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Building Airtightness: Research and Practice[1]

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ABSTRACT

This report summarizes the state of the art on building air tightness by reviewing the current and recent literature on both research and practice. The focus of this report is on techniques to measure the tightness of the building envelope and on what has been learned by doing so. This report reviews over 100 of the most important publications relating to the topic. The report covered the fundamentals of air leakage including the hydrodynamics of leaks, which has led to all of the measurement techniques currently in use. The measurement techniques reviewed focus on the fan pressurization technique and its derivates, but the report covers novel techniques as well. Air tightness metrics allow data to be shared and compared and the basic air tightness metrics are reviewed and discussed as well as a brief discussion on norms and normalization. The bulk of the report discusses data which has been taken over the last twenty years and what it can tell us about buildings of different types, locations and properties.

KEYWORDS: Air leakage; airtightness; fan pressurization; leakage area

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INTRODUCTION

"Air Tightness" is the property of building envelopes most important to understanding ventilation. It is quantified in a variety of ways all of which typically go under the label of "air leakage". In this report we will review the state of the art of air tightness research. Before reviewing what is known about air tightness, we will summarize the key roles air tightness play in understanding ventilation.

Air tightness is important from a variety of perspectives, but most of them relate to the fact that air tightness is the fundamental building property that impacts infiltration. There are a variety of definitions of infiltration, but fundamentally infiltration is the movement of air through leaks, cracks, or other adventitious openings in the building envelope.

The modeling of infiltration (and thus ventilation) is a separate topic, but almost all infiltration models require a measure of air tightness as a starting point. While the magnitude of infiltration depends on the pressures across the building envelope, the air tightness does not, making air tightness a quantity worth knowing in its own right for such reasons as stock characterization, modeling assumptions or construction quality.

Infiltration, and therefore air tightness, is important because it impacts building energy use, and the transport of contaminants between indoor air and outdoor air (i.e. ventilation). From an energy standpoint alone it is almost always desirable to increase air tightness, but if infiltration is providing useful dilution of indoor contaminants, indoor air quality may suffer. In many countries infiltration is the dominant source of outdoor air. Providing appropriate IAQ at minimal energy costs is a complex optimization process that includes, but may not be dominated by air tightness concerns. A high degree of air tightness will provide insufficient air through infiltration and thus necessitates a designed ventilation system.

In buildings with designed ventilation systems, especially those with heat recovery, air tightness may be a determining factor in the performance of that system. For example unbalanced ventilations systems such as exhaust fans require that make-up air come through building leaks. Overly leaky or overly tight buildings could reduce the effectiveness of such systems.

When poor air tightness allows air to be drawn in from contaminated areas, indoor air quality can be reduced even though total ventilation may be increased. These contaminated areas could be attics, crawlspaces or even the outdoors. Sometimes the building envelope itself may be a source of contamination because of mold or toxic materials. .

Moisture is a special class of contaminant because it commonly exists in both liquid and vapor form and is a limiting factor in the growth of molds and fungus. Poor air tightness that allows damp air to come in contact with cool surfaces is quite likely to lead to the growth of microbiologicals. In cold climates poor air tightness can lead to the formation of ice in and on exterior envelope components.

Often the most noticeable impact of poor air tightness is draught and noise. Tight buildings provide increased comfort levels to the occupants, which in turn can have impacts on energy use and acceptability of the indoor environment.

MEASUREMENT FUNDAMENTALS

From a measurement standpoint, air tightness means measuring the flow through the building envelope as a function of the pressure across the building envelope. This relationship often fits a power law, which is the most common way of expressing the data. The power law relationship has the form

$$Q = C\Delta p^n$$

where C [m^3/sPa^n] is the flow coefficient and n is the pressure exponent. The pressure exponent is normally found to be in the vicinity of 0.65 but has the limiting values of 0.5 and 1 from simple physical considerations. Because of the non-linear nature of this expression there are some interesting challenges in understanding any measured data; these issues will be addressed in subsequent sections.

In her general study of air flow measurement, McWilliams (2002) reviews of the techniques for measuring air tightness. The vast majority of techniques fall into the category of "fan pressurization" in which a fan (or blower) is used to create a steady state pressure difference across the envelope. The flow through the fan is measured at a variety of pressures. The most common incarnation of fan pressurization technique for dwellings and small buildings is known as a blower door. Although other methods for measuring air tightness have been examined we shall concern ourselves with principally with fan pressurization techniques.

BLOWER DOOR BACKGROUND

"*Blower Door*" is the popular name for a device that is capable of pressurizing or depressurizing a building and measuring the resultant air flow and pressure. The name comes from the fact that in the common utilization of the technology there is a fan (i.e. blower) mounted in a door; the generic term is "Fan Pressurization". Blower-Door technology was first used in Sweden around 1977 as a window-mounted fan (as reported by Kronvall, 1980) and to test the tightness of building envelopes (Blomsterberg, 1977). That same technology was being pursued by Caffey (1979) in Texas (again as a window unit) and by Harrje, Blomsterberg and Persily (1979) at Princeton University (in the form of a Blower *Door*) to help find and fix the leaks.

During this period the diagnostic potentials of Blower Doors began to become apparent. Blower Doors helped Harrje, Dutt and Beya (1979) to uncover hidden *bypasses* that accounted for a much greater percentage of building leakage than did the presumed culprits of window, door, and electrical outlet leakage. The use of Blower Doors as part of retrofitting and weatherization became known as *House Doctoring* both by Harrje and Dutt (1981) and the east coast and Diamond et al. (1982) on the west coast. This in turn led Harrje (1981) to the creation of instrumented audits to computerized optimizations.

While it was well understood that Blower Doors could be used to measure air tightness, the use of Blower-Door data could not be generally used to estimate real-time air flows under natural conditions or to estimate the behavior of complex ventilation systems. When compared with tracer-gas measurements, early modeling work by Caffey (1979) was found wanting. There was a rule of thumb, which Sherman (1988) attributes to Kronvall and Persily that seemed to relate Blower-Door data to seasonal air change data in spite of its simplicity. Modeling of infiltration, however, is discussed elsewhere.

THE HYDRODYNAMICS OF LEAKS

Before discussing measurement techniques in any more detail, it is important to understand the physical properties of the thing we are measuring, namely the leaks themselves.

Although the power-law has been found to be a reasonably good empirical description of the flow vs. pressure relationship, it does not simply correspond to any physical paradigm. There are physical paradigms that could be (and have been) applied to the problem of air tightness:

- If the leak is very short, frictional forces in the leak itself can be ignored and the leak may be treated as a orifice in which the flow is proportional to the square root of the pressure drop. The higher the flow rate (i.e. Reynolds number) the longer the leak can be and still be treated as an orifice.

- If the flow rate (Reynolds number) is low enough, the flow will be dominated by laminar frictional losses and the flow will be linearly proportional to the pressure drop.

Comparing to the power-law, the first case corresponds to an exponent of 0.5 while the second case corresponds to an exponent of 1. The fact that measured data typically results in an intermediate value indicates that neither of these two limits is a good explanation.

The Reynolds number of a typical leak is below that at which fully developed turbulent flow is an issue, but the length of many such leaks is such that laminar friction is neither negligible nor dominant. The problem becomes one of developing laminar flow in short pipes.

Sherman (1992) used the standard techniques for developing laminar flow to characterize the problem of short circular pipes. In such a development the pressure drop is the sum of that associated with the acceleration of the fluid and friction losses of the form:

$$\Delta P = \frac{128\mu l}{\pi d^4} Q + \frac{8\rho m}{\pi^2 d^4} Q^2$$

This expression can be used to derive a quadratic relationship for flow as a function of pressure, but the more interesting result is that it can be manipulated into a power-law formulation:

$$Q \propto S^n$$

Where S is a dimensionless pressure:

$$S = \frac{m\rho d^4}{4096\mu^2 l^2}\Delta P$$

Where the exponent can be determined from S (or vice-versa):

$$n = \frac{1}{2}\left(1 + \left(1 + 8S\right)^{-1/2}\right)$$

If the leak were a single circular pipe, this derivation could, in principle, be used to determine the diameter and length of the leak, but real envelopes are much more complicated. Walker, Wilson and Sherman (1997) expanded this derivation to look at more general crack geometries and the issue of series and parallel leaks.

The analysis assumes a smooth pipe. As shown by Kula and Sharples (1994) among others, roughness can have a substantial impact and must be considered if the parameters of this model are to be interpreted physically. The form of the model would only need be changed if the roughness induced a transition to fully-developed turbulence in the leaks that dominate the flow, but that has not been reported for real buildings.

The benefit of this analysis is not so much in providing an ability to infer the geometry of leaks, but to confirm that a power-law formulation is a robust description on which to base data analyses. It also tells us that the exponent is pressure dependent. This dependency is low, so that over a narrow range of pressures the exponent can be assumed to be fixed. If the pressure ranges over order of magnitude, however, one cannot assume it is a constant.

FAN PRESSURIZATION MEASUREMENT TECHNIQUES

The fan pressurization technique has been around a long time and there are many standard test methods that describe its use, such as ASTM (1999, 2002), CAN/CGSB (1986) and ISO (1996). The basic technique involves measuring the steady-state flow through the fan necessary to maintain a steady pressure across the building envelope.

The first level reporting of this data is generally the same. One reports the pressure and volumetric flow at whatever measurement stations were chosen. If necessary, the raw readings from the equipment may need to be corrected for zero offsets, temperature, altitude etc. Such corrections are standard experimental practice, but will depend on the details of the apparatus and experimental layout.

What separates the different test methods and protocols derived from them is the analyses of that pressure-flow data. The simplest protocol and the one that is used most often is simply to measure at a single pressure. The pressure chosen is conventionally 50 Pa; so much of the published data quotes air flow at 50 Pa.

As a metric air flow at 50 Pa has much to recommend it. 50 Pa is high enough to overpower pressure noise and zero drifts caused by wind or stack effects. Thus it is reasonably precise and therefore reproducible. The simplicity of a single-point measurement and its reproducibility are why it is the most popular measurement.

Unfortunately, the flow at 50 Pa is not the quantity of interest if one is trying to understand what envelope air flows are under natural driving pressures. The average pressure across a leak in a building envelope is closer to 1 Pa than to 50 Pa. To have an accurate estimate of air tightness is it necessary to determine it at normal pressures. Furthermore, higher pressures can induce non-linear effects such as valving that would not be relevant for normal pressures.

Depending on the metric chosen such reference pressures would be in the 1-4 Pa range, but because these pressures are the size of the natural pressure variations, it is very difficult to get a precise measurement of air flow. One must sacrifice precision to get accuracy or must sacrifice accuracy to get precision.

In order to mitigate these errors, many test methods require that the flow be measured over a range of pressures and then extrapolated to the reference pressure of interest using the power law. Because of the non-linearities of the power-law and the biases that can be associated with pressure measurements, care must be taken not to introduce unnecessary errors into the data analysis. Modera and Wilson (1990) looked at the impact that wind pressure variations have on the analysis of pressurization data and methods to mitigate them using pressure averaging.

Sherman and Palmiter (1995) have examined the errors associated with analyzing fan pressurization data including precision, bias and modelization errors. They examine the overall uncertainty for a variety of analysis strategies and recommend optimal strategies for selecting instrumentation and pressure stations.

MULTIZONE PRESSURIZATION TECHNIQUES

The discussion above has focused on single-zone pressurization techniques. Although such tests are vast majority of tests, in many circumstances the actual configuration is not single-zone. Some of this is due to a true multizone nature, but some of this can be due to the fact that there is no true air barrier between the "inside" and the "outside".

Attached housing has leakage paths both to outside and to other dwelling units. Even detached housing can have multizone properties when buffer spaces partially connect to the living area and partially connect to outside. For detached housing the experimental problem can often be solved by making a determination of what constitutes the air barrier and then opening up doors and windows that are not part of the air barrier; thus reducing the configuration to a single zone.

For apartments and other attached dwelling units, it is sometimes desirable to separately know the leakage to the outside and the leakage to other adjacent units. Although not used widely there are measurement approaches for determining these. Most methods such as that used by Levin (1991) in Sweden require access to adjacent units and often multiple blower doors. Some researchers, e.g., Shaw (1980), have used a single blower-door and auxiliary pressure measurements to infer component leakage.

DUCT LEAKAGE MEASUREMENTS

Duct leakage measurement techniques are a spin-off from envelope air tightness techniques. There are significant differences because of the fact that ducts operate under externally applied pressure differences. When the air handling system is not operational, duct leakage looks quite similar to envelope leakage and may represent a quarter of the total envelope leakage.

The topic of air distribution leakage is too broad to be reviewed herein. Francisco (2001) had reviewed five measurement techniques that have been under evaluation, but the field is active and there have been developments since then. Carrie et al (1997) have looked at some duct leakage issues an European context. A new standard test method in the U.S. (ASTM 2004) makes use of the novel DeltaQ method for determining leakage.

AIR TIGHTNESS METRICS

Etheridge (1977) has been a proponent of the quadratic representation of flow, but most researchers use the power law. In both cases, however, the representation is a two-parameter model, with a recognition that these parameters may vary when the range of applied pressure becomes large. Since Sherman (1992) showed that these representations can be interchanged, we will only discuss the common, power-law representation.

Although there is general agreement that the power law is a good descriptor of air tightness data, there is no real agreement on the best metrics to use in quoting air tightness data. The best way to quote air tightness data will depend on what you plan to use it for. Issues such as how many parameters to be used in quoting air tightness data and whether or not air tightness data should be normalized by the size of the building are important when deciding upon the optimal metric.

THE EXPONENT: THE SECOND METRIC

Whenever a two-parameter description of the air tightness is used, the second parameter is always the power-law exponent, n. The exponent is critical for extrapolating measurements from one pressure regime to another. When the actual measurements are made in the pressure regime for which the data is desired—as often happens for 50 Pa metrics—extrapolation is not necessary and high accuracy determination of the exponent is unnecessary. For such cases it is often sufficient to use the average exponent found from large datasets, which has been found by Orme et al. (1994) to be approximately 0.65.

The exponent is also interesting from a research and/or diagnostic perspective because it provides an indication of the relative size of the dominant leaks. If the leakage paths are dominated by large, short leaks (e.g. orifices) one would expect the exponent to be closer to

0.5; if the leakage is dominated by long-path leaks one would expect the exponent to be closer to 1.

When making measurements before and after some retrofit or other sealing operation, it is especially important to consider changes in the exponent. The exponent can be different before and after such an operation. If an extrapolation is done without taking this into account, the change in air tightness can significantly mis-estimated. Usually it is easier to seal the large leaks, which tends to imply that a post-sealing measurement will tend to have a higher exponent.

THE MAIN AIR LEAKAGE METRIC

Whether found by extrapolation, interpolation or direct measurement, the principle metric used to quantify air tightness is the air flow through the envelope at a specific reference pressure. The most common reference pressures are 50 Pa and 4 Pa, but 1 Pa, 10 Pa, 25 Pa, and 75 Pa are used as well. The air flow is often denoted with the reference pressure as a sub-script (e.g. Q_{50} or Q_{25}).

75 Pa was once suggested as a reference pressure because other envelope components are sometimes tested at this pressure (e.g. windows (Henry and Patenaude (1998)). In practice this pressure is too high to use both because some components may change under that much pressure and because the pressurization equipment is often too small to achieve that pressure directly. The air flow required to reach this pressure may itself be a problem because of the flow required or in severe climates.

50 Pa, by contrast, is the most common pressure to measure the air flow. This has been the traditional value since blower door techniques became popular. It is low enough for standard blower doors to achieve in most houses and high enough to be reasonably independent of weather influences. When single-point measurements are made, it is almost always at 50 Pa.

25 Pa, is a standard reference pressure for measuring duct leakage (Cummings et al., 1996). It is sometimes used as an envelope reference pressure for that reason. It is also sometimes used as an alternate single-point pressure station when the equipment cannot reach 50 Pa.

10 Pa is used as the reference pressure in the Canadian definition of equivalent leakage area, but not normally directly as a flow rate.

4 Pa is similarly used as the reference pressure in the ASTM (E779-99) definition of Effective Leakage Area (ELA) and in the ASHRAE Standards that reference it. ELA can be defined as the area (of unity discharge coefficient that would have the same flow rate at the specified reference pressure:

$$Q = ELA \cdot \sqrt{\frac{2P_r}{\rho}}$$

where 4 Pa is chosen as the reference pressure as being representative of weather-induced pressure

1 Pa is the lowest of the reference pressures used in the literature. At a pressure of unity the power-law coefficient is equal to the flow rate. This form appears to make this metric be independent of the power-law exponent, but because of the non-linearities and cross-correlations associated with the measurement process, this is an illusion based on the system of units used. Furthermore, extrapolation of the measured data, which is normally collected at much higher pressures, is more uncertain than for any other reference pressure.

Flow rate at a specified pressure and leakage area at a specified pressure contain the same information, just in different forms. Flow rate formulations are easier for those doing the measurements because it relates more directly to their equipment. Leakage area formulations are sometimes more intuitive for the occupant or owner because they can imagine an amount of holes in their structure of a certain size.

NORMS AND NORMALIZATION

The metrics above all refer to the total amount of leakage of the tested envelope. For setting norms or standards, or for comparing one structure to another it is often desirable to normalize this total by something that scales with the size of building. In that way buildings of different sizes can be evaluated to the same norm.

There are three quantities commonly used to normalize the air leakage: building volume, envelope area, and floor area. Each has advantages and disadvantages and each is useful for evaluating different issues:

Building volume is particularly useful when normalizing air flows. When building volume is used to normalize such data the result is normally expressed in air changes per hour at the reference pressure; ACH_{50} is probably the most common air tightness metric reported. Many people find this metric convenient since infiltration and ventilation rates are often quoted in air changes per hour.

Envelope area is particularly useful if one is looking to define the quality of the envelope as a uniform “fabric”. Dividing (especially a leakage area) by the envelope area makes the normalized quantity a kind of porosity. Although this normalization can sometimes be the hardest to use, it can be particularly useful in attached buildings were some walls are exposed to the outdoors and some are not.

Floor area can often be the easiest to determine from a practical standpoint. Because usable living space scales most closely to floor area, this normalization is sometimes viewed as being more equitable. This normalization is used most often with ELA measurements and can be converted to a different kind of dimensionless leakage, such as the normalized leakage used by ASHRAE (2001).

AIR TIGHTNESS DATA

Air tightness data can be expensive to collect. The larger and more complex the building, the more difficult and time-consuming it is to collect the data. Furthermore, air tightness in large buildings was not thought to be as important a consideration as for dwellings. Thus, the majority of existing data is for dwellings and more specifically for single-family homes. We shall review those first and then move on to the other kinds of data.

SINGLE-FAMILY HOUSES

AIVC NUMERICAL DATABASE

A report by Orme et al. (1994) describes the AIVC air tightness numerical database. Over 2,000 measurements on single and multi-family dwellings are summarized. These data were collected from ten countries as listed in Table 1. Mean air flow rates at 50 Pa are shown by country in the report but it should be emphasized that they only act as guidelines because air tightness can vary a lot from building to building.

Expected values for air tightness have been developed for number of generic forms of construction, namely: timber frame and block-and-brick for low-rises, concrete/curtain wall for high-rises, concrete panel and metal panel for industrial buildings. For each of these construction types, the effects to air tightness from a number of building characteristics are tabulated. For example, the ‘basic leakage’ for a low-rise building with a timber frame is suggested to be 3 ACH_{50}. If no vapor barrier is present, the dwelling is expected to be leakier and the air leakage value should be increased by 3 ACH_{50}. On the other hand, if the dwelling has gasket window/door frames, then 1 ACH_{50} should be subtracted from the default value.

Apart from these generic air leakage guidelines, Orme et al. (1994) also summarized 1,758 flow exponent measurements from Canada, Netherlands, New Zealand, the UK and the US. The distribution of flow exponent is roughly normal with a mean value of approximately 0.66. The authors did not observe meaningful relationship between ACH_{50} and the corresponding flow exponent.

Factors that affect air tightness include age of construction, building type (single-family versus multi-family dwellings), severe climate, and construction materials. Many of the findings are confirmed by recent studies, which are discussed in more detail below.

WHOLE BUILDING MEASUREMENTS

Air tightness measurements of single-family dwellings are by far the most abundant among the different building types. Many studies measured air tightness as a starting point and then make use of the findings to address problems such as ventilation, energy cost, and indoor air quality. There are also some focuses in research on air tightness of energy-efficient dwellings and techniques to achieve higher level of air tightness.

Air tightness is known to vary greatly among dwellings. This is not only true in countries where the climate is relatively mild, such as that in the US (Sherman and Dickerhoff, 1998) and the UK (Stephen, 1998), wide variation has also been observed in more severe zones, such as in Canada (Parent et al., 1996) and Sweden (Kronvall and Boman, 1993). A ten-fold difference between the leakiest and tightest dwellings has been observed in those studies where the size of sample is relatively large. The same variation in air tightness is evident even among new dwellings according to studies in Canada (Hamlin and Gusdorf, 1997), Belgium (Wouters et al., 1997), and the US (Sherman and Matson, 2001).

ERROR ANALYSIS OF PRESSURIZATION DATA

It is almost impossible to do a good job of analyzing measurement data without an understanding of the uncertainties that go along with the measurements. Standard texts describe considerations of precision and accuracy as well as error propagation and robustness; such information will not be repeated here. Sherman and Palmiter (1995) have used these techniques to develop specific expressions for fan pressurization and to optimize the measurement process.

Few of the references in this section, however, report rigorous uncertainty analyses. In fact, some of the relatively early publications have included incorrect error analyses because they failed to properly account for the fact that the non-linear nature of the power law, makes parameter errors highly correlated. When this error happens during an extrapolation it greatly increases the apparent error (e.g. in the ELA).

Most of the reported data is based on single-point measurements and assumed exponents. Using extant exponent data as a prior in a Bayesian analysis, it is possible in principle to estimate the extrapolation bias caused by the assumed exponents, but this kind of analysis is very rare.

In looking at large datasets, one hopes that the central limit theorem will apply and that all of the biases and other uncertainties will be reflected in the standard deviations of the data themselves.

Table 1 List of data sources and sample sizes in AIVC database and more recent studies.

Country	**AIVC Database**		**Recent Studies**	
	Sources	**Size**	**Sources**	**Measurements**
Canada	CMHC	475	Gusdorf (2003) Hamlin (1997) Buchan (1996) Parent (1996), Proskiw (1998) Buchan (1992), Fugler (1994) Scanada (2001) Elmahdy (2003), Proskiw (1995) Fugler (1999) Petrone Architects (2000) Air-Ins Inc. (1998, 1998b)	37,490 mostly S-F[2] 2,263 S-F Dwellings (incl. 63 R-2000 Houses) 11 Log Houses 47 S-F Dwellings Basements & Crawlspaces Attached Garages Windows Attics Air Barriers Building Materials & Joints
US	LBNL	435	Sherman (2001) Desjarlais (1998), Yuill (1998) Kosny (1998), Petrie (2003) Brennan (1990) Louis (1995) Wilcox (2001)	70,000 S-F Dwellings Exterior envelopes ICF Systems Crawlspaces Windows Air Barriers
UK	BRE	385	Stephen (1998) Lowe (1997) McGrath (1996)	96 S-F Dwellings 15 2–Storey Dwellings Basements
Sweden	SIB	144	Sikander (1998)	3 S-F Dwellings
France	CETE de Lyon	66	Litvak (2000)	37 S-F Dwellings
Belgium	BBRI	57	Bossaer (1998) Pittomvils (1996)	200 S-F Dwellings & Apartment Units 6 Low-Energy Houses
Germany			Zeller (1993)	48 S-F Dwellings & Apartment Units
Netherlands	TNO	303		
New Zealand	BRANZ	83		
Norway	NBI	40		
Switzerland	NEFF, EMPA, Schweizer Ingenieur und Architekt	37		

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[2] S-F denotes single-family dwellings

TRENDS BY BUILDING CHARACTERISTICS

Among the largest database to date on air tightness of single-family dwellings is the LBNL Residential Diagnostics Database which has over 73,000 measurements from across the US. Data collection is an ongoing effort by the Energy Performance of Buildings Group at LBNL. A recent report by Chan et al. (2003) summarizes the measurements in terms of year of construction, size of dwelling, presence of heating ducts, and floor/basement construction type. The database also contains measurements from two special groups of houses, namely energy efficiency programs and weatherization program for low income families.

Among the building characteristics mentioned, year of construction and size of dwellings are found to be the most influential factors related to air leakage. The distribution of normalized leakage is roughly lognormal. Regression analyses show that the geometric mean of normalized leakage can be predicted by year of construction and size of dwelling.

Using regression analysis, additional variables were tested to see if the inclusion of them improves prediction. Neither the location of dwelling, the presence of heating ducts, and the floor/basement construction type was found to be significant. The result is a simple model that can predict the air leakage distribution for a housing stock in the US using only distributions of year of construction and size of dwellings as inputs.

Many studies have observed similar trend by comparing the air leakage of dwellings built from different periods of time. Analysis based on over 2,000 houses showed consistent increase in air tightness across all regions of Canada (Hamlin and Gusdorf, 1997). Kronvall and Boman (1993) concluded similarly from an analysis of 50 single-family houses in Sweden. The authors observed over 2 folds reduction in the mean ACH_{50} of houses built before 1940 and those that were built in 1976-88.

In countries where the maximum allowable air leakage for new dwellings is written into building codes, e.g., Sweden, the reason for air tightness improvement over time is obvious. However, in milder-climate countries where there is no air tightness standard or code on new dwellings, newer dwellings are not necessarily more air tight than older ones. Stephen (1998) analyzed the air tightness measurements of 471 UK dwellings carried out by BRE and found no apparent systemic differences. On the other hand, voluntarily changes in construction practices in the US have resulted in tighter buildings. Analysis on earlier version of the LBNL Residential Diagnostics Database by Sherman and Dickerhoff (1998) showed a clear decrease in air leakage from the oldest constructions to those that were built around 1980. After that, air leakage is fairly constant with year built.

Age of dwelling is a measure of deterioration from wear-and-tear which can induce air leakage. This is different from using year of construction as the measure which captures the possible influence from change of building practices on air tightness. Recent constructions, however, appear to be fairly resistant to age-induced leakages. A study by Bossaer et al. (1998) showed that among the 51 Belgian dwellings built between 1990 and 1995, there is no meaningful relationship between duration of occupancy and air tightness. Similarly, Proskiw

(1995b) measured the air tightness of 24 houses over periods of up to three years and observed no significant degradation.

Influence of building geometry on air tightness has been studied by Bassett (1985) from measurements on 80 single-family houses in New Zealand. The author showed that envelope area normalized air flow rate at 50 Pa increases as the geometry of the envelope gets more complex. Envelope complexity is defined as the joint length between wall, floor, and ceiling, divided by the envelope area. Chan et al. (2003) also observed that floor area normalized leakage is a function of dwelling size. While it is speculated that larger dwellings tend to have better constructions and therefore tighter building envelopes, the explanation can also be that larger dwellings have more favorable surface area to volume ratios and/or less envelope complexity.

Dwellings in severe climate such as Sweden, Norway, and Canada are known to be more air tight than those that are located in milder climate such as the US and the UK. The main reasons for tighter construction are to conserve energy cost and maintain thermal comfort. Within Canada, Hamlin and Gusdorf (1997) observed consistent regional difference in air leakage of houses built from different period of time. For a qualitative sense of how air tightness of dwellings from different countries compares, Orme et al. (1994) showed up to two to three-fold differences in mean ACH_{50} among the ten countries listed in the AIVC numeric database. The data used to compute those mean values included both single-family and multi-family dwellings and are not adjusted for other influential factors, such as year of construction. The findings nonetheless support the general notion that dwellings in more severe climate are more air tight.

ENERGY-EFFICIENCY DWELLINGS

Few energy-efficiency programs in the US have specific air leakage performance requirement. As a result, it is not clear whether the air tightness of energy-efficiency program houses is guarantee, even though common practices of these programs, such as caulking and weather-stripping, are known to help reduce air leakage. Persily (1986) measured the air tightness of 74 passive solar homes located throughout the US and found little difference in air tightness when compared to other dwellings in the country. At that time the data on conventional houses being compared to were quite limited and cannot be considered as representative of the US. It is nonetheless a surprising finding as noted by the author because the passive solar homes were designed to consume relatively low levels of energy for space conditioning, and were therefore expected to be more air tight.

More recently, Sherman and Matson (2001) compared the air leakage of new energy-efficient houses against other new conventional houses. They found that energy-efficient houses are tighter built in general, but the key benefit is that these programs promote consistency in construction practice. This is demonstrated by less variation in the air tightness of houses built under energy-efficiency programs compared to the others. In

Canada, Hamlin and Gusdorf (1997) found that energy efficient R-2000[3] houses are at least twice as airtight as new conventional houses in most regions of the country. However, the gap between the two is narrowing as builders and house buyers are now generally more aware of the problems associated with excessive air leakage.

There are also examples where consistency in construction practice is not realized by the energy-efficiency program. In another air tightness comparison between 47 energy-efficient residential buildings in New York State and 50 nearby conventional houses as controls, the two groups have similar standard deviations (Matson et al., 1994).

The air tightness of low energy houses is particular important when the dwellings are equipped with heat recovery ventilation system in order to achieve energy-efficiency. Pittomvils et al. (1996) studied the air tightness of 6 low energy houses in Belgium for this reason and found that the values ranged from 3.8 to 4.9 ACH_{50}. Despite that these values are half of those from conventional Belgian dwellings (Bossaer et al., 1998), air leakage at these levels still compromise the fractional reduction in ventilation related building load. In Germany, Zeller and Werner (1993) measured the air tightness of 48 dwellings where some of them are designed to be low energy. About 40% of the dwellings tested have ACH_{50} greater than 3 at which the ventilation system cannot be run energy efficiently.

KEY LEAKAGE PATHWAYS

The types of leakage problems have much to do with the construction of the dwellings. In a project that studied the effectiveness of various retrofitting strategies, Lowe et al. (1997) found that one of the most important factors is the method used to construct the walls. Load-bearing masonry walls with timber-framed are common forms of construction in the UK. If plasterboard-on-dabs is used, all the leakage paths in the house will become interconnected which makes air sealing difficult. Lowe et al. (1994) found, however, that when wet plastered masonry wall can potentially be several orders of magnitude more air tight.

On the other hand, timber-framed walls are more popular in northern Europe and North America. A study by Stephen (1998) on the BRE database found that timber framed structures are on average tighter than masonry ones. However, after adjusting for age of dwellings, this difference appears to be smaller. This is because most timber framed houses in UK were recent constructions.

In a research project which goal was to give guidance in choosing appropriate materials for air barrier system, Air-Ins Inc. (1998) tested 36 common building materials for air leakage using laboratory test chamber experimental setup. Only half of the samples are found to be in compliance with the Canada National Building Code limit of 0.02 $l/s{\cdot}m^2$ at 75

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[3] R-2000 is a program offered by Natural Resources Canada's Office of Energy Efficiency, which encourages and certifies the building of energy efficient houses according certain criteria.

Pa. The testing found much non-homogeneity within individual sample and from one sample to another for some of the materials.

The use of polyethylene air barrier is a common practice to reduce air leakage at walls. A recent study by Wilcox and Weston (2001) measured the air tightness of four pairs of new California homes built with and without spun-bonded polyolefin housewrap. The authors found that houses with housewrap are on average 13% tighter than their counterparts. It is expected that the impact of a housewrap air barrier would be significantly greater if the air barrier were installed as part of a continuous pressure envelope instead of as an external finish done in the study. Yuill and Yuill (1998) also found the technique of using housewrap over untapped extruded polystyrene foam sheathing has the highest flow resistance among the different materials studied. However, a longevity study by Air-Ins Inc. (1998b) showed that spun bounded olefin paper can fail to stretch around joints under high temperature and break away.

There are alternatives to the use of plastic film as air barrier in timber frame buildings without sacrificing air tightness. Sikander and Olsson-Jonsson (1998) tested diffusion-permitting polymer-based fiber sheets (sometimes known as 'windproof' sheets) and gypsum board panels on three detached houses and a test structure in laboratory. Measurements showed that it is possible to meet the Sweden Building Regulations provided if the technical designs and quality of contractor work are of high standard. Likewise, Proskiw (1998) concluded that both polyethylene air barrier and airtight drywall approach can meet requirement of the Canadian R-2000 Standard based on measurements on 17 dwellings taken over a period of eleven years. However, a study by Air-Ins Inc. (1998) found some types of perforated polyethylene are permeable to air. After a test period of five months at some pressure and temperature differentials, improvement in air tightness was noted due to dust which blocked the holes.

A longevity study on the behavior of various air barrier connection techniques submitted to pressure and temperature differentials showed that silicone base sealant and adhesive tape are the most durable (Air-Ins Inc., 1998b). On the other hand, open cell gaskets, mineral wool, and perforated polyethylene should not be used due to their high permeability. Spun bonded olefin and acrylic sealant can exhibit problems at high temperatures. There are now recommendations on specific assembly instructions for rigid air barrier published by the Canada Mortgage and Housing Corporation (Petrone Architects, 2000).

Recent laboratory studies by Kosny et al. (1998) on insulated concrete form (ICF) system suggested that dwellings of this sort can be more air tight than wood frame constructions Petrie et al. (2003) tested two identical houses located side-by-side with the only difference being one had ICF as the exterior walls and the other had conventional wood-framed exterior walls. Air leakage measurements showed that the ICF house was 6% to 23% less leaky than the wood-framed one, depending on the components sealed and climate condition during the test.

A few studies in Canada and the US have shown that log houses can also be quite air tight (Buchan et al., 1996). Lateral joints were often found not to be the major leakage source. Instead, smoke pencil tests suggested that significant leakage occurred at the corners, the transitions between log walls and other building components, around doors and windows, and other wall penetrations.

Apart from leakage through wall, other important components contributing to air leakage include windows and doors, flue and fireplace, heating ducts, and the connections to attic, basement, crawl space, and garage. Effective leakage areas of many of these building components, including walls, are tabulated in chapter 26 of the 2001 ASHRAE Fundamentals Handbook. About half of the data have been updated by Colliver et al. (1994) from the 1989 version. The authors found that the best estimate values remain unchanged with few exceptions, though the ranges of values recorded are in general much wider as the number of data sources increased.

Window air leakage appears to be most studied and some suggested that reductions have been successful. In Canada, a study by Henry and Patenaude (1998) tested 35 windows for their air leakage at cold temperatures. They found that the majority of windows met or exceeded the highest levels of air leakage performance of Canadian window standards at normal temperatures, and many did very well even at the lowest temperatures tested. There have also been many studies on the impaction of window air leakage on other problems such as heat transfer (Haile et al., 1998) and condensation (Elmahdy, 2003). Desjarlais et al. (1998) found that the air leakage of windows can be further reduced by 60% to 80% when an additional storm window is added.

Despite so, current window testing standards do not include air leakage from the joint between window and wall assemblies or from the sides of the windows. Louis and Nelson (1995) presented a test methodology for quantifying this portion of air leakage. Measurements from a few case studies show that the extraneous air leakage from window perimeters is often higher than the air leakage through the window unit. Proskiw (1995) showed that conventional rough-opening sealing method (i.e., packed fiber glass) can contribute up to 14% of the total leakage of a single-family detached dwelling. This source of air leakage can be reduced greatly by using alternative sealing method, such as casing tape, poly-return, poly-wrap, and foamed-in-place urethane.

Dumont (1993) reports detailed measurements of air tightness revealing significant leakage at many of the components interfaces in building. By visualization with smoke and by reductive sealing method, Pittomvils et al. (1996) found that the connections between wall and roof and at the top of the roof are common sources of leaks among the six low-energy houses studied in Belgium. A solution to this problem has been addressed in a summary report by Adalberth (1997) which provides some guidelines to practitioners on how to achieve good air tightness. The document not only includes drawings and specifications, but also suggests suitable materials and a quality assurance system for meeting the goal.

Research on attic-related heat and moisture flows has been underway for over a decade in Canada. Among the first effort was quantifying the attic interface leakage areas by method of subtraction (i.e., house ELA including the attic interface minus house ELA with attic equally depressurized). The attic interface leakage areas were found to be fairly uniform with an average ELA_{10} of $330cm^2$ among the 20 houses tested. Only tightly built R-2000 houses had an interface leakage area of $20cm^2$. Wouters et al. (1997) also found insulated attics to be a significant source of air leakage (1/3 of the total) in new Belgian dwellings.

Significant interface leakage at crawl space has also been observed. Brennan et al. (1990) compared the ELA of the crawl space of nine dwellings against the rest of the building envelopes and found that even with passive vents closed, crawl spaces are much leakier. Among the 10 houses measured in British Columbia, Fugler and Moffatt (1994) found that the interface leakage between crawl space and the rest of the house is more pronounced with the presence of forced-air systems, instead of radiant heating. Air leakage from basement can also bring moisture and soil contaminants into the living space. McGrath and McManus (1996) used tracer gas techniques to measure the air flow through the basement ceiling to the room above in two homes in UK. By visual inspection, the reason for leakiness was the cracks between the floor-boards and between the floor and wall.

Houses built slab-on-grade or have fully conditioned basement are known to have much less floor leakage. Sherman and Dickerhoff (1998) and Stephen (1998) observed that this group of houses are 6% and 27% more air tight respectively than those that were built with crawl space or have unconditioned basement. In the interest of reducing radon exposure, sub-slab polyethylene air barriers have shown to be very effective in making concrete basement floors airtight (Yuill et al., 2000). After proper installation, the effective leakage area of the slab dropped to undetectable level. Buchan et al. (1992) measured the air leakage of 13 heated basements and 1 crawl space with which preserved wood foundations were used. Test results show that the foundations were in general tightly constructed and that most of the air leakage occurred around the windows and headers in the basement.

Air leakage between garages and the houses have found to be significant among the 25 Canadian dwellings tested (Scanada Consultants Limited, 2001). The technique used to measure the interface leakage area is similar to that described above for attic measurements – the difference between depressurization of the house with the garage door opened and with the garage simultaneously depressurized. The average ELA_{10} is found to be $140cm^2$, which is about 13% of the total air leakage. This is roughly proportional to the ratio of interface area to house envelope area, meaning the house/garage interface is built with the same tightness as the rest of the house envelope.

Studies by Bossaer et al. (1998) and Pittomvils et al. (1996) on Belgian dwellings also revealed similar observations. Bossaer et al. (1998) determined the room-by-room air flow rates at 50 Pa by means of compensating flow meter. The average garage interface air leakage among 26 dwellings tested accounts to about 1/3 of the total leakage. Pittomvils et al. (1996) also found that the interface between garages and the houses to be quite leaky even among the six low-energy houses tested.

IMPLICATIONS OF AIR TIGHTNESS MEASUREMENTS

Studies on the relationship between air tightness, ventilation, and energy use have revealed the interdependency of these factors. For example, Yoshino and Zhao (1996) made recommendations on the optimum air tightness for dwellings in using various ventilation systems different climatic regions of Japan. Sherman and Matson (1997) estimated the energy liability associated with providing the current levels of ventilation in US dwellings, and found substantial energy saving by tightening building envelopes while maintaining adequate ventilation. Zmeureanu (2000) on the other hand, found that by considering the life-cycle energy consumption, the initial cost of renovation, and the carbon dioxide tax credits, increase in air tightness of existing houses is not always cost-effective in the Montreal (Canada) area.

Whole building air tightness measurements provide useful information about the energy demand of dwellings. However, the correlation between the measured air tightness of houses and indoor air quality is less clear. Parent et al. (1996) found that the carbon dioxide levels measured in 30 single-family dwellings in Canada during heating season have little to do with their respective air tightness. Bossaer et al. (1998) found the air tightness of rooms can vary greatly in a given house, which can be part of the reason why whole building air tightness is a poor predictor for indoor air quality.

MULTI-FAMILY DWELLINGS

The problem of air leakage in multi-family dwellings is more complex due to the partition wall between units and the sheer size of the building envelope. Furthermore, there are additional leakage pathways to be considered, e.g. adjacent units, stairwell doors, garage chutes, elevator shafts, etc. If fan pressurization method is used, multiple blower doors and/or very large scale equipments will be needed. Not only is the test procedure more time and labor intensive, it also requires more cooperation from residents for accessing multiple units simultaneously. Some of the studies discussed below used tracer gas method to measure inter-zonal air flow. Even though the measurements themselves are not direct measure of air tightness of the units tested, some of the findings provide insights about the relative importance of various leakage pathways in the building.

Relative to the amount of data on single-family dwellings, there are fewer measurements on the air leakage of multi-family dwellings. Table 2 shows some of the major studies available from various countries. While the list is not all inclusive of past measurements, it captures most of the recent studies on air leakage of various types of multi-family dwellings.

LOWER-RISE BUILDING MEASUREMENTS

Measurements of air leakage of multi-family dwellings can be divided into whole building envelope measurements, zonal measurements (floor-by-floor or unit-by-unit), and component leakage measurements. Most data are available on unit-by-unit bases. Levin (1991) summarized the air leakage of 53 units measured under the Stockholm Project, of which many of them are quite air tight (0.45 to 0.9 ACH_{50}). The air tightness of a number of apartment units in this study was measured under the condition that the adjacent units were also pressurized. Using this method, the internal air leakage between apartment units were found to account for 12% to 33% of the total air leakage at 50 Pa. Similar relative leakage to internal walls has been reported by Lagus and King (1986), Reardon et al. (1987), and Love (1990) in Canada, and Cornish (1989) in the UK, of which the test dwellings were all row house type.

Table 2 List of recent studies on air leakage of multi-family dwellings

Country	**Sources**	**Buildings**	**# Units**
Sweden	Blomsterberg et al. (1995)	3 Buildings	6
	Levin (1991)	7 Buildings	53
	Boman & Lyberg (1986)	3–Story Buildings	150
	Lundin (1981)	2 Terraced Houses	2
Canada	Nichols & Gerbasi (1997)	10 Mid-Size Buildings	-
	Gulay et al. (1993)	10 High-Rises	12
	Shaw et al. (1991)	1 5–Story Buildings	10
	Love (1990)	9 Row Houses	42
	Shaw et al. (1990)	2 High-Rises	2
	Shaw (1980)	5 High-Rises	-
	Reardon et al. (1987)	2 Row Houses	3
US	Lagus & King (1986)	4 Row Houses	24
	Palmiter et al. (1995)[4]	3–Story Buildings	6
	Flanders (1995)	3 Quadra-plexs	7
	Dietz et al. (1985)[4]	2 Quadra-plexs	8
	Zuercher & Feustel (1983)	1 High Rise	-
France	Barles & Boulanger (2000)	3 Buildings	35
	Litvak et al. (2000)	Multi-Family Dwellings	26
Russia	Armstrong et al. (1996)	12 Buildings	50
Lithuania	Juodis (2000)	High-Rises	33
Japan	Murakami & Yoshino (1983)	7 Buildings	16
UK	Cornish et al. (1989)	Large Panel System Dwellings	9
Finland	Kovanen & Sateri (1997)	3 Buildings	8

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[4] The study used tracer gas method to measure infiltration and not air tightness directly.

Borman and Lyberg (1986) analyzed 150 units from some 3-story buildings and found that they were similar to single-family dwellings in air tightness. But such is not always the case. Later studies by Blomsterberg et al. (1995) and Kronvall and Boman (1993) also carried out in Sweden suggested that multi-family dwellings have lower ACH_{50} than single-family ones. The authors attributed this to the fact that multi-family dwellings have higher volume to surface area ratio, and therefore lower ACH_{50} values. Litvak et al. (2000) and Murakami and Yoshino (1983) also observed that multi-family building units to be more air tight than single-family ones in France and Japan respectively. Despite so, the air tightness of many multi-family dwellings still does not meet the building code and standard in many countries. In Canada for example, the air tightness of 10 typical mid-size buildings tested were found to be well below the requirements of the National Building Code 1995 (Nichols and Gerbasi, 1997).

By using a multi-tracer measurement system, Palmiter et al. (1995) found significant flow from the ground floor units directly into the top floor units in some 3-storey buildings due to stack effect. The average flow measured in common walls with plumbing and electrical utilities running from the ground floor to the top was larger than most of the horizontal interzonal flows. The building tested was of standard wood frame construction, with slab-on-grade foundation. An earlier study by Cornish (1989) in UK and Dietz et al. (1985) in US also found similar stack induced leakage between units.

Reardon et al. (1987) found that units on the upper level were much leakier than those below. The reason for this is because the structure was built with a concrete lower level and wood frame upper level. Furthermore, the lower units have one less air leakage pathway – the roof top. Vertical distribution of leakage is a concern because according to a modeling parametric study by Sateri et al. (1995), this is the most important factor affecting infiltration.

Recent studies in countries where measurements on multi-family dwellings were not previously available, such as in France (Barles and Boulanger, 2000) and Lithuania (Juodis, 2000), found that there is large variation in air tightness of units in a same building. At the most extremes, 10-fold difference has been observed.

Flanders (1995) compared the air leakage of some multi-family units measured using four fan pressurization protocols based on standards by the International Standards Organization (ISO 9972), American Society for Testing and Materials (ASTM E779), and Canadian General Standard Board (CAN/CGSB-149.10). The author concluded that the three standards gave similar flow coefficient and exponent values when the weather condition was clam, but uncertainty increases as the outdoor became windier. He recommended that the door of the adjacent units should be left opened, instead of closed, when carrying out blower test if the units cannot be pressurized simultaneously.

HIGH-RISE BUILDING MEASUREMENTS

Most of the studies mentioned above are low-rise multi-family dwellings. Air leakage of high-rise buildings has been measured in relatively large-scale study in Canada (Gulay et al., 1993) and in Russia (Armstrong et al., 1996). Recent measurements by Barles and Boulanger

(2000) in France and Juodis (2000) in Lithuania also included some high-rise residential buildings. The Canadian study included measurements on whole building leakage, floor-by-floor leakage, unit leakage, and component leakage. Findings confirmed that the air leakage rates for the high-rise residential buildings far exceeded NRCC's proposed guidelines of 0.05 to 0.15 $l/s \cdot m^2$ at 75 Pa.

Whole building air leakage test requires access to every unit and room located around the perimeter of the building. This method requires the most cooperation from tenants and owners. It also requires access to large-scale fan pressurization equipments. Parekh (1992) measured two buildings before and after air sealing of the building envelope and observed 32% and 38% reduction in air leakage. The author also suggested some guidelines for qualitative assessment of the air leakage characteristics of the building envelope by components: windows, external doors, building envelope, elevator shafts and services shafts, and miscellaneous including exhaust fan dampers and ducts, etc. In the summary report, Gulay et al. (1993) tabulated the percent distribution of the whole building leakage by component estimated based on those guidelines: 42% windows, 26% doors, 14% vertical shafts, and 6% building envelopes.

Shaw et al. (1991, 1990, and 1980) used similar method to measure the whole building air tightness of four high-rise apartment buildings. They found the pressure difference across the envelope to be decreasing with building height due to large flow resistance in the stairwell. The air flow corresponding to a height-averaged pressure difference of 50 Pa ranged from 1.8 $l/s \cdot m^2$ to 3.6 $l/s \cdot m^2$. The value reported by Gulay et al. (1993) which was measured before air sealing work lied somewhere in between at 2.15 $l/s \cdot m^2$.

Armstrong et al. (1996) measured the air leakage of 50 apartments located in 12 buildings and found correlation between ELA_4 and the apartment volume. This correlation was particularly profound when the blower door tests were carried out with major leakage pathways sealed, such as the windows, the balcony door, and the kitchen and bathroom exhaust grilles. Windows and patio doors were found to contribute less than 1/3 of the total ELA under "vents-sealed" condition. These results were, unfortunately, compromised by variation in the incremental sealing techniques and non-uniform outside pressure on the envelope of the tested apartment.

Leakage characteristics of stairwells have been studied by Zuercher and Feustel (1983) on a nine-storey student dormitory. Flow coefficients and exponents were reported from the pressurization and depressurization tests carried out under various doors/emergency doors operation conditions. Tracer gas measurements were also carried out to study the influence of wind and stack effect upon air infiltration.

Smoke control is another common concern in high-rise buildings. Tamura and Shaw (1981) measured the pressure differences and flow velocities in various parts of two high-rise buildings. Results demonstrated that the performance of the smoke shaft in venting the fire floor can be seriously impaired by the extraneous leakage flow into the smoke shaft through the shaft wall construction from other floors. Related studies regarding the ventilation and infiltration characteristics of lift shafts and stairwells have recently been summarized by Limb (1998).

KEY LEAKAGE PATHWAYS

Shaw (1980) used an airtight test chamber to measure the leakage through windows, walls, balcony doors, and various joints. Most of the air leakage values vary widely from building to building, and even within the same unit. Of all the windows tested, only 1/3 of them passed the ASHRAE 90-75 Standard. A larger fraction (2/3) of balcony doors meets the Standard. The major air leakage sources in exterior walls are found to be floor-wall joints, windows, and window sills.

Kovanen and Sateri (1997) measured the component leakage of two multi-family dwellings using direct (pressure chamber) and indirect (reductive sealing) method. The main leakage route is found, again, to be the balcony door. Three out of eight apartment units became less air tight after renovation that was carried out without special attention on envelope sealing, even though the air tightness of the windows and apartment doors improved in every apartment. The most problematic component appeared to be the balcony wall.

Measurements of the equivalent leakage areas of ten suite-access doors in some mid to high rise apartment buildings in Canada was taken to understand their ventilation characteristics (Wray, 2000). The leakages were found to be highly variable and did not meet smoke control requirements, which is probably because the airflow entering the suites from the corridor is often used as the primary ventilation air supply.

Murakami and Yoshino (1983) tested the component leakage of a few apartment units and rooms and found there are many background leakages other than widows, doors, ventilation inlet, and pipe openings. For example, in a bedroom tested, the leakage through ceiling, ceiling/wall, and floor/wall joints together accounted for 3/5 of the total leakage. Installed windows were often found to have air tightness far inferior to the performance expected.

Exterior wall air tightness values were found to be approximately nine times greater than those of the floor/ceiling separations in a 5-storey apartment building tested (Shaw, 1991). Leakage to left and right partition was somewhere in between the two extremes. Good agreement between the summations of individual leakage component and the measured overall leakage for a unit is observed.

TRENDS BY BUILDING CHARACTERISTICS

Juodis (2000) and Hill (2001) did not find year built to be a determining factor for the air tightness of multi-family residential buildings. The study by Kronvall and Boman (1993), however, found the opposite. This difference can perhaps be explained by the fact that the later study was on Swedish dwellings where building codes have more stringent specifications on air tightness over the years. Boman and Lyberg (1986) found that if older buildings have been retrofitted or weatherstripped, the age effect may become less significant.

Boman and Lyberg (1986) also found that the presence of a fireplace tends to correlate with higher air leakage in both single-family and multi-family dwellings. For dwellings that were built between 1940 and 1960, those with fireplace have an averaged normalized leakage area nearly twice of those without fireplace. Blomsterberg et al. (1995) found that apartments with passive stack ventilation are much tighter than the ones with exhaust ventilation.

Shaw (1991) observed that the overall air tightness values of four buildings with different wall constructions are not very different from each other. This is because the air tightness value of a wall assembly is mostly dependent on how well the vapor barrier/interior component is installed. Lundin (1981) found significant air leakage induced by air/vapor barrier that breaks at the walls that separate apartment units. As a result, apartment separating walls should be connected to the inside of the exterior wall to ensure a continuous air/vapor barrier enclosing the entire wooden frame.

NON-RESIDENTIAL BUILDINGS

A recent analysis on existing air tightness data of 139 commercial and institutional buildings by Persily (1999) found that non-residential buildings are often not air tight enough. About half of the data analyzed were part of a study conducted by Cummings et al. (1996) on small, predominately one-story commercial buildings. The rest include office, industrial and retail buildings, as well as schools, from Canada, Sweden, the UK, and the US. No correlation between air tightness and building age or wall construction was observed. Part of the reason was that there were simply not enough data for trends to be identified. There were some indications, however, that taller buildings tends to have more air tight envelopes. This might be a result of more careful design and construction necessary to deal with more demanding structural requirements, such as increased wind loads and the control of rain penetration.

Few other measurements have been made available and they are listed in Table 3 together with those included in Persily's analysis. Even with the new additions, air tightness measurements of non-residential buildings remain scarce and they do not adequately represent the existing building stock. A recent literature review by Proskiw and Phillips (2001) summarized most of the same data as Persily's, but with few additions of measurements made in Canada. The bulk of their report focused on test methods and specifications for large buildings.

Table 3 List of studies on the air tightness of non-residential buildings

Country	Source	Buildings
Canada	NRCC	8 Office Buildings
		11 Schools
		9 Supermarkets
		1 Shopping Mall
		1 Indoor Swimming Pool
	University of Saskatchewan	1 Swine Building
US	NIST	8 Office Buildings
	Florida Solar Energy Center	69 Small Commercial Buildings
	Pennsylvania State University	1 Office Building
		1 Library Wing
UK	BSRIA	12 Office Buildings
		12 Industrial Buildings
	BRE	10 Office Buildings
		6 Industrial Buildings
	Wales School of Architecture	3 Industrial Buildings
Sweden	NTRI	9 Industrial Buildings
France	CETE de Lyon	2 Office Buildings
		4 Schools
		4 Hotels
		2 Polyvalent Halls
	CSTB	4 Industrial Buildings
Belgium	WTCE/CSTC	45 Schools
Japan	KICT	3 Office Buildings

One of the earliest efforts was by Tamura and Shaw (1976) who tested eight new office buildings in the Ottawa area. More recently, Shaw and Reardon (1995) went back to six of these buildings which are still in use to determine the changes in their air tightness. Comparisons indicated that as a result of various retrofit measures applied, all but two building envelope became more air tight than 20 years ago. The improvement in the overall air tightness value at 50 Pa ranges from 25% to 43% of its original value. The two exceptions were one that received no retrofit measure, which deteriorated by 23% with time. The other exception had all joints in the curtain wall recaulked in 1990, and the building showed no change in air tightness which suggested that the retrofit measure was just sufficient to offset the effect of aging. This study demonstrated significant improvements can be realized in the overall air tightness by retrofit measures.

The experimental setups used by Tamura and Shaw (1976) and Shaw and Reardon (1995) were identical, which involves pressurizing the test building using the building's supply air system and measuring the corresponding pressure differences across the building envelope. In the US, Persily and Grot, (1986) tested the air tightness of seven federal buildings in a similar manner. The difference between the two test methods lay in the way the air flow through the air-handler system was measured. While the former used a pair of total pressure averaging tubes together with a static pressure probe to measure air flow, the later used constant-injection tracer gas technique.

Persily and Grot (1986) also found that the federal buildings tested were comparable in air tightness to the Canadian buildings. However, the authors commented that it was probably more appropriate to normalize the air flow by wall area only, instead of including roof area because the roofs were constructed to be impervious to air. Normalizing the leakage rate with the wall area only would lead to higher values as a result.

In countries like the UK where most buildings are naturally ventilated, alternative approach is needed. Measurements by BRE (Perera et al., 1990 and 1992) and BSRIA (Potter et al., 1995) were obtained by attaching an external large-scale fan to the building. While the low-energy office building tested by BRE had air tightness average of those tested in North America, most conventional office buildings were found to be leakier by a few-folds. Litvak et al. (2001) found that only two out of the twelve buildings sampled are in compliance with the French RT2000 regulation. Most of the large commercial buildings tested had air tightness in the range of that those tested in North America.

Hayakawa and Togari (1990) developed a simple test method that utilizes buoyancy caused by the stack effect instead of using fans to pressurize test building. While the stack effect is active, test building can be pressurized or depressurized by opening doors and windows on the bottom floor or top floors. Under calm weather conditions, the authors measured the equivalent effective leakage area for three high-rise office buildings. This method had been found to be effective given if no large unknown cracks are present and the friction resistance of the air flow in the building is small.

The study by Florida Solar Energy Center tested 69 small commercial buildings and found that a large fraction of them were leakier than the residential homes in the area (Cummings et al., 1996). Strip mall units were found to be 2.5 times leakier than detached buildings. The reason for this is that the attached units were often well connected to each other above the ceiling level.

Study by Shaw and Jones (1979) measured the air tightness of eleven Canadian schools and found lower values than those of office buildings (Tamura and Shaw, 1976). The results indicated that there was no meaningful relation between total energy consumption and the measured air leakage rate. Instead, poor workmanship and sealing were observed to be the cause of high air leakage. The air tightness of 45 Belgian schools tested by Wouters et al. (1988) revealed a much wider range of values, even among the newly constructed schools.

The air tightness of industrial buildings has been tested by a few researchers using similar large scale fan pressurization method. The buildings tested by Lundin (1986) in Sweden were found to be a few folds tighter than those in the UK (Potter and Jones (1992), Perera and Parkins (1992), Jones and Powell (1994)) and France (Fleury et al., 1998). A wider range in air tightness values were also observed in the UK and France compare to those in Sweden.

Restaurants tend to have large exhaust but without enough make-up air which often causes them to have unique uncontrolled airflow problems. Cummings et al. (1996) found that most of the seven restaurants tested have the air barrier and the thermal barrier at different planes, resulting in air-transported heat transfer problems. Another special type of building tested was livestock buildings. Zhang and Barber (1995) tested the air leakage of a new swine building and found it to be quite tight compared with office buildings also tested in Canada (Shaw and Reardon, 1995).

Bahnfleth et al. (1999) attempted to measure the envelope air leakage of one floor of a university library by floor-by-floor blower door method. However, the authors found that it was impossible to adequately sealing a single floor to isolate it from its neighbors. Proskiw and Parekh (2001) proposed a new air tightness procedure to separate the exterior envelope air leakage from interior partition air leakage in a multi-zone building. The preliminary test result at an indoor swimming pool which was attached to a recreational complex showed this procedure seems to offer advantages over those of the pressure-masking technique.

To answer the need of assessing the installation of air barrier during construction period, Knight et al. (1995) developed test equipment that is capable to handle all materials and design configurations involved. The end product is called a Pressure Activated Chamber Test System which used soap solution to visualize the leaks present. The authors tested the equipment at three swimming pools, two health care facilities, and a seven-storey building and found the test procedure to be effective in identifying leaks.

In light of the fact that many of the air leakage problems are caused by poor designs and workmanship, practical guidelines for designers, contractors, and developers have been made available by various agencies. For example, CMHC recommended certain jointing materials, primary air barriers, and prefabricated assemblies that are effective in controlling air leakage in high-rise commercial buildings (Canam Building Envelope Specialists Inc., 1999). NIST published a document on envelope design guidelines for federal office buildings to ensure thermal integrity and air tightness (Persily, 1993). Aside from its guidelines (Perera et al., 1994), BRE also developed a tool for predicting the air tightness of office buildings envelopes either at the design stage or before a major refurbishment (Perera et al., 1997). Comparison with ten office buildings in the BRE database showed good agreement between measurements and predictions.

TRENDS BY BUILDING CHARACTERISTICS

Unlike residential buildings where multiple studies have suggested that new dwellings are built tighter, Potter et al. (1995) concluded otherwise from comparison of office buildings built before and after 1990. Similarly, Cummings et al. (1996) found that the small commercial buildings tested did not demonstrate a clear age trend. Shaw (1981) noticed that newly constructed supermarkets were found to be generally much leakier than the older ones, which could be explained by the opening around the receiving doors with hydraulic ramp.

No significant trend has been observed between air leakage and construction materials of commercial buildings. However, building type can be an important factor because of the differences in typical architecture according to their functions. For example, when compare against hotels and schools, office buildings and polyvalent halls appear to be leakier because of the presence of suspended ceilings (Litvak et al., 2001). The air leakages of the supermarkets and mall tested by Shaw (1981) were also found to be higher and more spread out than schools and high-rise office buildings measured in Canada.

Ideally air-conditioned buildings should have minimal air infiltration and naturally ventilated buildings should have air infiltration under occupant control. By comparing among the twelve buildings tested for air tightness, Potter et al. (1995) found that the four naturally ventilated buildings tend to be tighter than the reminding eight which have air-conditioning. This discloses construction practices and defects often have larger influence on air tightness than building design.

KEY LEAKAGE PATHWAYS

Air leakage at suspended ceilings where electrical, lighting, and ventilation equipments are housed has found to be significant among many of the 12 non-residential buildings tested in France (Litvak et al., 2001). Study by the Florida Solar Energy Center (Cummings et al., 1996) also found similarly among smaller commercial buildings. Perhaps more surprising is that some studies from the UK have shown even the roof tops of large buildings are not guaranteed to be impervious to air infiltration (Perera and Parkins, 1992, Potter et al., 1995). This is somewhat counterintuitive because most would assume rain penetration problems would have prevented any buildings from having a leaky roof top.

Cracks along the top edge of most operable windows were also found to be an important source at a building tested, which was known to have air leakage induced problems (Perera and Parkins, 1992). When compared to the ASHRAE window leakage standard of 0.77 l/s/m, Persily and Grot (1986) also found that many of the windows tested in the federal buildings exceeded that standard. However, it should be noted that the window leakage standard exclude leakage through the window frame, which the test procedure included besides leakage through sash.

In relative terms, Potter et al. (1995) found exposed cavities to be more problematic than windows. This means that electrical and service penetrations through the structure into the cavity are in need of careful sealant. Cummings et al. (1996) found this problem is particularly disastrous among small commercial buildings where cavities are commonly used as ducts or plenums

Duct leakage among commercial buildings is profound even after accounting for the fact that they have greater surface area than those in residential buildings (Cummings et al., 1996). The duct systems tested were about 70 times leakier than the SMACNA standard

(Sheet Metal and Air Conditioning Contractors National Association). Depending where the ducts are located, the impact on energy consumption can vary. However, excessive air leakage among non-residential buildings is quite common. Among the eleven schools tested, Shaw and Jones (1979) found that 15 to 43% of the overall air leakage can be attributed to the air intake and exhaust openings. The leakage through roof ventilators among leaky UK industrial buildings was found to be a bit less significant at 9% (Jones and Powell, 1994).

Despite that the test results on loading doors among UK industrial buildings were satisfactory, Potter and Jones (1992) noticed a wide variation in the quality of the roller shutter doors among the 12 industrial buildings tested. As improvements in the air tightness of other parts of the building progress, this leakage component should not be neglected. Recent work by Yuill et al. (2000b) estimated flow coefficients of automatic doors as function of door type and rate of use.

Another common air leakage pathway is the elevator shafts as they are normally vented to atmosphere (Potter et al., 1995). It is therefore essential for elevator doors to be fitted with adequate seals. In an effort to insolate one floor from the others, Bahnfleth et al. (1999) found numerous holes and cracks that could not be reached and sealed in return risers and elevator shafts. Among other leakage components such as the stairway, a literature search by Edwards (1999) concluded that the data on air leakage associated with elevator shafts are very limited. Data on many other important leakage pathways, such as underground parking garage access door and garage chutes, are even nonexistent. Nonetheless the author has summarized some component leakage data needed to model mid- and high-rise apartment buildings.

DYNAMIC AIR FLOW

Before concluding this state-of-the-art review it would be remiss not to mention some of the more innovative techniques for measuring air tightness, even if they have not generated a lot of data. The discussion so far and the vast majority of published air tightness work is on steady-state flow. The closest most cracks and leaks actually get to steady-state are during fan pressurization tests. In this section we will review the issues associated with non-steady flow through relating to air tightness.

When considering time-varying air flows, there are two regimes, which we shall call pseudo-steady state and unsteady. The difference comes about because the change in air flow (or driving pressure) is either long or short compared to the characteristic time of the problem at hand. The characteristic may be the time it takes sound to cross the leak or cross the building, or it may be the time it takes a boundary layer (or jet) to form or flow the fluid to be accelerated to steady state.

In pseudo-steady state flow, the driving pressures are changing slowly enough that the individual leaks are presumed to be instantaneously in equilibrium. Because the air leakage is inherently non-linear, pseudo-steady state can generate complex phenomena despite the assumption of equilibrium.

Siren (1997) has shown that turbulence can cause a 5% bias in the power law flows using pseudo-state state assumptions due to non-linearities. Whether a 5% bias from turbulence is acceptable will be depend on the intended use of the data. Measurements by Sharples and Thompson (1996) confirm that there is no large difference due to these non-linearities, but does not contain an error analysis sufficient to separate out a 5% bias from a null result.

AC PRESSURIZATION

Siren (1997) and Sharples and Thompson (1996) refer to the well-known phenomena that occur when the flow actually begins to reverse (i.e. fluctuate). The issue of how to treat fluctuating air flows from the perspective of ventilation is beyond our scope here, but the physical principles of fluctuating pressures led to the development of dynamic air tightness measurement technique knows as AC Pressurization.

Sherman and Modera (1986) describe the physics of AC Pressurization. The system operates by putting a sinusoidal volume change (of order 1 Hz) on the inside of the building and measuring the pressure response. At this frequency, the flow pseudo-steady with respect to flow through cracks, but is fast enough to allow compression in the building and thus phase shifts from which information can be extracted. The approach breaks down when any individual opening gets sufficiently large that it can be considered unsteady. This typically can happen for open windows or undampered chimneys, but not for more normal building leaks.

PULSE PRESSURIZATION

AC Pressurization has no "DC" component and uses repeated sinusoidal variations, but Sherman and Modera (1988) have also devised a dynamic air tightness measurement approach that has a single perturbation. Pulse Pressurization works by providing a pressure pulse to the inside of a building (e.g. from a compressed air tank) and then watching the pressure decay. The power-law equation predicts a finite recovery time for such a decay and can be used to analyze the data to determine leakage and volume.

Like AC Pressurization the limitation of this procedure is when unsteady flow develops. The problem for pulse pressurization comes not from large external openings, but from the need for the pressure to be the same throughout the volume of the space. This tends to limit the application to small homes or apartments, unless multiple injectors are used.

In a pair of papers, Dewsbury (1996, 1996a) has examined some additional analysis approaches involving low frequencies, Fourier analysis and non-linear optimization strategies. The lower the frequency the less susceptible the analysis is to effects of inertia and flexing of the envelope. Since low frequencies imply low pressure, signal-to-noise ratios can become an issue.

Because of its relative complexity compared to fan pressurization, AC Pressurization has not seen wide-spread use. It has, however, been used in some special circumstances when fan pressurization was undesirable.

SUMMARY

The physics of air leakage through building components is non-linear. The non-linearity of the process can lead to some challenging measurement and interpretation problems. The fundamental form of the air leakage equations are not a priori clear, but there is general agreement that a power-law formulation is theoretically justifiable and empirically valid.

There is less consensus on how to report air leakage data and several metrics are commonly in use. The difference of opinion comes in part from the fact that different quantities are useful for different purposes. Assuming a power-law description, all two-parameter (unnormalized) formalizations are interchangeable. Single parameter forms provide less accuracy, but can be useful for specific purposes.

Regardless of the parameterization chosen air leakage data shows a huge scatter even within ostensibly homogeneous populations. It is not atypical to see log-normal distributions with the standard deviation being equal to the mean. The large variation can be attributable to variations in workmanship, variations in structure use and maintenance and variations in renovation and repair activities.

Despite the variance there are some very general and not overly surprising trends that can be teased from the data. The air leakage characteristics of single-family dwellings are better understood than multi-family dwellings or non-residential buildings because more measurements are available. Dwellings in more severe climate, like those in Sweden and Canada, have shown to be more air tight than those in the US and the UK, where the climate is milder. In countries where there is a demand for tighter envelopes driven by building codes or energy savings, new constructions has been shown to more air tight than older ones. Dwellings of different construction types have different envelope air tightness properties, but some air leakage pathways are common among many dwellings, such as the connections between building materials and components. Leakage to attics, basements, crawl spaces, and garages is significant and raises addition energy and health concerns. Many studies have addressed the effectiveness of air barriers and building materials to minimize leakage, but it is often the quality of workmanship and careful design that are the determining factors in achieving desirable air tightness.

When compared to single-family dwellings, individual units in multi-family dwellings tend to be more air tight. However, this does not mean that multi-family buildings are sufficiently air tight, particularly for the high-rise buildings. Despite that the air leakage to the exteriors still dominates, studies have also revealed significant air leakage between units in multi-family dwellings. Stack induced vertical air flow between units and in elevator shafts and stairwells are among some of the concerns. Partly limited by the number of measurements available, few trends have been observed between building characteristics and air tightness. The task of identifying air leakage trends is further complicated by large variations in air tightness found between units in a same building. Many of the findings observed among single-family dwellings also apply to multi-family dwellings, such as: dwellings with fireplaces tend to be leakier, and the integrity of the air barrier system is crucial to ensure air tightness of the unit.

Office buildings, industrial buildings, schools, and retail stores are among the few non-residential building types of which air tightness measurements are available. As measurements in these buildings often required large scale equipment, a few alternative methods have been proposed such that measurements can be made more easily and less costly. However, the applications of these methods remain research-grade. In fact, the most recent measurements were collected using large-scale fan pressurization almost exclusively. It is evident that commercial buildings are rarely air tight enough. There is a slight geographical difference in the air tightness of buildings in Sweden (most tight), the UK (most leaky), and the North America (somewhere in between). On the other hand, air tightness is unrelated to age or construction materials. Suspended ceilings, exposed cavities, and ventilation ducts are among the key leakage pathways. Due to the architectural differences of different building types, some tend to be leakier than the others. But until more data have been collected, these trends remain scattered observations that cannot be generalize to various commercial building type. To provide more immediate help to designers and contractors, various organizations have recently published practical guidelines to effectively control air leakage in commercial buildings.

NOMENCLATURE

A	Area [m^2]
C_d	Discharge coefficient [-]
C	Power-law coefficient [$m^3/s\text{-}Pa^n$]
d	Diameter of pipe [m]
l	Length (along flow path) of pipe [m]
m	Mass flow correction [2.28]
n	Power-law exponent [-]
Q	Air flow [m^3/s]
Re	Reynolds number [-]
SS	Number [-]
ΔP	Pressure drop [Pa]
μ	Viscosity of fluid [kg/m-s]
ν	Kinematic viscosity of fluid (μ/ρ)
ϕ	Exponential form factor [-]
ρ	Density [kg/m^3]

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