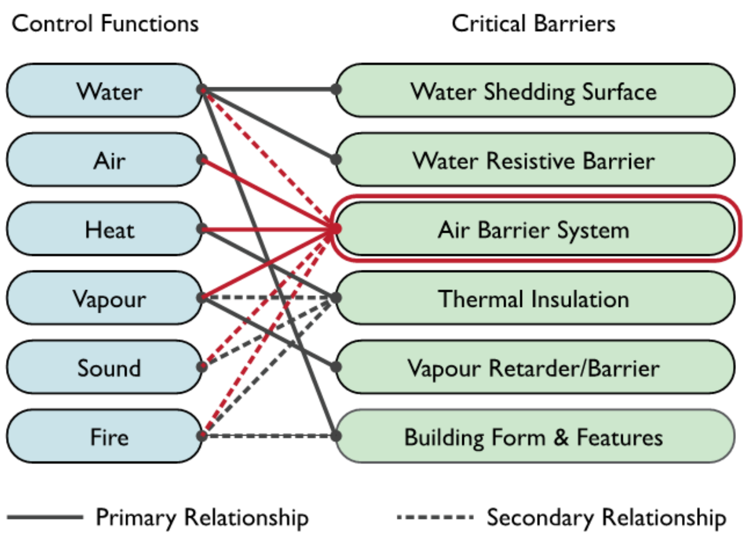


Figure 1.1 Diagram of Typical ICF Wall
Fox Blocks Graphic

1.2 Building Enclosure Control Functions

The building enclosure is a system of materials, components and assemblies that physically separate the exterior and interior environments. It comprises various elements including: roofs, above-grade walls, windows, doors, skylights, below-grade walls and floors. In combination, these assemblies must control water, air, heat, water vapour, fire, smoke and sound. The diagram below lists major enclosure control functions and associated critical barriers.



In a typical ICF wall, liquid water (e.g. rain, snow melt, etc.) control is typically addressed with cladding installed outboard of the ICF system. The outer surface of the ICF shell is typically used as the water resistive barrier behind the cladding. Intersections, windows, doors, and other penetrations must be drained, sealed, and/or detailed to prevent the penetration of liquid water beyond these water control layers.

The continuous concrete as well as the interior and exterior rigid insulation board skins all provide resistance to airflow in a typical ICF wall. Unlike conventional wood frame construction, ICF walls do not rely on membranes and tapes for air barrier continuity in the field of the wall area.

Resistance to heat flow in a typical ICF wall assembly is provided by the rigid insulation shell. The continuous EPS layers on the interior and exterior of the concrete are uninterrupted by framing and therefore provide the full R-value of the insulation. If desired, additional insulation can be installed outboard of the ICF wall behind the exterior cladding or within the ICF cavity with an EPS insulation insert.

The location of the thermal control layer(s) in conventional wood frame construction has important implications for durability. If there is more insulation on the interior than the exterior of the sheathing plane, discontinuities in the air control layer increases the risk of air leakage vapour condensation. ICF wall assemblies are less susceptible to these durability issues because both the concrete core and EPS shell provide sufficient vapor diffusion resistance to control vapor driven from either direction. Furthermore, unlike conventional wood frame construction, the materials of the ICF wall itself are not susceptible to moisture related issues.

1.3 The Importance of Airflow Control

Building airflow can typically be characterized as either air leakage, natural ventilation or mechanical ventilation. "Air leakage" is unintentional and uncontrolled airflow through inadvertent openings in an enclosure.

The restriction of air leakage by the air barriers system is one of the most important functions of the building enclosure. This is because air is a transport mechanism for water, vapour, heat energy, sound, and airborne contaminants. Uncontrolled air leakage can lead to moisture issues from condensation, discomfort, energy waste, and poor indoor air quality.

Building codes acknowledge the importance of controlling unintended airflow by requiring that building enclosures include an air barrier. Air barrier design requires careful consideration of materials, components, transitions, and penetration details to provide a durable and continuous air barrier across the entire building enclosure.

Airflow control in typical ICF buildings is the primary focus of this report.

1.4 Airtightness Metrics

The ability of the building enclosure to resist airflow is often quantified in terms of various airtightness metrics. Airtightness testing is typically completed at the building level using blower fans to pressurize and depressurize the whole building. The various measured results of testing, including fan airflow and pressure difference across the enclosure, are used to indicate the overall building airtightness characteristics and performance level.

Unless otherwise specified, airtightness metrics refer to the performance of a building as a whole. It is important to highlight that the reported airtightness values of low- and mid-rise ICF buildings in this report reflect not only the performance of the ICF walls and associated details but also the performance of other building enclosure assemblies (such as floors and roofs) and the airtightness of mechanical system distribution and penetrations. Common airtightness testing metrics are summarized below.

1.4.1 Airflow / Air Leakage Rate

The total airflow or air leakage rate is the volume of the air per unit time required to maintain a given pressure difference across the test boundary. In airtightness testing, a fan is used to draw air into or expel air from a building to maintain a specified level of pressurization or depressurization. Since airflow into a building must equal airflow out of the building, airflow through the fan represents the leakage airflow across the boundary. This is determined from a power law equation for flow, Q (L/s or cfm), at a given pressure difference (ΔP):

$$Q_{\Delta P} = C \Delta P^{n}$$

The airflow must be given at a specific pressure difference (ΔP) for it to be meaningful and is denoted as $Q_{\Delta P}$; 50 Pa and 75 P are commonly reported values. The flow coefficient, C, and the flow exponent, n, are determined from airtightness testing and are unique to each test instance. This is summarized in Figure 1.2 below.

1.4.2 Normalized Air Leakage Rate

Normalized air leakage rate, q (L/s · m² or cfm/ft²), is the airflow at a given pressure, $Q_{\Delta P}$, divided by the area of the pressure boundary A (i.e. the building enclosure area):

$$q_{\Delta P} = \frac{Q_{\Delta P}}{A}$$

Normalizing by enclosure area allows for comparison with benchmarks and performance requirements. Summarized in Figure 1.2, this is the most commonly used metric for whole-building airtightness measurement and targets. The normalized air leakage rate should not be confused with "normalized leakage" (NL) reported by some researchers which represents effective leakage area normalized to building floor area and height.

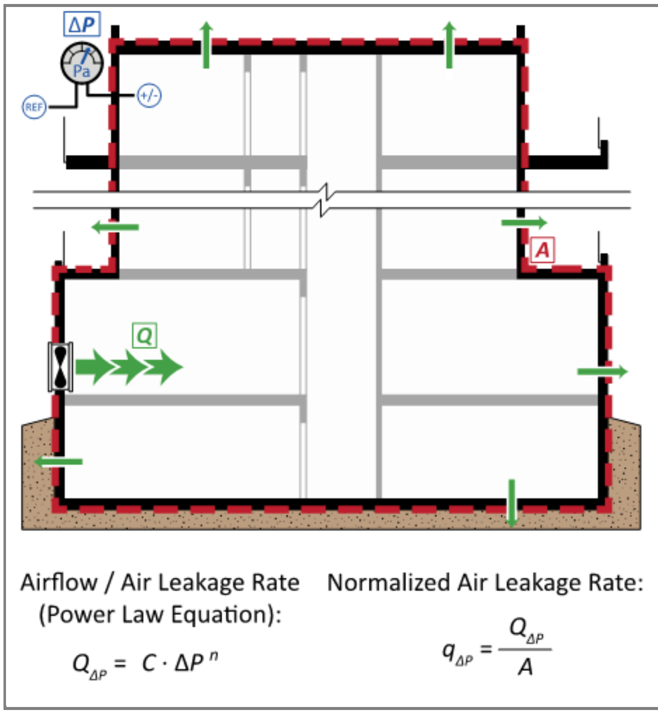


Figure 1.2 Airflow/Air Leakage Rate

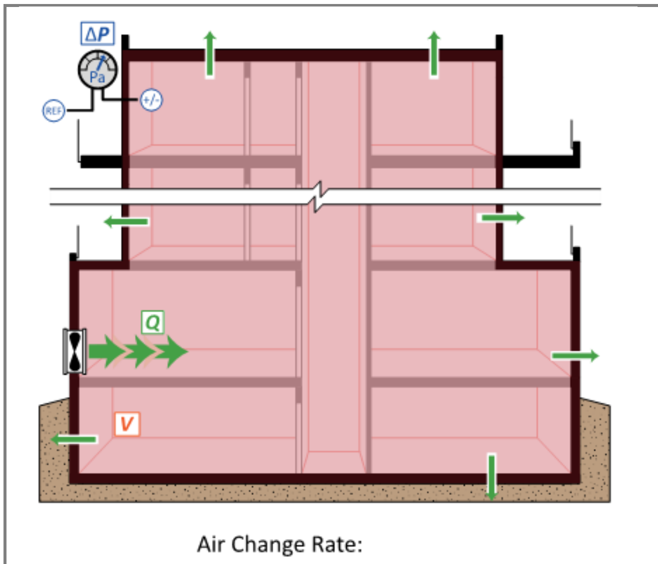
Determining airflow/air leakage rate and normalized air leakage rate from airtightness testing. From RDH's Illustrated Guide to Achieving Airtight Buildings (2017).

1.4.3 Air Change Rate

Air change rate measures how frequently the building air volume would be replaced due to air leakage at a given pressure difference. This value is determined by dividing the flow rate, $Q_{\Delta P}$, by the volume, V, of the enclosure.

$$ACH_{\Delta P} = \frac{Q_{\Delta P}}{V}$$

Air change rate is typically measured in air changes per hour (ACH) at a given pressure difference, denoted as $ACH_{\Delta P}$. ACH@50Pa is commonly used as a relative indicator of airtightness for smaller buildings such as single-family houses.



$$ACH_{\Delta P} = \frac{Q_{\Delta P}}{V} \cdot \text{(hourly airflow conversion)}$$

Figure 1.3 Air Change Rate

Determining air change rate from airtightness testing. From RDH's Illustrated Guide to Achieving Airtight Buildings (2017).[1]

2 Air Barrier Systems in ICF Buildings

2.1 Air Impermeability of ICF Wall Systems

An air impermeable material or assembly is an air control layer. A material or assembly is considered to be air impermeable if it has an air permeance equal to or less than 0.02 L/s·m^2 (0.004 cfm/ft^2) at a 75 Pa pressure difference when tested in accordance with ASTM E 2178 or E 283. The air permeability of ICF wall system products have been measured by others[2] demonstrating compliance with this requirement.

2.2 Air Barrier Continuity of ICF Wall Systems

Continuity is the single most important criteria for an effective air barrier system. However, it is also one of the most challenging to achieve. The air barrier system must be continuous around penetrations, at transitions, and at interfaces between enclosure assemblies to ensure air tightness.

It is generally assumed that the air barrier approach for typical wood framed exterior walls is loose laid mechanically attached building paper (i.e. "house wrap") and interior drywall; in the colder climates, interior polyethylene sheet vapour barriers also function as air barriers. The air sealing measures for air tight drywall approach in conventional wood frame construction are described in Figure 2.2 (e.g. rim joist caulked or gasketed to top plate) rely on a high degree of construction quality to achieve air barrier continuity. In typical construction, many of these air sealing measures are not installed at all. The air sealing of interior polyethylene sheet vapour barriers also requires several measures to ensure air tightness at wall interfaces and from sheet to sheet. Both approaches also require air sealing at electrical outlet and other penetration of the interior finish which would not be required for an ICF wall. These penetrations are noteworthy because they

[1] Illustrated Guide – Achieving Airtight Buildings (2017). Prepared by RDH Building Science Inc. and published by BC Housing, BC Hydro, and the City of Vancouver.
[2] Intertek (2017) Technical Bulletin 1.12.01 – Air Barrier (Permeance)

can be anticipated to occur in the future as occupant install wall mounted items (e.g. televisions, mirrors, floating shelfs, etc.).

In ICF walls, because there is no need to transition between air barrier materials at floor-to-wall transitions as illustrated in Figure 2.1. These walls should consistently achieve a high degree of air tightness in these key locations regardless of construction quality. Holes made in drywall also do not penetrate the air barrier in ICF wall assemblies unless they penetration the whole wall.

Another common air barrier approach for wood frame construction involves detailing the loose laid mechanically attached building paper (i.e. "house wrap") as the air barrier by tape sealing laps in the sheets. This approach is designed to be continuous at the exterior sheathing plane, bridging the wood framed floor-to-wall interfaces. While this addresses some of the issues of interior polyethylene air/vapour barriers or airtight drywall described above, it also introduces a different set of air barrier continuity issues that rely on construction quality, such as the consistent taping or sealing of laps in the loose laid sheets in the field of the wall. The continuous concrete core of the ICF wall assembly eliminates the need to seal laps in sheet applied air barrier materials, resulting in a consistently high degree of airtightness in the field of the wall regardless of construction quality.

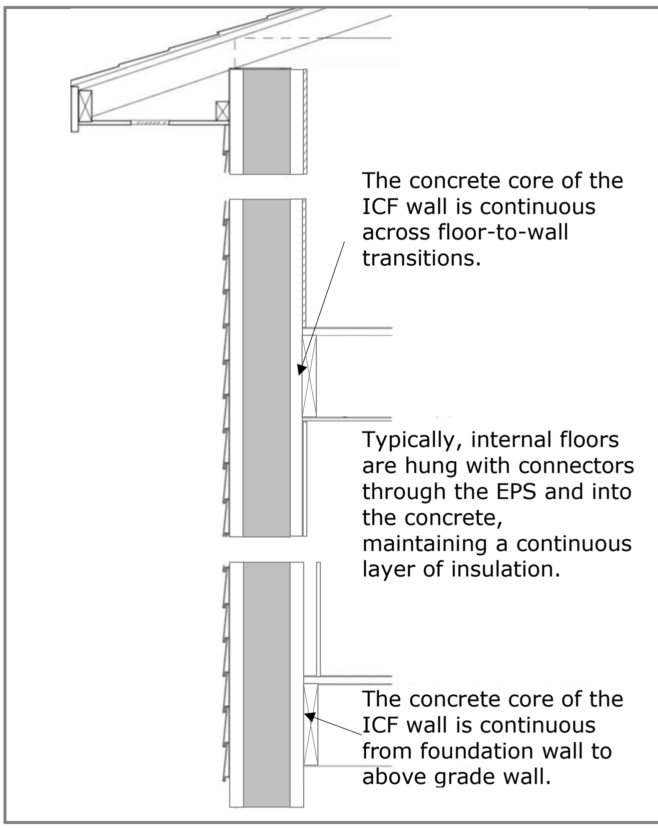


Figure 2.1 ICF Wall Section

The notes on the drawing illustrate how the concrete core serves at an effective air barrier at wall to floor transitions.

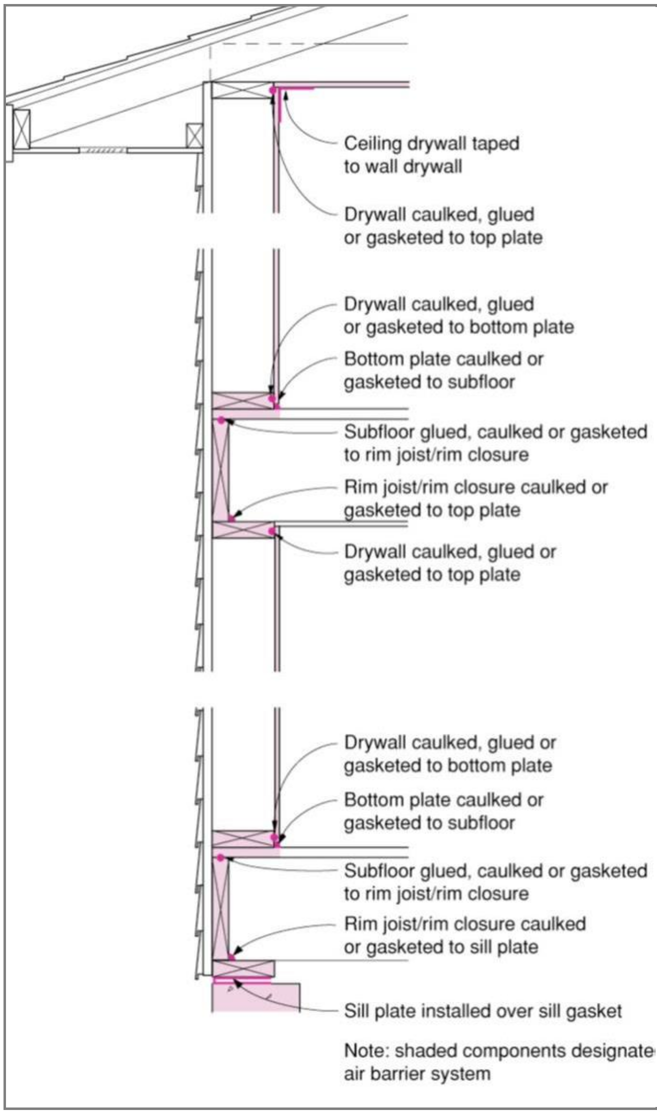


Figure 2.2 Wood Framed Wall w/ Airtight Drywall Approach Air Barrier

The notes indicate air sealing measures needed to achieve a high degree of air tightness

And while it is acknowledged that air barrier continuity at walls is only one component of overall airtightness, it is one of the most important. As shown in Figure 2.3, wall interfaces are estimated to be the single largest contributor to the total air leakage in houses, accounting for approximately 35% overall. The inherent ability of ICF walls to manage these problematic interfaces offers a significant airtightness advantage compared to wood frame construction.

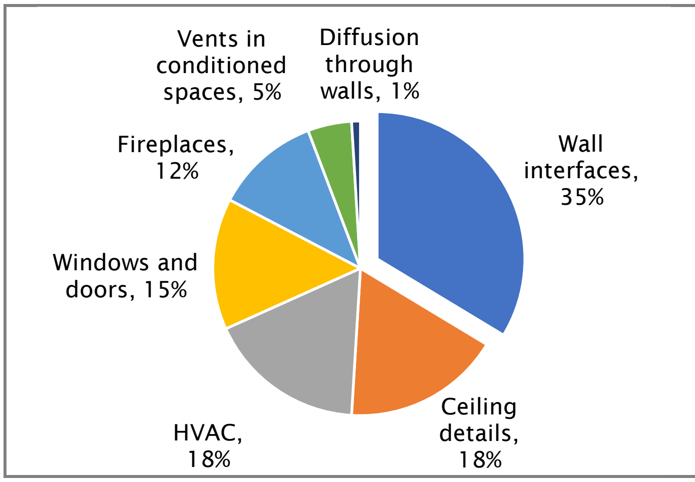


Figure 2.3 Distribution of Air Leakage in Houses

Distribution of air leakage in houses[3]

It can also be seen in Figure 2.3 that windows and doors are another major source of air leakage in houses. RDH conducted a study in 2014[4] that included air tightness testing of several different window installation methods in ICF walls. It was found that all installation methods resulted in air permeance equal to or less than 0.02 L/s·m^2 (0.004 cfm/ft^2) at a 75 Pa pressure difference when tested in accordance with ASTM E 283. These results demonstrate that effective air barrier detailing around windows and doors can be successfully achieved in ICF construction.

2.3 Durability of Residential Air Barriers

The air barrier system must be designed to last for the entire service life of the building (or at least the service life of the major materials or components to which it is integral). The concrete layer within ICF wall systems is very durable and can be expected to maintain its airtightness for the life of the building without degradation. It may be necessary to regularly maintain sealants or other air barrier transition materials at ICF wall penetrations and interfaces with other systems; these should be designed to be easily accessible for this purpose.

The long-term durability of air barriers in wood frame construction has not been well characterized. To capture the in-service performance of barriers in conventional wood frame construction, Proskiw and Parehk (2004) conducted a study[5] where 22 wood framed houses in central Canada were repeatedly tested for airtightness during a 10 to 14-year period following construction. The study included wood frame wall assemblies with interior polyethylene air/vapour barriers and airtight drywall air barriers. Much of air barrier performance loss observed in the study was associated with leakage at floor drains, doors and windows, and mechanical and electrical penetrations and due to adjacent excavations and renovations.

The Proskiw and Parehk study is the only long-term in-service air barrier performance study found by RDH in a search of available published literature. As noted, their work focussed on the long-term durability of interior polyethylene sheet air barriers and airtight drywall air barriers only; it did not address the in-service performance of loose laid

[3] ASHRAE Handbook of Fundamentals (2013)

[4] RDH Building Engineering Ltd. (2014). *ICF Wall Testing and Modelling – Lab Testing Report* Prepared for BC Housing House Owner Protection Office and BC Ready-Mixed Concrete Association.

[5] Proskiw, G., & Parekh, A. (2004). Airtightness performance of wood frame houses over a 14 year period. *Proceedings of the thermal performance of exterior envelope of whole buildings IX*, 5-9.

mechanically attached building paper when detailed as the air barrier. Others have made field observations indicating degradation of a specific sheet applied housewrap product installed behind wood siding (Figure 2.4). The observed degradation was found to be due to the unforeseen effect of surfactants from the wood. It is understood by RDH that current formulations of the product are different and are no longer susceptible to degradation by wood surfactants. However, the current long-term performance of housewraps and the tapes and adhesive that make them air tight is uncertain.

Figure 2.4 Photo of Building Paper after 30 years Behind Wood Siding.

Note the specific product, Tyvek, was significantly affected by surfactants in the wood. It is understood that current formulations of this product are quite different and address the surfactant issue. (Wilson 2013)[6]

2.4 Strength and Stiffness of Residential Air Barriers

From construction to occupancy, the air barrier system must resist forces acting on it. The design should account for mechanical forces such as those created by wind and stack effect pressures as well as allow for dimensional changes in the structure caused by thermal expansion and moisture absorption. Wood framed construction is more vulnerable to such forces and, when loose laid sheet products are used as part of the air barrier system, they rely on a combination of fasteners, tapes, sealants, strapping, and exterior insulation to perform adequately. In contrast, ICF wall system are very strong and stiff and not significantly affected by mechanical forces or dimension changes.

Figure 2.5 Poor House Wrap Installation

The effectiveness of loose laid house wrap as an air and water barrier will depend on how well joints are repaired and taped prior to cladding installation.[7]

RDH conducted a study assembling whole building airtightness data for multi-unit residential buildings (i.e. apartments, dormitories, etc.) in Washington State[8]. The study

[6] Wilson, A. (2013) "What's New with Water Resistive Barriers", Green Building Advisor Posting, June 27, 2013.

[7] Fitzgerald-Redd, S. (2017) "Avoiding a Bad Wrap" Insulation Institute Blog. Retrieved from http://information.insulationinstitute.org/blog/avoiding-a-bad-wrap.

[8] Jones, D., Brown, B., & Thompson, T. (2014). Building Enclosure Airtightness Testing in Washington State-Lessons Learned about Air Barrier Systems and Large Building Testing Procedures. ASHRAE Transactions, 120.

found that buildings with loose laid sheet air barriers had an average of 20% to 30% worse airtightness and about 3 times greater airtightness variability compared to buildings with solid air barrier components similar to ICF. This is partly related to the ability of the stronger and stiffer air barrier materials such as concrete to resist weathering from air "pumping".

Air pumping occurs when flow is generated by the deformation of a large membrane, such as a roof membrane or loose laid sheet air barriers, under gusting and dynamic wind pressures (Figure 2.6). Airtightness testing of buildings do not capture the influence of this phenomenon of air leakage during building operation. Unlike wood frame construction with sheet air barriers, ICF wall systems are not subject to wind pumping effects.

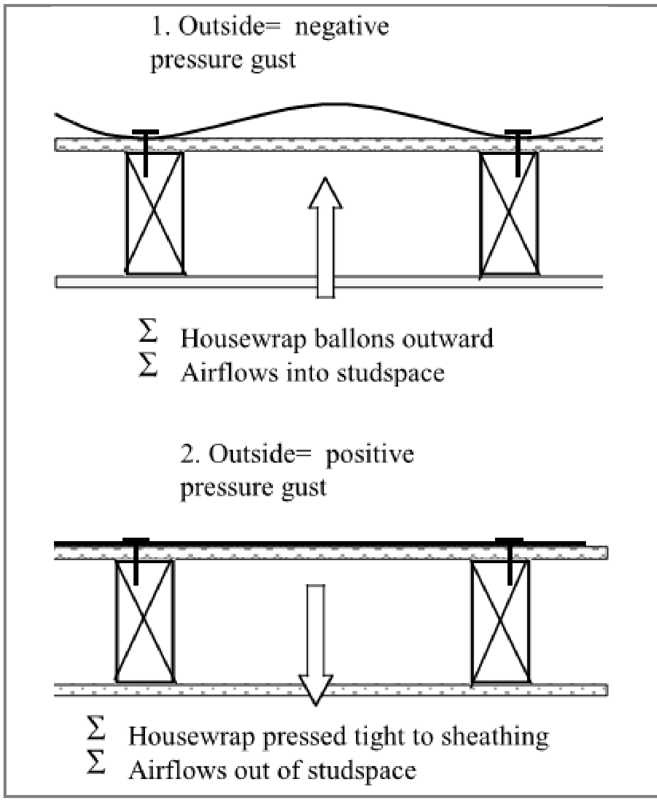


Figure 2.6 Wind Pumping of Loose Laid Sheet Air Barriers

Loose laid mechanically attached sheet membrane air barriers can pulse and flutter in dynamic wind conditions, thereby causing air "pumping"

2.5 Previous Studies of ICF Wall System Airtightness

In 1998, Oak Ridge National Lab (ORNL) published a study[9] proposing an effective wall R-value for ICF constructions including benefits for thermal mass impact and improved airtightness inherent of the wall system. They assumed that the use of ICF walls reduced overall house air leakage by 20%. This was based on a 1995 survey of blower door tests for 7 ICF houses[10] and an understanding that use of ICF would reduce the air leakage at some common building transitions (e.g. sill plate to foundation interface, electrical outlets, and plumbing penetrations).

[9] Kosny, J., Christian, J. E., Desjarlais, A. O., Kossecka, E., & Berrenberg, L. (1998). Performance check between whole building thermal performance criteria and exterior wall measured clear wall R-value, thermal bridging, thermal mass, and airtightness/Discussion. *ASHRAE Transactions*, 104, 1379.

[10] Thompson, G.L., (1995). "Airtightness Tests for American Polysteel Form Houses " *Contract No. SW1547AF*, Southwest Infrared Inc.

The ORNL study (1998) includes modelling which projects equivalent wall R-value impact of thermal mass effect and improved airtightness effects for an R-12 ICF wall (38mm EPS insulation board on each face). As summarized in below, the estimated R-value impacts for airtightness alone (i.e. thermal mass impacts not included) are large.

This study is referenced in current ICF manufacturer studies to justify reductions in air leakage for these wall systems[11]. However, the study was based on airtightness test results for only 7 houses constructed more than 20 years ago. Given the limitations of the ORNL study, it is recommended that the airtightness impacts of ICF be re-evaluated based on the available data in a more current context.

TABLE 2.1 AIRTIGHTNESS R-VALUE IMPACTS FOR ICF WALLS REPORTED IN ORNL STUDY [FT²°FHR/BTU (M²K/W)]

LOCATION	NOMINAL WALL R-VALUE	ORNL STUDY AIRTIGHTNESS IMPACT	PROPOSED WALL R-VALUE INCLUDING IMPACT OF AIRTIGHTNESS	% DIFFERENCE
Atlanta	R12 (2.1 RSI)	R9.4 (1.7 RSI)	R21.3	78%
Denver		R7.6 (1.3 RSI)	R19.6	64%
Miami		R23.2 (4.1 RSI)	R35.2	193%
Minneapolis		R13.0 (2.3 RSI)	R15	109%
Washington DC		R8.3 (1.5 RSI)	R20.3	69%

A more recent study out of MIT by Durschlag[12] (referred to in this report as the “MIT Study”) assessed airtightness testing data from 43 ICF houses. In this study, ICF houses were compared to an analysis of the blower door test result database from Lawrence Berkley National Laboratory (LBNL). Specifically, the 43 ICF houses, which have a median construction year of 2007 and median size of 314 m^2 (3,380 ft^2), were compared to a subset of the LBNL database representing wood frame houses constructed in 2000 and larger than 139 m^2 (1,496 ft^2).

Based on this analysis, the ICF houses in the MIT study were found to be only marginally more air tight than the conventional wood frame houses of similar vintage and size. The author suggests that this is because wood frame houses are generally being built more and more airtight. In other words, as the benchmark for wood frame airtightness improves, the comparative performance margin gets smaller and smaller. The study also investigated the variables influencing the range of airtightness among ICF houses and concluded that the best predictors of airtightness were house volume and window area.

Again, limitations of this study such as the limited sample size and geographic distribution, point to the need for further evaluation of ICF air tightness.

[11] Gajda, J. (2001). Energy use of single-family houses with various exterior walls. CD026, Portland Cement Association, Skokie, IL.

[12] Durschlag, H (2012) Air Leakage of Insulated Concrete Form Houses, Massachusetts Institute of Technology.

3 Low-Rise ICF Residential Airtightness Data

Low-rise residential buildings include detached houses, attached houses (row houses, townhouses, etc.), and multi-unit residential (apartment, dormitory, condominium, etc.) buildings up to and including 3 storeys. Within this section the dataset is presented and compared to published airtightness data from typical wood framed houses. This presentation of the data is followed by analysis of location/climate, detached vs attached construction, and house size impacts.

3.1 Overview of Low-Rise ICF Residential Dataset

Airtightness of 49 low-rise ICF houses were provided by ICFMA members. The collected dataset and calculated ACH50 values are given in Appendix A. It is noted that the dataset would need to be larger and measures taken to ensure random sampling to ensure the findings are statistically significant. However, the data does provide valuable insights on the airtightness levels of ICF buildings that are being achieved in the field to inform strategies for meeting energy codes explored in further phases of the study. **The findings from this study will be strengthened as the ICFMA provide more airtightness testing results to build this database.**

A plot of the 49 reported house airtightness measurements, along with reported data from the ORNL and MIT studies discussed in Section 2.5, is given in Figure 3.1. The mean and median values of the 49 houses in the ICFMA dataset are 1.26 and 1.33 ACH50, respectively.

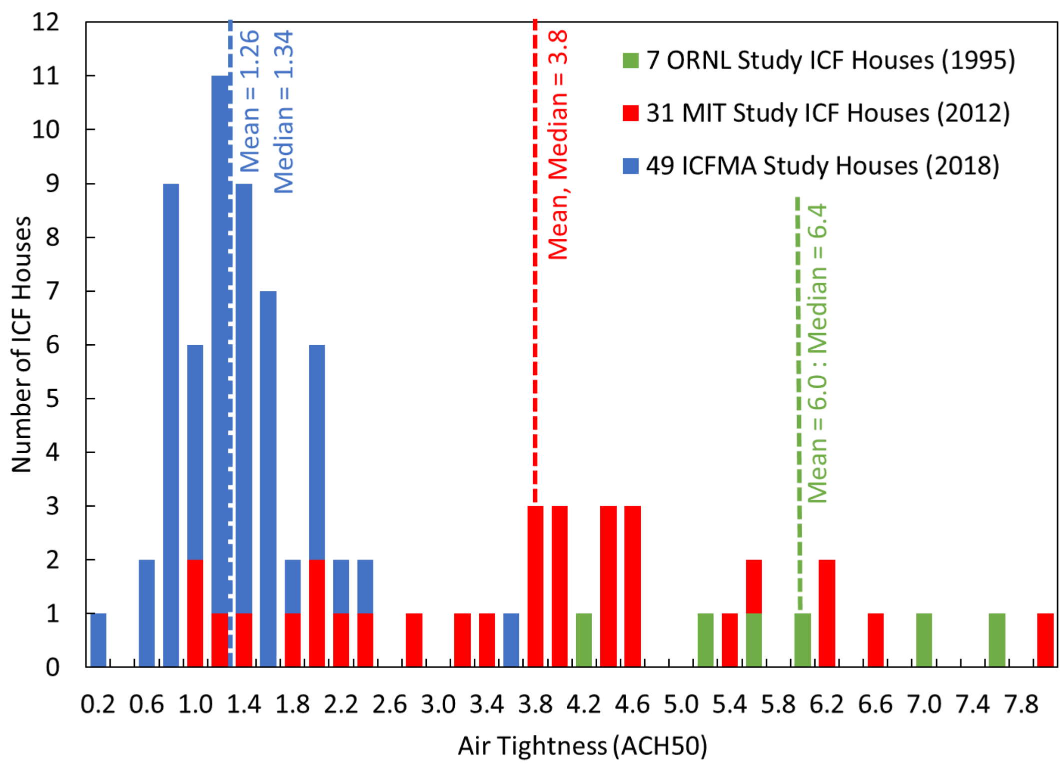


Figure 3.1 Airtightness Data for ICF Houses from All Studies

The plots show that the airtightness of the 49 ICF houses in the ICFMA dataset are much more air tightness than those from the ORNL study. This is to be expected as the ORNL study was based on ICF construction over 20 years ago; improvements in ICF construction since this study would be expected to result in better airtightness.

The airtightness of the 49 houses in the ICFMA dataset are somewhat more airtight than those from the MIT study. Houses in the MIT study are less than 10 years old and are assumed to generally reflect current construction practices. These 31 houses are therefore combined with the 49 houses from the ICFMA to create a larger ICF dataset for analysis. This larger ICFMA-MIT dataset of 80 houses constructed in the last 10 years results in a mean and median of 2.23 and 1.47 ACH50. These results will be used to characterize the airtightness of ICF houses built today.

3.2 Low-Rise ICF Residential Case Study: Ontario House

RDH performed airtightness testing on a southern Ontario ICF house for Fox Block at the same time as this study. The house had an airtightness of 0.81 ACH50, well below the assumed an airtightness of 3 ACH50 in the Ontario Building Code. This performance is also exceptional considering that it is a "regular" house and not being certified under Energy Star or other energy efficiency rating program, demonstrating the ease of achieving a high degree of air tightness with ICF construction.

The testing also provided insights on air leakage paths for ICF houses. The observed air leakage points are listed below:

→ Kitchen hood (note that the general contractor indicated that the duct had a metal bi-fold backdraft damper); bathroom exhaust fan (note that a plastic backdraft damper is suspected to be making the seal in these ducts).

→ Closed cell spray foam sealed HRV duct penetration of foundation wall.

→ Patio door vents; edges of front door with poor weather stripping.

→ Low expansion spray foam filled gap between the bottom corner of the basement window and the rough opening.

→ Basement cold room's exposed ceiling under the front step.

→ Top corner of kitchen cabinets and electrical outlets near front door (assumed to connect to leakage path through ceiling).

Please contact ICFMA for a copy of the full report.

3.3 Comparison to Typical Wood Frames Houses

3.3.1 Mean and Median Airtightness

Predominantly wood frame construction, low-rise residential is the most thoroughly studied building type in North America with respect to airtightness due to ventilation concerns, energy incentive programs, and because they represent a large portion of building stock. It is generally assumed that the air barrier approach for typical wood framed exterior walls is loose laid mechanically attached building paper (i.e. "house wrap") and interior drywall; in the colder climates, interior polyethylene sheet vapour barriers also function as air barriers.

A plot from a dataset of over 82,000 Canadian houses (Figure 3.2) compiled by Parekh et al. shows median airtightness of 3.8 ACH50 for house built from 1991 to 2007 with 25th and 75th percentiles of 2.8 to 5.1 ACH50. Analysis of a US dataset of 147,000 existing houses by LNBL (Figure 3.3) reveals a similar trend as the Canadian study of steadily improving airtightness of house. It is assumed that most of the houses in both studies are wood framed. Mean airtightness values of 4.8 ACH50 were estimated for houses built from 2002 to 2012 houses in climate zones 6 and 7. **These studies suggest that Canadian houses are on average better than 4 ACH50 and US houses are better than 5 ACH50. This is roughly double the air leakage values reported for the 80 ICF houses from the ICFMA dataset and MIT Study.**

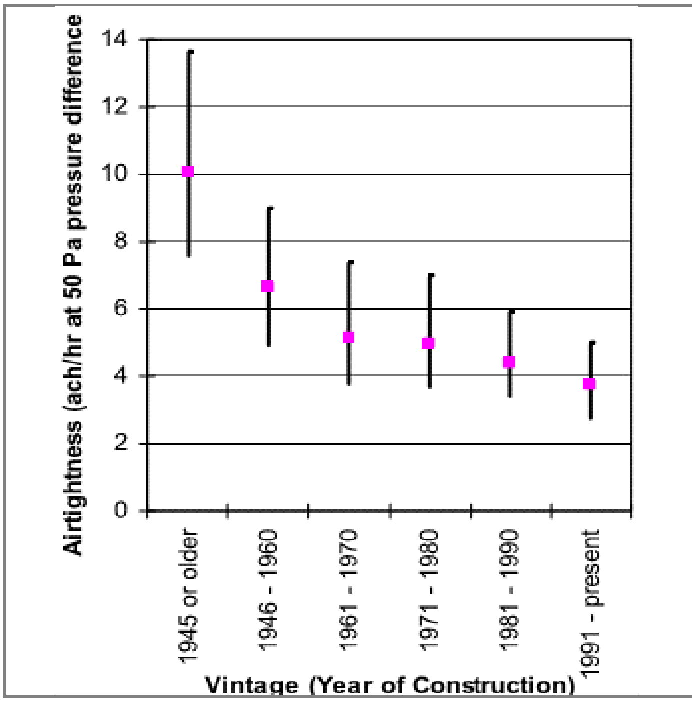


Figure 3.2 Canadian Houses Airtightness vs Vintage

Airtightness profiles for Canadian housing from a 2007 study by Parekh et al.[13]

Each bar represents a range of values from the 25th to 75th percentile with median value highlighted (magenta).

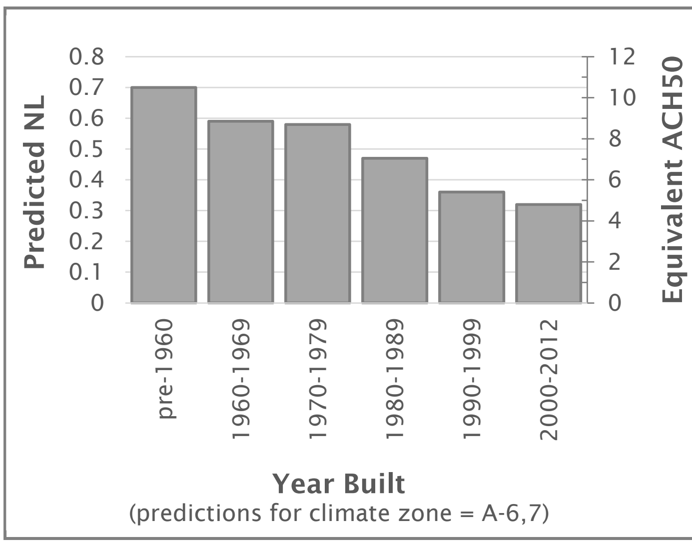


Figure 3.3 US Houses Airtightness vs Vintage

Adapted by RDH from Figure 6 in Chan et al. (2012)[14]

Normalized leakage (NL) based on regression modeling of US dataset for houses as a function of year built (climate zone A-6,7).

RDH conversions to ACH50 are made based on a one-story (height = 3 m) house with floor area = 150 m²

[13] Parekh, A., Roux, L., & Gallant, P. (2007). Thermal and air leakage characteristics of Canadian housing. In 11th Annual Canadian Conference on Building Science and Technology, Banff, Alberta

[14] Chan, W. R., Joh, I., & Sherman, M. H. (2012). *Analysis of air leakage measurements from residential diagnostics database* (No. LBNL-5967E). Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US).

3.3.2 Impact of Location and Climate

Parekh et al. reported air tightness results for 3,200 recently constructed houses (1996 to 2005) across various Canadian provinces and territories. A plot from the study (Figure 3.4) indicates that houses in cold climates such as Saskatchewan (SK) and Manitoba (MB) are more airtight (median between 2 and 2.5 ACH50) and with less variability in airtightness (+/- 0.5 ACH50) than in the milder climates (BC, NB, NS, and PE). This is consistent with the expectation that houses in colder climates are generally more air tight than those in warmer climates, as noted in the previous section of this report. The poor airtightness and high variability report for some cold regions (QC, NT, YK) could be due to biases in the underlying dataset (i.e. data collection restricted to specific sub-sets of the housing stock such as social housing or energy efficiency program participants) or regional differences in construction approaches and/or quality.

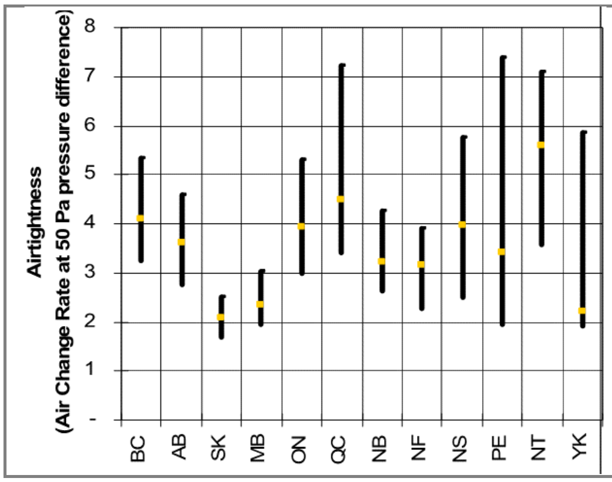


Figure 3.4 Canadian Housing Airtightness vs Location Plot

Airtightness of 3,200 recently built housing (1996 to 2005) in Canada from a 2007 study by Parekh et al.[15]

Each bar represents a range of values from the 25^{th} to 75^{th} percentile with median value highlighted (yellow).

The general trend of tighter houses in colder climates is also seen in the previously described LBNL study of US housing. Figure 3.5 shows an analysis of a subset of the study data for houses built between 1980 and 1989 across different climate zones. Hot humid climates like Miami (A1) have an estimated airtightness of 11 ACH50 compared to severe cold climates like northern Alaska (AK8) estimated at approximately 4 ACH50. The climate dependency is less clear for all other climates with results ranging from 7 to 10 ACH50.

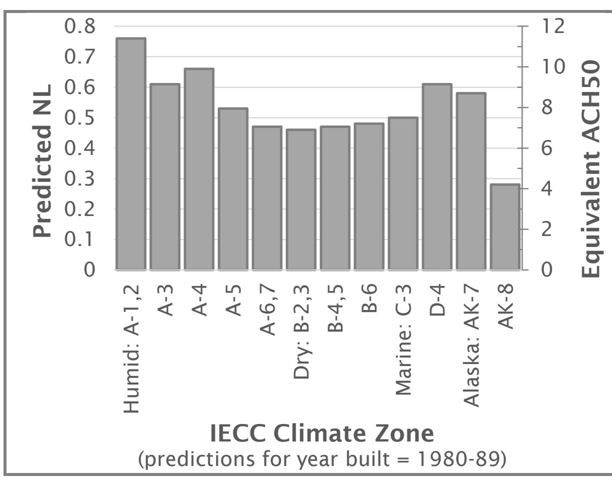


Figure 3.5 US Housing Airtightness vs Climate Zone

Adapted by RDH from Figure 6 in Chan et al. (2012)[16]

Normalized leakage (NL) based on regression modeling of US dataset for houses in different climate zones (1980-89 constructions)

RDH conversions to ACH50 are made based on a one-story (height = 3 m) house with floor area = $150\ m^2$.

[15] Parekh, A., Roux, L., & Gallant, P. (2007). Thermal and air leakage characteristics of Canadian housing. In *11th Annual Canadian Conference on Building Science and Technology, Banff, Alberta*

[16] Chan, W. R., Joh, I., & Sherman, M. H. (2012). *Analysis of air leakage measurements from residential diagnostics database* (No. LBNL-5967E). Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US).

Chan et al.'s analysis of newer houses (built since 2000) is shown in Figure 3.6. This study shows a trend of more airtightness in Wisconsin (75^{th} percentile within 2 to 3 ACH50) relative to California, Nevada, and Texas (75^{th} percentile within 3 to 5 ACH50). However, data from Alaska showed a large range in performance (75^{th} percentile within 3 to 7 ACH50), including several very leaky new houses reaching over 10 ACH50. Similar to the Canadian data, the US data could have been skewed by data gathering from specific sub-sets of the housing stock (such as social housing or energy efficiency program participants) or due to regional differences in construction approaches and/or quality. Overall, this dataset suggests that the airtightness of a typical US house is between 3.7 ACH at 5.8 ACH50.

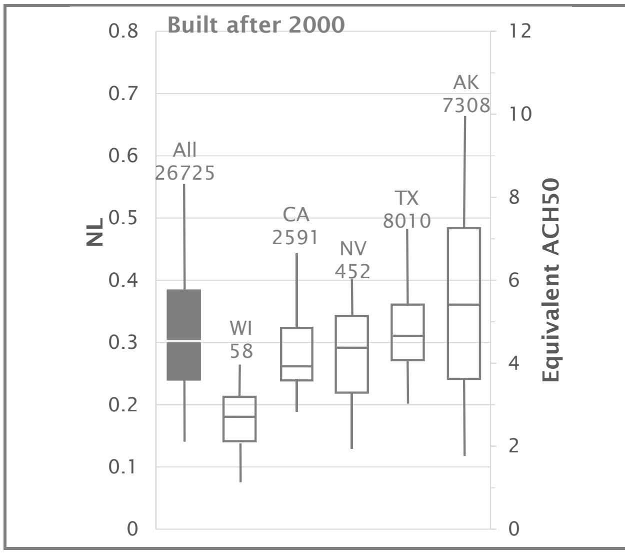


Figure 3.6 US Housing Airtightness vs Location Plot

Adapted from Figure 1 in Chan et al. (2013) [17]

Normalized leakage (NL) based on regression modeling of US dataset for houses in different states built after 2000. Each box plot shows the median and interquartile range, and whiskers show 5^{th} and 95^{th} percentiles.

Conversions to ACH50 are made based on a one-story (height = 3 m) house with floor area = 150 m^2.

An indication of a climate/location dependency trend is also seen in the ICFMA-MIT dataset introduced in Section 3.1. The locations and climate zones of the 80 ICF houses are plotted relative to airtightness in Figure 3.7.

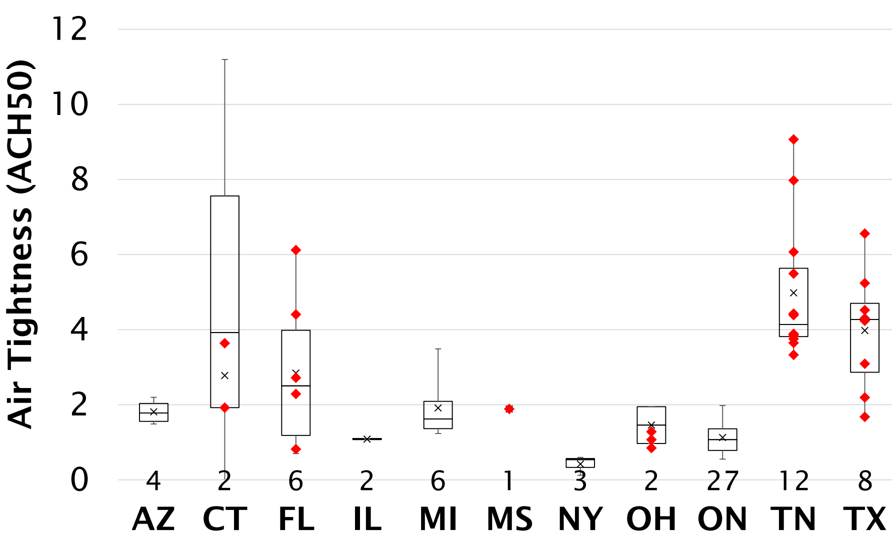


Figure 3.7 Airtightness and Location of ICF Houses in the ICFMA-MIT Dataset
Mean shown as x, 25th and 75^{th} percentiles shown in boxed columns, minimum and maximum values shown in error bars, and number of data points listed below. MIT data shown as red triangles.

[17] Chan, W. R., and M. H. Sherman. (2013) "Building Envelope & Duct Airtightness of New US Dwellings." Building XII, Clearwater FL (US).

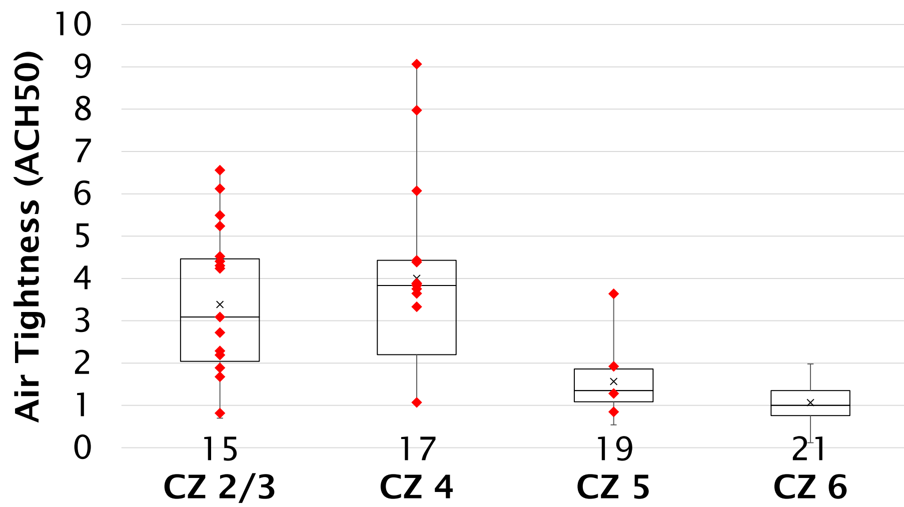


Figure 3.8 Airtightness and ASHRAE Climate Zone of ICF Houses in the ICFMA-MIT Mean shown as x, 25th percentiles shown in boxed columns, minimum and maximum values shown in error bars. MIT data highlighted in red.

Based on these studies, location and climate appear to have an impact on airtightness of both wood frame and ICF houses. **Both wood frame and ICF houses in cold climates are expected to be more airtight than houses in hot climates. However, other factors such as local construction quality and approaches as well as local energy efficiency programs appear to also significantly affect airtightness, making it difficult to predict the extent of climate dependency.**

3.3.3 Detached Versus Attached Houses

Studies have found as much as 60% of air leakage in attached wood framed houses across the separating walls[18]. The challenges in constructing air tight wood frame separating walls is reflected in the **additional 0.5 ACH50 air leakage allowance for detached houses relative to attached houses in Canadian standards** as summarized in Table 3.1.

TABLE 3.1 CODE ALLOWANCES FOR DETACHED VS ATTACHED HOUSES		
Code	Detached House	Attached House
Ontario Building Code (SB12)	3.0 ACH50	3.5 ACH50
Energy Star (Canada)	2.5 ACH50	3.0 ACH50
Energy Star (US)	Same for Detached and Attached	

Poor air tightness of separating walls in attached houses and multi-unit residential buildings results in noise and odour issues. The ease of achieving greater air tightness of exterior ICF walls also applies to ICF separating walls. Hence, use of ICF separating walls in attached houses is expected to lower measured unit airtightness and achieve accompanying noise and odour control advantages. Note that the airtightness measurement for the one attached ICF house in the ICFMA sample set was for the entire structure and not individual units. **ICFMA is encouraged to seek measurements from attached houses to assess the advantages of ICF separating walls.**

[18] Diamond, R.C., M.P. Modera, and H.E. Feustel. 1986. Ventilation and occupant behaviour in two apartment buildings. Proceedings of the 7th IEA Conference of the Air Infiltration and Ventilation Centre, Stratford-upon-Avon, U.K. Report LBL-21862. Lawrence Berkeley National Laboratory, Berkeley, CA.

3.3.4 Impacts of House Size

In general, building form affects the ACH50 airtightness metric because of differing ratios of interior volume (i.e. the volume of an "air change") to enclosure area. To illustrate the effect, a simple analysis calculating ACH50 for different building forms using the same air leakage per unit area of building enclosure (i.e. the same normalized airflow rate or normalized air leakage rate, NLR) is shown in Figure 3.9 below. For the same air leakage per unit area of building enclosure, a three-storey building will have an ACH50 value that is approximately 40% less than a one-storey building of the same floor plate. **Because of this relationship between volume and enclosure area, larger buildings are generally expected to have significantly lower ACH50 values.**

Trends in new residential construction show that houses are getting bigger (see Figure 3.11). Hence, **the trend toward a larger house may inherently be leading to lower ACH50 numbers regardless of actual enclosure airtightness improvements**.

Simple rectangular and L shaped forms are also compared in Figure 3.9 to demonstrate the influence of form complexity. In general, more complex building forms result in greater enclosure area per volume. For the forms analyzed, the L-shaped form had a 25% greater ACH50. It is also acknowledged that, in practice, more complex building form also tends to result in more difficult air barrier installation, further contributing to a higher ACH50.

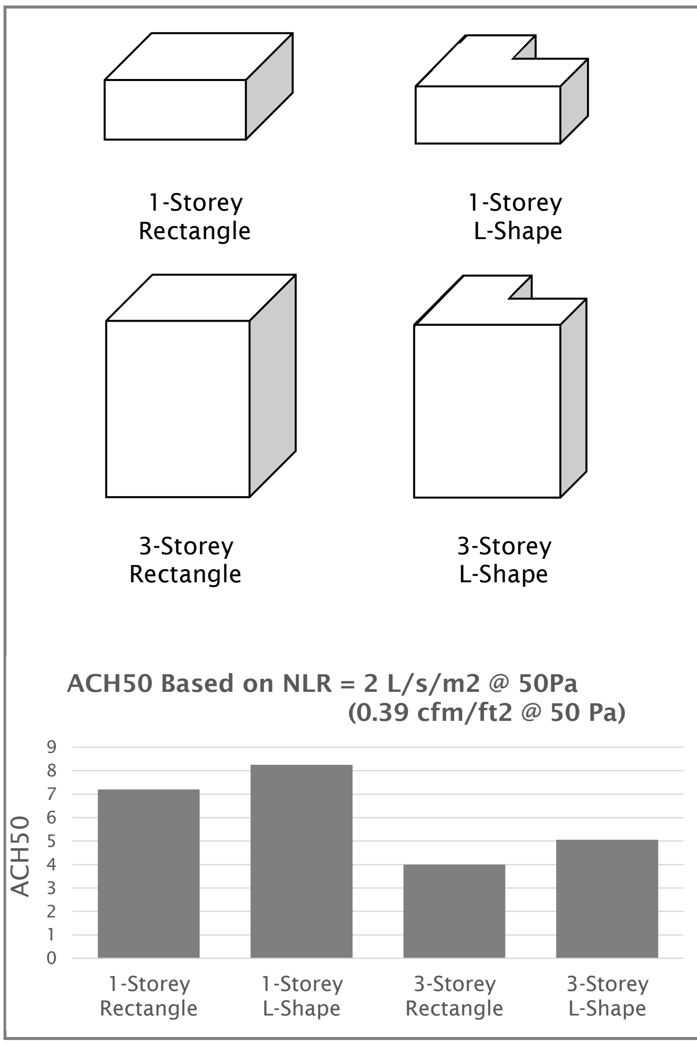


Figure 3.9 Analysis of Building Forms Effects on ACH

Four hypothetical house types based on one- and three-storey rectangle or L-shaped floor plans.

For the same normalized air leakage rate (NLR), houses with a larger volume-to-surface area ratio (i.e. larger buildings, simple floorplate) will have lower ACH50 compared to houses with a lower volume-to-surface area ratio (i.e. smaller buildings, more complex floor plate).

In Figure 3.10, the conditioned floor areas of the 49 ICF houses from the ICFMA dataset were plotted relative to airtightness showing that airtightness tends to be lower for larger houses. Linear regression analysis was applied to the data showing a **0.09 ACH50 improvement in airtightness values for every additional 100 m² (1000 ft²) of conditioned floor area**. The correlation is weak; thus, RDH recommends expanding the dataset to improve the analysis. The lower ACH50 may be due to form factor impacts and/or may be due to generally better construction quality and building components in larger houses.

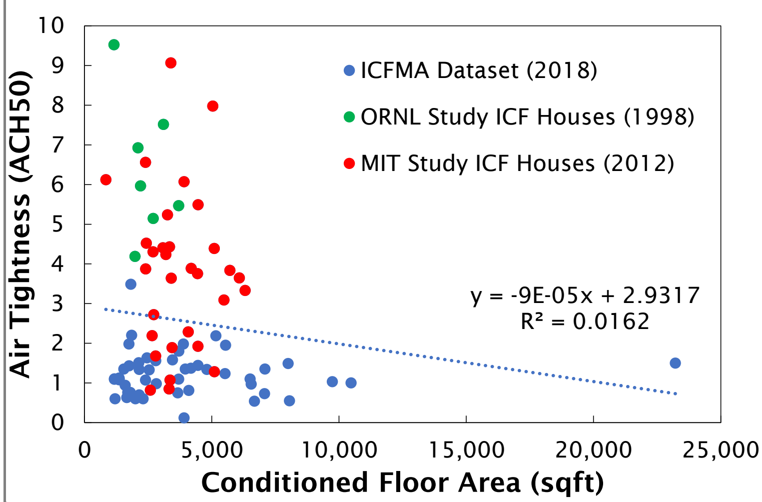


Figure 3.10 Airtightness vs Conditioned Floor Area for ICF Houses: ICFMA, ORNL & MIT Datasets

Method of least squares linear regression analysis was applied to the dataset (78 entries with reported floor area) resulting in a 0.09 ACH50 improvement in airtightness with every additional 1000 sqft of household floor area.

It is noted that the average house size in the ICFMA, MIT, and ORNL ICF datasets are larger than the average North American house. A plot of typical house size trends is shown in Figure 3.1 below, with the ICF datasets highlighted.

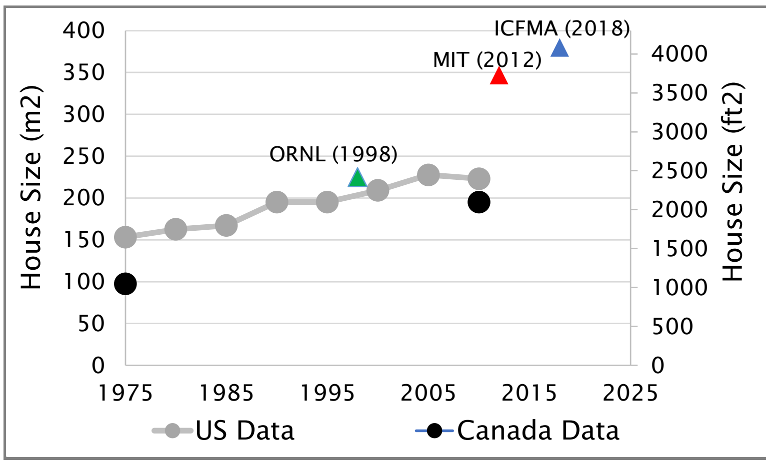


Figure 3.11 US and Canadian House Size Trends

Trends show new US and Canadian houses are getting larger over time (StatsCan and US Census data).

This is likely because the data included in the studies reflects a high proportion of custom houses which tend to be larger than average. As noted above, larger houses are likely to have lower ACH50 airtightness values due to form factor (i.e. higher surface area to volume ratios) and this should be considered when comparing the ACH50 of the ICFMA-MIT dataset of 80 ICF buildings to the average for typical wood frame houses.

4 Mid-Rise ICF Residential Airtightness Data

Mid-rise residential buildings are multi-unit residential buildings (apartments, dormitories, condominiums, etc.) between 4- and 6-storeys. ICF data to date is only available for one mid-rise residential ICF building and is the focus of this section. The datapoint is compared to values published for other mid-rise residential buildings. **We encourage ICFMA members to provide data on mid-rise residential building for the benefit of this study.**

4.1 Cedar Creek ICF Apartment

In 2005 Enermodal Engineering conducted blower door testing of the Cedar Creek Apartment building in Waterloo, Ontario. The building is a 7 storey ICF multi-unit residential building. The testing found that the building had a normalized air leakage rate of 1.25 L/s m^2 (0.25 cfm/ft^2) @75Pa. This building would meet air tightness requirement of the U.S. Army Corps of Engineers (2012) and is 37% better than the default ASHRAE 90.1 performance path modelling value of (2.3 L/s m^2 (0.40 cfm/ft^2) @75Pa.

The observed air leakage paths were around through-wall air conditioning units, sliding glass doors, window/door rough openings, sliding windows, range hood/bathroom fans, front vestibule pot lights, sprinkler risers in garbage room, the front office AC sleeve, a garbage room light switch, and garbage room penetrating duct work. **It was noted that the building was not complete during testing**: 20% of caulking had yet to be completed and door hardware installation and commissioning of condensers was in progress. Hence, it is likely the completed building's air leakage rate would have been further reduced.

4.2 Comparison to Typical Mid-Rise Residential Buildings

RDH has assembled a dataset of air leakage rates for buildings not classified as low-rise residential for a separate National Research Council of Canada study[19]. A sub-set of fifty-five (55) mid-rise residential buildings from the dataset were selected for comparison to similar ICF buildings. As illustrated in Figure 4.1, twenty-one (21) of the sample mid-rise residential buildings were military barracks and residences tested as part of the US Army Corp of Engineering new building performance standard. Others were part of the testing and reporting requirements in Washington State (2) and City of Seattle (12). The remaining twenty (20) were tested as parts of various studies.

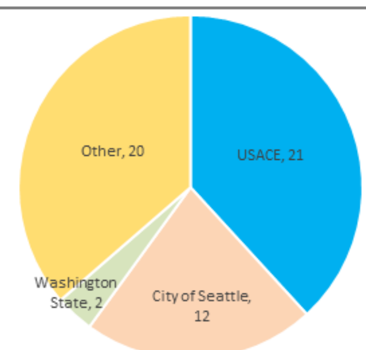


Figure 4.1 RDH Study Mid Rise Residential Airtightness Data Sources

[19] RDH Building Science Inc. (2015) *Study of Part 3 Building Airtightness* Report for National Research Council of Canada (available for download at https://rdh.com/wp-content/uploads/2016/06/Whole-Building-Airtightness-Testing-and-Results-Report.pdf)

The average airtightness of the 55 mid-rise residential buildings from the RDH dataset was 2.1 L/s m² (0.41 cfm/ft²) @75Pa. Most of these buildings were tested under the USACE with a performance compliance requirement of 1.27 L/s m² (0.25 cfm/ft²) @75Pa and 2012 City of Seattle and 2012 Washington State Energy Code testing benchmark of 2.3 L/s m² (0.40 cfm/ft²) @75Pa. The airtightness values for the 55 mid-rise residential buildings in this dataset are indicated in red in Figure 4.2 below. The mid-rise residential buildings appear to generally fit the Airtightness vs Year of Construction trend for the overall dataset.

Only one published data point was found in the literature for a mid-rise residential ICF building. The datapoint is plotted in Figure 4.2 (black star) and aligns with findings from low-rise residential data suggesting that ICF building have better-than-average airtightness.

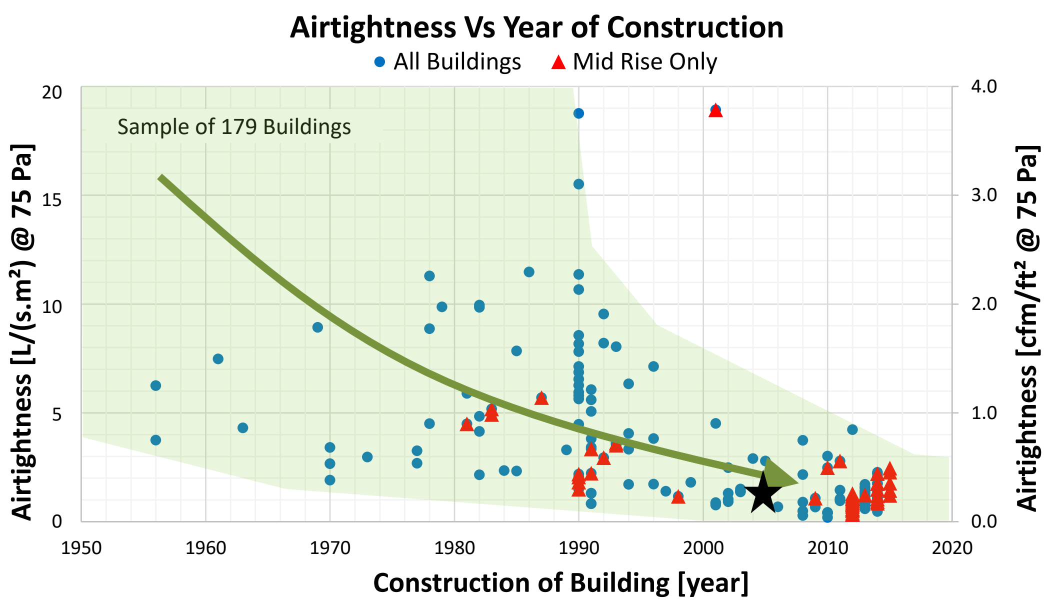


Figure 4.2 Airtightness vs Year of Construction w/ICF Data Point
Adapted from Jones et al. (2014) [20] *to show mid-rise MURBS, indicated in red; also includes new data from 2015 and Enermodal ICF building measurement shown as a black star.*

[20] Jones, D., Brown, B., & Thompson, T. (2014). Building Enclosure Airtightness Testing in Washington State-Lessons Learned about Air Barrier Systems and Large Building Testing Procedures. ASHRAE Transactions, 120.

5 Conclusions and Recommendations

5.1 Low-Rise ICF Housing Airtightness Insights

Based on analysis of published data, typical Canadian houses are on average better than 4 ACH50 and US houses better than 5 ACH50. In both markets, houses the airtightness of new houses appear to be getting more air tight over time.

A 1995 and 2012 study involving seven and thirty-one ICF house found an average airtightness of 6.39 and 3.82 ACH50, respectively. The ACH50 values for both studies were estimated based on reported effective leakage area measurements and assumed typical house dimensions. The average airtightness of 49 ICF houses collected from ICFMA for this study was found to be 1.26 ACH50. Combining all ICF data results in an average of 2.57 ACH50 and median of 1.56 ACH50.

→ The airtightness data of the ICF houses in the study showed much greater air tightness than typical wood framed houses.

There are several general insights on air tightness of houses which have been demonstrated in this study.

→ Houses in cold climates are expected to be more air tight than houses in hot climates,

→ Local construction quality and approaches as well as local energy efficiency programs appear to also significantly affect airtightness.

→ Attached houses are expected to have greater measured air leakage than detached houses due to air leakage between units (Canadian codes suggest a 0.5 ACH50 penalty).

  → Attached ICF houses using ICF for separating walls may have better measured airtightness because the reductions in suite-to-suite air leakage can be more easily achieved than for wood framed constructions.

→ There is a significant reduction in ACH50 expected for larger buildings due to form factor advantages within the calculation.

  → Linear regression analysis was applied to the data for ICF houses showing a 0.09 ACH50 improvement in airtightness values for every additional 1,000 sqft of conditioned floor area.

→ The potential for decay of air barrier systems in modern wood framed houses has not been well studied to date.

  → ICF walls are expected to have long-term airtightness performance benefits over loose-laid house wrap air barriers in that they are rigid, strong, durable, and continuous in the field of the wall. This is expected to limit wind induced billowing which may also affect in-service air leakage.

5.2 Mid-Rise ICF Housing Airtightness Insights

The airtightness of the one mid-rise residential ICF building with published results had good airtightness and the air leakage paths in the building were similar to those reported for other mid/high rise multi-unit residential building.

→ ICF walls are expected to have better and more reliable airtightness than walls systems using loose laid house wraps are air barriers. More data is needed to draw more specific insights.

There is a current movement by building codes across Canada and the US to require blower door testing to verify air tightness in new construction, making air tightness performance a key issue for compliance. The application of reliable air tightness performance, the listed general performance insights, and the thermal performance of ICF's relative to energy code compliance will be explored in the next phase of this study.

Appendix A
Study ICF Airtightness Dataset

LOCATION	ASHRAE CLIMATE ZONE	GFA	VOLUME	AIR TIGHTNESS	
		(ft^2)	(ft^3)	ACH_{50}	REPORTED
AZ	4	3,460	*34,600*	1.58	ACH_{50} = 1.58
AZ	4	1,855	*18,550*	2.20	ACH_{50} = 2.20
AZ	4	*8,000*	*80,000*	1.49	ACH_{50} = 1.49
AZ	4	3,889	*38,890*	1.98	ACH_{50} = 1.98
FL	2	*2,150*	*21,500*	0.70	ACH_{50} = 0.70
IL	5	6,506	61,852	1.10	ACH_{50} = 1.10
IL	4	*2,400*	*21,600*	1.07	ACH_{50} = 1.07
IR	N/A	*3,703*	32,242	1.10	ACH_{50} = 1.10
MI	5	4,456	40,528	1.44	ACH_{50} = 1.44
MI	5	4,809	47,780	1.34	ACH_{50} = 1.34
MI	5	5,521	52,452	1.23	ACH_{50} = 1.23
MI	5	1,819	17,172	*3.49*	Q_{50} = 998 cfm
MI	5	3,708	34,764	1.80	ACH_{50} = 1.80
MI	5	5,161	51,063	2.19	ACH_{50} = 2.19
NY	6	3,912	*39,120*	0.12	ACH_{50} = 0.12
NY	6	2,304	*23,040*	0.60	ACH_{50} = 0.60
NY	5	6,680	61,356	*0.54*	Q_{50} = 552 cfm
OH	5	6,552	64,267	0.97	ACH_{50} = 0.97
OH	5	5,542	49,270	*1.95*	Q_{50} = 1600 cfm
ON	6	4,096	39,936	0.81	ACH_{50} = 0.81
ON	6	2,134	21,861	1.51	ACH_{50} = 1.51
ON	6	1,748	18,327	1.98	ACH_{50} = 1.98
ON	6	1,545	25,905	1.35	ACH_{50} = 1.35
ON	6	2,150	40,851	1.34	ACH_{50} = 1.34
ON	6	2,456	40,797	1.63	ACH_{50} = 1.63
ON	6	1,750	29,737	1.43	ACH_{50} = 1.43
ON	6	*2,823*	25,404	1.33	ACH_{50} = 1.33
ON	6	*2,823*	25,404	0.98	ACH_{50} = 0.98
ON	6	*1,600*	*16,000*	0.94	ACH_{50} = 0.94
ON	6	*2,000*	*20,000*	0.60	ACH_{50} = 0.60
ON	6	*9,737*	87,633	1.03	ACH_{50} = 1.03
ON	6	*3,663*	32,964	0.75	ACH_{50} = 0.75
ON	6	*1,800*	*18,000*	0.76	ACH_{50} = 0.76
ON	6	*8,054*	72,489	0.55	ACH_{50} = 0.55
ON	6	*7,090*	63,808	1.35	ACH_{50} = 1.35
ON	6	*1,200*	*12,000*	0.60	ACH_{50} = 0.60
ON	6	*1,700*	*17,000*	0.76	ACH_{50} = 0.76
ON	6	*2,800*	*28,000*	1.56	ACH_{50} = 1.56
ON	6	*10,473*	94,255	1.00	ACH_{50} = 1.00
ON	5	*7,077*	63,690	0.73	ACH_{50} = 0.73
ON	5	*4,184*	37,656	1.37	ACH_{50} = 1.37
ON	5	*3,959*	35,633	1.35	ACH_{50} = 1.35
ON	5	*23,216*	208,946	1.50	ACH_{50} = 1.50
UK	N/A	*1,177*	10,594	*1.09*	Q_{50}/A = 0.92 $m^3/h/m^2$
UK	N/A	*1,362*	12,254	*1.12*	Q_{50}/A = 0.97 $m^3/h/m^2$
UK	N/A	*1,362*	12,254	*1.10*	Q_{50}/A = 0.95 $m^3/h/m^2$
UK	N/A	*1,362*	12,254	*1.08*	Q_{50}/A = 0.93 $m^3/h/m^2$
UK	N/A	*1,177*	10,594	*1.10*	Q_{50}/A = 0.93 $m^3/h/m^2$
UK	N/A	*1,660*	14,938	*0.63*	Q_{50}/A = 0.56 $m^3/h/m^2$

Estimated values are shown in italics