

# The Origin and Application of Leakage-Infiltration Ratios

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## ABSTRACT HEADING

*Infiltration is the ingress of outdoor air under normal operating conditions through adventitious openings located in the façade of a building. The importance of reducing infiltration to save energy is highlighted by standards and building codes in many countries. The mean heating season, or other typical, infiltration rate is often inferred from a measurement of an air leakage rate at a pressure differential of 50 Pa from a whole building pressurization test, often made using a blower door. A simple linear relationship between the air leakage rate and the infiltration rate (infiltration equals air leakage divided by 20) is sometimes used and is known by many terms, such as the rule-of-20, leakage-infiltration ratio, Sherman's ratio, or the Kronvall-Persily rule. In practice, the value of 20 is not applicable to all buildings and climates, and should be adjusted according to a number of factors, such as building height, shielding, air leakage path size, and climate. The origins of this relationship and its proper application have previously been unclear, which is problematic if a ratio is to be used with any confidence.*

*This paper investigates the origins of leakage-infiltration ratios (LIRs) and shows that they emerged in the early 1980s from various studies (some unpublished) that measured airtightness and air change rates in a range of single-family dwellings and established empirical relationships between them. It is shown that there is no physical basis for LIRs, yet they are applied by building codes around the world and used to make policy decisions. Their widespread use is likely a function of their simplicity, yet they have significant limitations. Accordingly, it is recommended that their use be limited to quick estimations at best and that more technically-sound models be used to obtain more rigorous predictions of infiltration rates.*

## 1 INTRODUCTION

Openings located in the thermal envelope of a building comprise those that are intentional, known as *purpose-provided* openings, and those that are unintentional, known as *adventitious* openings. Infiltration is the ingress of outdoor air under normal operating conditions through adventitious openings and is driven by outdoor weather effects (temperature and wind) and the operation of building equipment, such as exhaust fans. Buildings are the largest energy-consuming sector in the world, responsible for over one-third of total energy demand (half of all electricity demand) and a comparable proportion of equivalent carbon dioxide (CO<sub>2</sub>e) emissions (IEA, 2013). An important strategy to reduce building energy demand is the reduction of heating and cooling loads by minimizing infiltration by making building envelopes more airtight.

The airflow rate through adventitious openings is assessed by artificially and systematically increasing the difference between the internal and external air pressures and measuring the total airflow across the thermal envelope required to do so (ASTM, 2010; BSI, 2001). The airflow rate and pressure difference are conventionally related by a

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power law that can be used to report an airflow rate at a specific pressure difference, commonly 50 Pa, known as an *Airleakage Rate* (ALR). In order to compare ALRs measured in different buildings, it is normalized by a common parameter; for example, by the building volume to become an air change rate ( $N_{50}$ ), by the area of the whole thermal envelope to become an *Air Permeability* (BSI, 2001), or by the area of the thermal envelope excluding the ground floor area to become an *Air Leakage Index*,  $I_{50}$  ( $\text{m}^3/\text{h}\cdot\text{m}^2$ ) (CIBSE, 2000).

Obtaining seasonal average infiltration rates is important for estimating energy savings that may result from measures that either eliminate or significantly reduce adventitious openings. Infiltration rates are also important as they are an importation portion, in some cases 100 %, of the outdoor air ventilation of building, which is critical for ensuring adequate indoor air quality (IAQ). For example, Persily *et al.* (2010) used CONTAM (Dols & Polidoro, 2015) to implement a multizone modelling approach to predict cumulative distribution functions (CDFs) of hourly mean infiltration rates in dwellings in the USA by region and dwelling type, and aggregated nationally. They show that the infiltration is  $< 0.5 \text{ h}^{-1}$  for 57 % of the time, which is significant given that this is a threshold ventilation rate recommended by many European countries, below which the perception of poor IAQ increases (Jones *et al.*, 2015). Similarly, Shi *et al.* (2015) predict CDFs of annual and seasonal mean infiltration rates in dwellings in Beijing, China, also using CONTAM. These CDFs suggest that the annual mean infiltration rate is less than  $0.5 \text{ h}^{-1}$  for 95 % of the time and less than  $0.5 \text{ h}^{-1}$  for more than 75 % of the time in winter. Jones *et al.* (2015) also use a probabilistic approach and a single zone model of infiltration, known as DOMVENT, to predict CDFs of heating season infiltration and associated heat loss for the English housing stock. They used these CDFs to estimate that infiltration is responsible for 3 % to 5 % of total UK energy demand, 11 % to 15 % UK housing stock energy demand, and 10 % to 14 % of UK housing stock  $\text{CO}_2\text{e}$  emissions. They also predict that up to 79 % of English dwellings have a mean infiltration rate of less than  $0.5 \text{ h}^{-1}$  and so may require additional purpose provided ventilation to ensure adequate IAQ.

These studies all use physically-based modelling approaches that may be impractical on a dwelling by dwelling basis in some policy contexts or when the computational time must be short. Accordingly, it is common to infer the mean heating season infiltration rate (MHSIR), or another typical metric, from a measurement of air leakage rate using a simple linear relationship. These *leakage-infiltration relationships* (LIR) form that basis of a calculation of the MHSIR in the UK's standard assessment procedure (Henderson & Hart, 2012), a government tool used to assess building energy performance. However, it is obviously problematic to use a steady-state weather-independent measurement of mono-directional airflow to predict one that is highly dynamic, weather dependent, and bi-directional and concern about the use of these heuristics has been raised (Jones *et al.*, 2013; 2015). The origins of these relationships have previously been unclear, which makes it challenging to understand their application and in some cases to use them with any confidence.

This paper investigates the origins of LIRs and discusses their application. As background, Section 2 describes the measurement of an air leakage rate, and Section 3 identifies the origins of LIRs. Section 4 discusses validity of LIRs and presents more complex alternatives when more rigorous predictions of infiltration rates are required.

## 2 MEASURING AIR LEAKAGE

The oil crisis of the mid 1970s led to a general interest in the thermal efficiency of buildings and house builders were encouraged to *build tight and ventilate right* (Elmroth, 1978). Maximum air leakage rates were incorporated into building codes, such as the Swedish Building Code, as early as 1977 (Kronvall, 1978). Sherman (1995) reports that early devices for measuring air leakage rates were developed from window-mounted fans that were used as a diagnostic tool for finding and fixing leaks and determining building quality. The subsequent *blower door* test is the generic name for a door mounted device that is capable of pressurizing and depressurizing a building, while simultaneously measuring the airflow rate through its fabric and the difference between internal and external air pressures. The resistance of the thermal envelope to airflow is assessed by systematically increasing the difference between the internal and external air pressures  $\Delta P$  (Pa) and measuring the airflow rate  $\dot{V}$  ( $\text{m}^3/\text{h}$ ) across it. These parameters are conventionally related by a power law

$$\dot{V} = C\{\Delta P\}^n \quad (1)$$

where  $C$  ( $\text{m}^3/\text{h}\cdot\text{Pa}^n$ ) and  $n$  are the flow coefficient and flow exponent, respectively (ASTM, 2010; BSI, 2001; CIBSE, 2000; CGSB, 2010). Standard procedures used to determine  $C$  and  $n$  prescribe the measurement of  $\dot{V}$  at intervals between  $10 \leq \Delta P \leq 100$  Pa to limit the effect of pressures from naturally occurring wind and buoyancy on the measurement.

Both Sherman and Palmiter (1995) and Carrié and Leprince (2016) highlight uncertainties in measurements of air leakage. It is recommended that multiple measurements are made with equipment that is regularly calibrated under still conditions where the difference between internal and external temperatures is minimal. They also show that uncertainty in a reported value of  $\dot{V}$  is smaller when interpolated than when extrapolated outside the measurement range. Concerns have been raised about the repeatability of blower door tests. Murphy *et al.* (1991) investigated 4 different blower-door systems used by 3 operators in 4 test houses. They find that the measurements, interpolated to a pressure difference of 50 Pa, produced a 95 % reproducibility interval of  $\pm 7.5$  % when averaged for all 4 houses. The operator is estimated to contribute less than 2 % of the error. More recently, Zero Carbon Hub (ZCH, 2014) initiated a *round-robin* assessment of 6 buildings located on 2 different sites (3 on each site) in the UK by 5 measurement companies showed significant variation in measurements of air permeability (minimum < 50 % of maximum value) and in the reporting of basic parameters, such as envelope area (minimum < 40 % of maximum value).

A measurement of air leakage in a multi-family dwelling unit, such as an apartment, using a single blower door unit could be misleading because it is unable to differentiate between airflow through external walls and party walls shared by adjacent dwellings. From an energy point of view this is important because air exchanged between dwellings can be assumed to be conditioned, whereas air exchanged with the outdoor environment will not be (Jones *et al.*, 2013). If one is interested in pollutant transport or fire risk mitigation, then an understanding of party wall airflow is also important. Protocols and techniques for so called *guarded zone* tests that isolate airflow through specific walls, ceilings, and floors have been established by Feustel (1990) and Fernández-Agüera *et al.* (2011) and uncertainties in these tests are discussed by Fürbringer and Roulet (1991). Recently, Faakye *et al.* (2013) have begun to tackle the problem by measuring outside and internal airflow rates using conventional and guarded-zone techniques. They then apply a number of statistical regression techniques, such as multivariate linear regression analysis and the Random Forest approach, to identify important physical parameters that can be used with a blower door test to estimate the proportion of an air leakage rate that occurs through external surfaces in similar dwellings. Their preliminary analysis suggests that the methods warrant further investigation.

For an alternative perspective on airflow through adventitious openings, see Etheridge (2015).

### 3 LEAKAGE-INFILTRATION RELATIONSHIPS

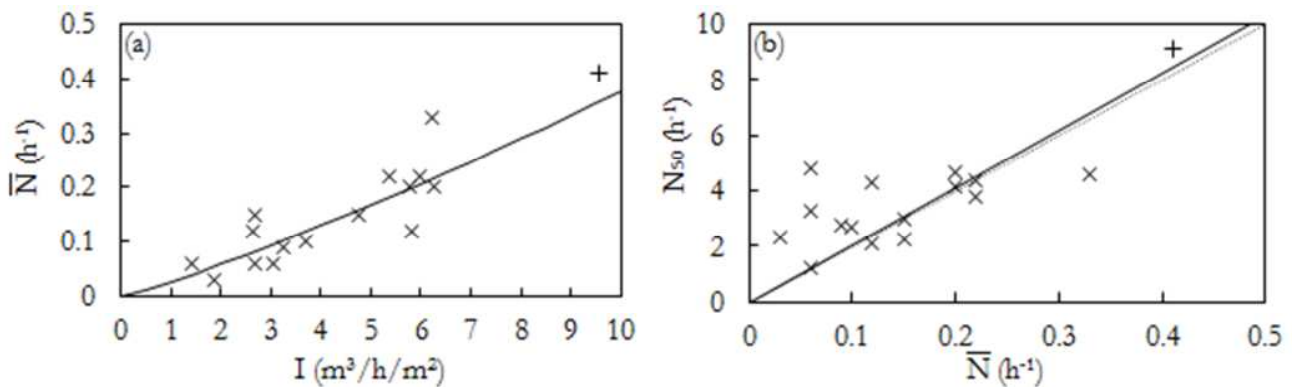
While the measurement of infiltration *in-situ* is the only way to actually determine these rates, it can be time consuming, technically difficult, and invasive. Accordingly, it is desirable and convenient to be able to infer infiltration rates, including mean infiltration rates,  $\bar{N}$  ( $\text{h}^{-1}$ ), from a measurement of  $N_{50}$  (or a similar metric). Possibly the most widely known method is the application of a *leakage infiltration ratio* (LIR) where

$$\bar{N} = N_{50}/20. \quad (2)$$

Equation (2) is known by many names such as the *rule-of-20*, the *leakage-infiltration ratio*, *Sherman's ratio*, or the *Kronvall-Persily rule*. Its origins are unclear and there are no known publications that explicitly provide evidence for Equation (2). Sherman mentions Equation (2) in several publications (Sherman, 1987; Sherman, 1995; Sherman & Dickerhoff, 1998) as a rule-of-thumb and it is possible that these are the source of the confusion in the literature. . Later, Sherman and Dickerhoff (1998) state that the usefulness of Equation (2) as a predictor of infiltration rates “was

found wanting”.

There are many references that purport to know the origins of Equation (2) in the academic (Keig *et al.* 2014) and wider professional literatures (Meier, 1986) that have since transcended into myth. For example, Meier (1986) reports that in the late 1970s a simple relationship between a one-time pressurization test and an average infiltration rate grew out of experimentation at Princeton University. For a few years, the correlation remained Princeton folklore despite the fact that there were no reports by Princeton that supported the relationship. In 1982, Kronvall and Persily compared pressurization tests to infiltration rates measured with tracer gas for groups of houses in New Jersey and Sweden (Kronvall, 1978; Persily, 1982). They used the results of pressurization tests at 50 Pa, in part because this reference pressure was being used in Sweden in their building standards. Sherman and Dickerhoff (1998) are clear that although Equation (2) is attributed to Kronvall and Persily it is “often denied” by them. There is no evidence of Equation (2) in any of Persily’s literature, such as Persily (1982), which is cited as a possible source by Sherman (1987).



**Figure 1** Relationships between air leakage parameters and mean infiltration rates (Kronvall, 1978). ×, detached dwellings; +, terraced (row) dwellings. (a)  $\bar{N} = 0.03I^{1.1}$ . (b) —, All houses where  $\bar{N} = 20.68N_{50}$ ; ·····, All detached houses where  $\bar{N} = 19.96N_{50}$ .

In 1978 Kronvall presented measurements of air leakage rates and infiltration rates in 29 houses made using an unspecified tracer gas technique and over an unknown time period. The data from 13 houses was rejected because the wind speed was  $\geq 5$  m/s when the air leakage rate was measured. This left a cohort of 15 detached houses and 1 terraced (row) house. Kronvall plots (see Figure 1a) air leakage index against the mean infiltration air change rate,  $\bar{N}$  ( $\text{h}^{-1}$ ), yielding a relationship of  $\bar{N} = 0.03I^{1.1}$  with a coefficient of determination of  $R^2 = 0.74$ . (Here, we note that our  $R^2$  does not agree with Kronvall’s.) The same data can be used to determine a linear relationship between  $\bar{N}$  and  $N_{50}$  where  $\bar{N} = 20.68N_{50}$  with  $R^2 = 0.36$ , as shown in Figure 1b, showing that the fit is poor. If the single terraced house is removed from the regression (see Figure 1b) then  $\bar{N} = 19.96N_{50}$  with  $R^2 = -0.77$ , which suggests that a constant (a horizontal line) would be a more appropriate model of the relationship. The relationships given in Figure 1b are not included in Kronvall’s publication, and so it is impossible to say with any confidence that this is the origin of the *rule-of-20*. However, it can be said that two years and many blower door tests later Kronvall (1980) may have changed his thinking when he stated “that it is, however, quite obvious that there cannot exist a simple relationship (for example via a coefficient) as the test result from one of the tests is not dependent on the prevailing weather conditions while the other certainly is dependent on them.” He goes on to propose a power law model of the relationship between  $\bar{N}$  and  $N_{50}$  that considers the wind and buoyancy forces, making it perhaps unlikely that he later proposed a linear relationship.

Other work around the late 1970s and early 1980s used an air leakage measurement and consideration of the pressure distribution over a building’s envelope to predict infiltration rates (Grimsrud *et al.*, 1979; Sherman & Grimsrud, 1980b). This effort culminated in the LBL Infiltration Model (Sherman & Modera, 1986). Elsewhere,

similar approaches were trialled (Warren & Webb, 1980; Shaw, 1981); see Liddament and Allen (1983) for a comparison and validation of models of infiltrations. By the mid-1980s Sherman (1987) had considered Equation (2) further, treating the figure of 20 as a variable rather than a constant. Accordingly, he found that it scaled depending on a variety of factors such as dwelling height, shielding, air leakage path size, and local climate. It is this philosophy that has been incorporated into the building standard of a number of countries, which are discussed in Section 4.

Shortly after these developments, research efforts led to the creation of multizone network airflow models (Walton 1982 and 1989). These models represent buildings as a collection of interconnected zones with airflow paths describing those connections and then perform a simultaneous mass balance of air for all these zones to determine the pressure in each zone, which in turn are used to calculate all interzone flows as well as building air change rates. These models implement a complete physics-theory of building airflow and have achieved very short computational times with modern personal computer hardware. They do require the user to input data on building leakage characteristics, zonal air temperatures, ventilation system airflows and outdoor weather, which is not always easy to obtain. The air leakage characteristics of exterior walls, however, can be obtained via fan pressurization or blower door tests. Among such models, CONTAM (Dols and Polidoro, 2015) may be the most prominent example; others are described and compared by Orme and Leksmono (2002). Typical leakage characteristics are also given as a median and interquartile range for windows, doors, walls, ceilings, floors, various joints, service penetrations, roofing, chimneys, and trickle ventilators by the same source.

#### **4 DISCUSSION OF THE USE OF LIRS**

LIRs are used widely because of their simplicity. The National Building Code of Finland (Government of Finland, 2012) uses a ratio of 20 (see Equation (2)) for 3 and 4 storey dwellings but increases it as the number of storeys reduces. The British Standard 5925 (BSI, 1991) states that a ratio of 20 can be used to estimate the average heating season infiltration rate in UK dwellings, although no reference is provided. Furthermore, the Standard Assessment Procedure (SAP), the UK government's method of assessing the energy performance of dwellings, applies Equation (2) and attributes further infiltration to sources that cannot be measured by a blower door test, such as fans, chimneys, and ducts. It then scales the total infiltration rate according to the average wind speed and the number of sheltered sides. Professional literature, such as the CIBSE (2015) Environmental Design Guidance provides a range of LIRs for offices, factories, warehouses, schools, hospital, hotels, and dwellings with various forms of shielding that are described as “very approximate”. Jones *et al.*, (2013, 2015) have highlighted issues with LIRs in conjoined (multi-family) dwellings because they assume that there is no inter-dwelling airflow. They also highlight the differences in predictions between a physical model of infiltration (DOMVENT) and the SAP simplified model that applies Equation (2). They find that the SAP based model will predict a more significant impact if infiltration is reduced than the DOMVENT model. They also find that applying Equation (2) without any further amendment leads to much higher predictions of infiltration than those made by DOMVENT or SAP. These differences would affect payback periods of retrofitted energy efficiency measures that seek to reduce the number, or size, of air leakage paths.

Erhorn-Kluttig & Erhorn (2012) show that a ratio of 14.3 is commonly used in Germany to estimate an infiltration rate from a measurement of  $N_{50}$ , and is scaled according to local shielding and the presence of an operational fan. Early editions of the EN ISO 13790 (BSI, 2004) use a ratio with a value between 10 and 100 according to the number of exposed sides and outdoor shielding. However, we note that this relationship has been removed from the subsequent 2009 edition.

While LIRs do not generally provide accurate estimates of building air change rates, they can sometimes be useful as quick rules-of-thumb for estimating infiltration rates from measurements of air leakage made using a blower door test. Therefore, it should be of concern when these heuristics are integral components of methods that estimate the energy demand of dwellings at individual and stocks levels, as opposed to the more rigorous approaches outlined above. However, as buildings become more airtight the absolute importance of the systematic errors in using LIRs decreases. This is especially true if infiltration is much smaller than any mechanical ventilation.

Section 3 suggests that predictions made using a simple LIR are never accurate. However, they may be good enough for some purposes; for example, Turner *et al.* (2012) show that a LIR derived for energy purposes is always smaller than one for pollutant dilution. Accordingly, they are conservative with respect to IAQ but are likely to be liberal with respect to energy. ASHRAE Standard 62.2 (ASHRAE, 2010) essentially uses a form of LIR tuned for each of 1000 locations and adjusted for pollutant dilution rather than energy demand reduction. These LIRs can be used to determine an effective ventilation rates for a dwelling, which is defined by Turner *et al.* as the steady-state ventilation rate that would yield the same average pollutant concentration over some time period as the actual time varying ventilation would in that same time period.

## 5 CONCLUSIONS

This paper shows that Leakage Infiltration Ratios (LIRs) have evolved from hearsay rather than peer reviewed technical literature. However, their very simplicity makes them a useful rule-of-thumb for practitioners for some limited purposes. And, while this is acceptable for making rough estimates of infiltration, they are inappropriate for obtaining values to support building design decisions with significant economic consequences. Therein lies the problem, because there is evidence that largely unsubstantiated methods are used to make significant decisions at a national level, which could have air quality, health, energy, and economic consequences. Practitioners should be advised that LIRs are dwelling and location specific, and are a rule-of-thumb whose predictions of infiltration are *very approximate*.

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## NOMENCLATURE

ALR	=	air leakage rate
$C$	=	airflow coefficient ( $\text{m}^3/\text{h}\cdot\text{Pa}^n$ )
CDF	=	cumulative distribution function
CO <sub>2e</sub>	=	equivalent carbon dioxide emissions
$I_{50}$	=	air leakage index ( $\text{m}^3/\text{h}\cdot\text{m}^2$ )
IAQ	=	indoor air quality
LIR	=	leakage infiltration ratio
MHSIR	=	mean heating season infiltration rate
$N_{50}$	=	air change rate per hour measured at a 50 Pa pressure difference ( $\text{h}^{-1}$ )
$N$	=	air change rate per hour ( $\text{h}^{-1}$ )
$\bar{N}$	=	mean air change rate per hour ( $\text{h}^{-1}$ )
$n$	=	airflow exponent
$\dot{V}$	=	airflow rate ( $\text{m}^3/\text{h}$ )

## Subscripts

50 = magnitude of internal external pressure difference (Pa)

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