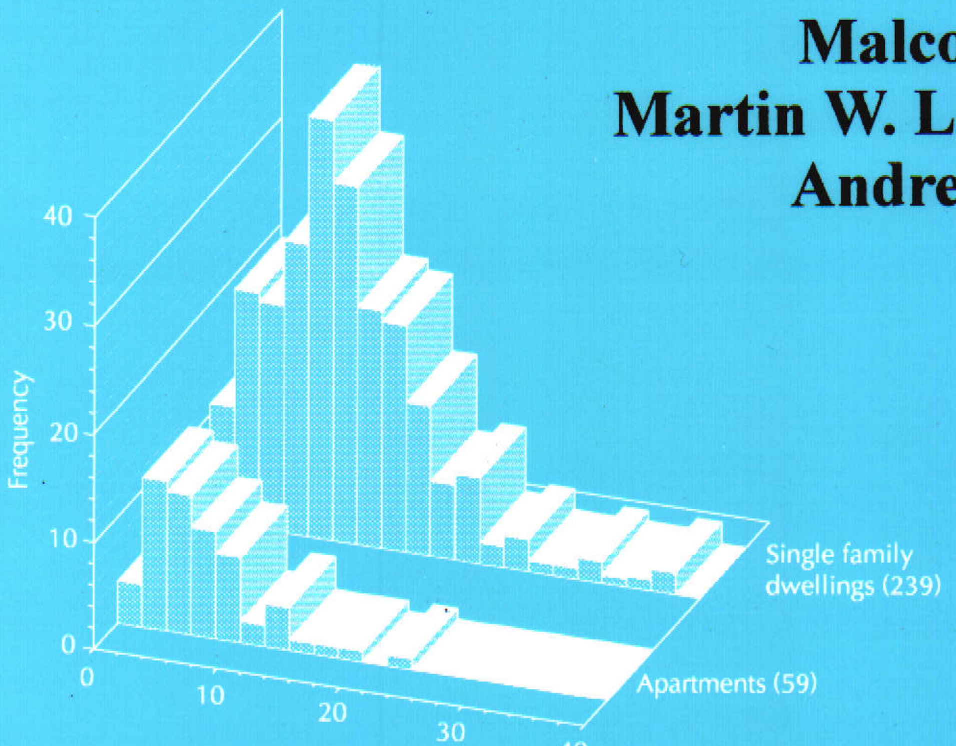
Energy Conservation in Buildings
and Community Systems Programme

Numerical Data for Air Infiltration & Natural Ventilation Calculations



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International Energy Agency

AIVC Air Infiltration and Ventilation Centre

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Contents

Part 1 – Component Leakage

Page

Part 2 – Whole Building Leakage

Part 3 – Wind Pressure Evaluation

Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

I	Load Energy Determination of Buildings*
II	Ekistics and Advanced Community Energy Systems*
III	Energy Conservation in Residential Buildings*
IV	Glasgow Commercial Building Monitoring*
V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
XII	Windows and Fenestration*
XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*
XVI	BEMS - 1: Energy Management Procedures*
XVII	BEMS - 2: Evaluation and Emulation Techniques*
XVIII	Demand Controlled Ventilating Systems*

XIX Low Slope Roof Systems*
XX Air Flow Patterns within Buildings*
XXI Thermal Modelling*
XXII Energy Efficient Communities*
XXIII Multizone Air Flow Modelling (COMIS)*
XXIV Heat Air and Moisture Transfer in Envelopes*
XXV Real Time HEVAC Simulation*
XXVI Energy Efficient Ventilation of Large Enclosures*
XXVII Evaluation and Demonstration of Domestic Ventilation Systems
XXVIII Low Energy Cooling Systems
XXIX Daylight in Buildings
XXX Bringing Simulation to Application
XXXI Energy Related Environmental Impact of Buildings
XXXII Integral Building Envelope Performance Assessment
XXXIII Advanced Local Energy Planning
XXXIV Computer-aided Evaluation of HVAC System Performance
XXXV Design of Energy Efficient Hybrid Ventilation (HYBVENT)

Annex V Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Canada, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom and the United States of America.

Introduction

The Air Infiltration and Ventilation Centre's Numerical Database has been developed in response to a need to establish a core of numerical data suitable for design purposes and model validation. It has also been developed to provide a focus for data derived from related International Energy Agency projects. Source information is contained within a computerised database from which direct searching for specific material is possible. The purpose of this report is to present an analysis of key database material which may be used for design purposes.

Data have been derived from as wide a range of sources as possible. Many organisations have contributed to the data presented. By combining information from these many sources, it has been possible to consider a far wider range of operating conditions than would be possible by using the results from a single set of measurements.

This report and analysis is presented in three sections; these cover:

Section 1 Component Leakage Data

Section 2 Whole Building Leakage Data

Section 3 Wind Pressure Evaluation

Data are presented as a summary of information contained within the database. Most information is presented in the form of median, upper and lower quartile values. Wherever possible, relevant Standards and recommendations for building or component performance are referenced.

Target Audience

This report is aimed at providing default data to designers and other users who need information on air leakage and ventilation characteristics for use in calculation models and design applications.

Caution

The data presented are based on measurements published in the literature and on data provided by various institutions for inclusion in this Guide. No responsibility is taken for the quality of data. Wherever possible, applicable Standards or airtightness recommendations appropriate to the country should be applied to new and retrofit construction.

Acknowledgements

Valuable assistance and data were given to the AIVC by numerous individuals and research organisations during the preparation of this document. The authors would like to thank the members of the AIVC Steering Group for their help:

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Sivert Uvsløkk, Norges byggsforskningsinstitutt, Trondheim, Norway

Additional data was kindly supplied direct from the following research centres, much of which is unpublished:

BBRI – Belgium Building Research Institute, rue de la Violette 21-23, 1000 Brussels, Belgium.

BRE – Building Research Establishment, Garston, Watford, Herts. WD2 7JR, UK.

CMHC – Canada Mortgage and Housing Corporation, Montreal Road, National Office, Ottawa, Ontario, Canada K1A OP7

CSTB – Centre Scientifique et Technique du Batiment, Centre de Recherche de Marne-la-Vallée, 84 Avenue Jean Jaur+s, Champs-sur-Marne, B.P. 02-77421, Marne-la-Vallée Cedex 2, France.

EMPA – EMPA, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland.

LBL – Lawrence Berkeley Laboratory, Berkeley, California 94720, USA.

NBI – Norges byggforskningsinstitutt, Postboks 123, Blindern, N-0314 Oslo, Norway.

SIB – Swedish Institute for Building Research, P.O. Box 785, S-80129 GÄVLE, Sweden.

TNO – TNO Building and Construction Research, PO Box 29, 2600 AA Delft, The Netherlands.

Part One

Component Leakage

Component Leakage

1.1 Overview

1.1.0 Introduction

Cracks and gaps in the fabric of buildings provide the routes for air infiltration. The size and flow characteristics of such gaps depend on the type of joint, material used and the quality of manufacture and fitting. Similar components may therefore be expected to exhibit widely varying leakage characteristics. It is the in-situ performance of components that will define the air leakage of a structure and, ultimately, contribute to any energy loss and comfort problems.

This section presents a summary of leakage characteristics of gaps and cracks to be found in buildings. The purpose is to provide numerical guidance on typical leakage values for use in design and simulation when no other sources of data are available. These data are based on measurements published in over 80 technical publications and on measurements provided directly by many research organisations and groups. Further information on the sources of data is included in a computerised database. The contents of the database along with the data format and software user instructions are provided in an accompanying publication. (See *AIVC Numerical Database User Guide*; Wilson and Orme, 1994.)

1.1.1 Scope of Data

Data on leakage values are based on an analysis of over 1700 components and fittings used in the construction of buildings. These range from gaps and cracks around door and window openings to gaps around service pipes and other penetrations. The leakage performances of typical construction materials are also presented. These data should allow the user to approximate the overall leakage characteristics of a building and to estimate the possible improvements by either retrofitting or installing tighter components. These data may also be used as source material for more extensive air flow studies.

1.1.2 Presentation of Data

Data are presented in a series of sections, with each being devoted to a specific component type. A common format for each section is applied. Following a brief description of the component, a Table of relevant airtightness Standards and recommendations is presented. This is followed by a Table of median, upper and lower quartile leakage values, based on measurement data. Most of the measurement values have been based on in-situ field test results. However, when such data were found to be limited or unavailable, laboratory test data were used. For some components, such as windows, both field and laboratory data were available in sufficient quantities to provide comparisons between each type of measurement. Whenever possible, leakage distributions are also presented in graphical form.

1.1.3 Using the Data

The data presented in this Guide should be regarded as default data for use when more reliable information is not available. Performance should always be verified by measurement.

Brief guidance on the use of the data is presented in Figures 1.1 and 1.2. As a general guideline, well constructed and properly installed components should be expected to have an airtightness performance in the median to lower quartile range. Aged components will have a leakage value between the median and upper quartile range. Retrofitting existing components is unlikely to improve airtightness beyond the median value. Each of these aspects is discussed in further detail below for:

- new components,
- existing components, and
- retrofit of existing components.

New Components

New components should always be constructed and installed to comply with relevant airtightness Standards. Most of these requirements and recommendations correspond to the airtight (lower quartile) extreme of measurement data. Post-constructive testing for compliance with the appropriate Standards is recommended.

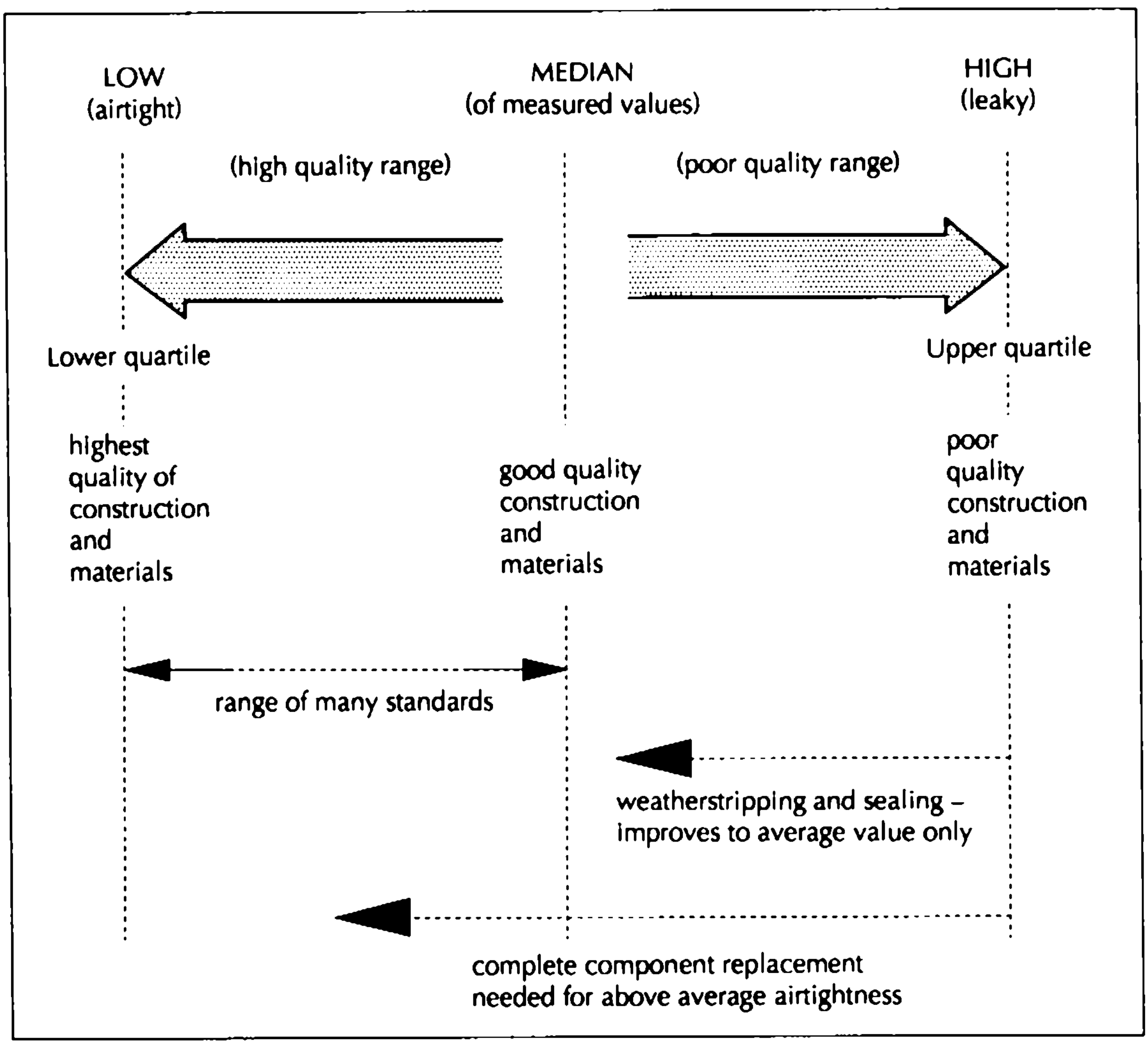


Figure 1.1 Air Leakage of Components

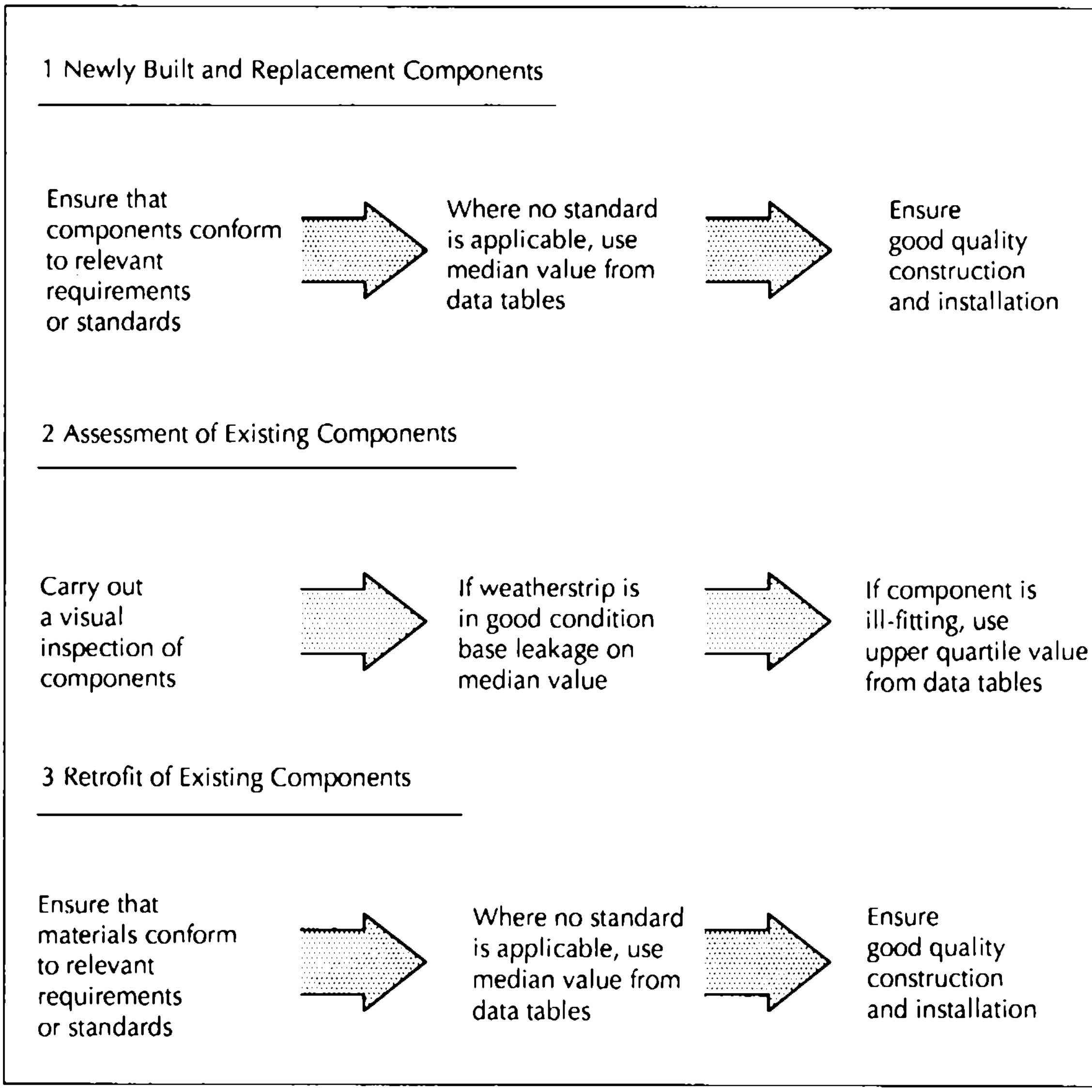


Figure 1.2 Application of Air Leakage Data

Existing Components

It may be necessary, as part of a parametric study for example, to estimate the leakage performance of existing components. This exercise may form part of a cost benefit exercise to evaluate the payback or benefit of retrofit measures. A visual inspection of the component should be made first. If the component fitting is deemed to be of good quality, then the median data presented in the data Tables should be applied. If components are ill-fitting then the upper quartile or even higher value should be used. When weatherstripping is missing or in a poor condition, leakage should be based on non-weatherstripped values. If daylight or an obviously large gap (0.5 mm) is observed, then the total area of opening should be determined and the leakage value should be based on applying the orifice flow equation (see Section 1.1.5).

Retrofit of Existing Components

Materials used in retrofit should comply with appropriate standards. It is unlikely that the retrofitting of a component will provide the airtightness performance of a new component. Therefore, in the absence of field testing, the performance of good quality retrofit should be based on the median airtightness value given in the data tables. Only when the user is certain that an exceptionally airtight retrofit measure has been applied should a tighter value be considered.

Ideally, components should be tested for performance after installation and, where necessary, remedial work undertaken.

1.1.4 Standards

The quality of construction and the airtightness performance of joints are frequently covered by standards, recommendations or legal codes of practice. Where this is the case, it is then the responsibility of the designer and installer to ensure adherence to the appropriate requirements. Information on available Standards is included within the data sections but precise statements are not given. Details about standards are frequently updated by the AIVC and incorporated into its Standards Database (Limb, 1994).

1.1.5 Theoretical Outline

Air infiltration and natural ventilation is governed by the airtightness of a building, the distribution of leakage openings and the magnitude of pressures acting at each opening. In the case of mechanical ventilation, driving pressure is generated by the fan, whereas with natural systems, the driving forces are those of wind and temperature.

Orifice Equation

For a given applied pressure across an opening, the rate of air flow through it is a function of size and geometry. For relatively large openings (for example purpose provided vents, visible gaps around service penetrations and very ill-fitting components) the air flow can sometimes be represented by an equivalent flow through a flat plate orifice. The orifice flow equation is given by:

$$Q = C_d A \sqrt{\frac{2}{\rho} \Delta P}$$

where

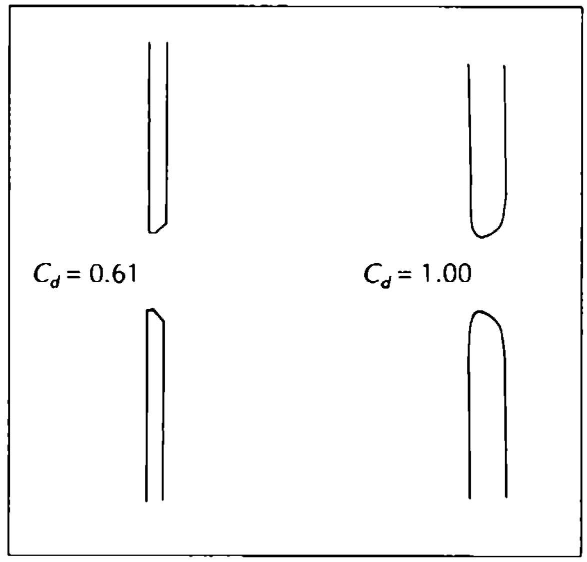
Q = air flow rate ($m^3.s^{-1}$),

C_d = discharge coefficient,

ρ = air density ($kg.m^{-3}$),

ΔP = pressure difference across opening (Pa), and

A = area of opening (m^2).



Power Law Equation

More generally, the flow of air through gaps and cracks in the building fabric is transitional between laminar and turbulent and this is frequently represented by the Power Law Equation:

$$Q = C\,\Delta P^n$$

where

C = flow coefficient ($m^3.s^{-1}.Pa^{-n}$),

n = flow exponent, and

ΔP = pressure difference across opening (Pa).

The flow coefficient, C, is related to the size of the opening and the flow exponent, n, characterises the flow regime. The flow exponent ranges in value between 0.5 for fully turbulent flow to 1.0 for fully laminar flow. Crack geometry and surface roughness are the causes of the formation of turbulent flow in the crack itself. Alternative representations of the air flow equation exist and, in most cases, can be derived from the C and n values. Examples include:

- quadratic formulation,
- Equivalent Leakage Area, ELA_4, (4 Pa representation), and
- Equivalent Leakage Area, ELA_{10}, (10 Pa representation).

Quadratic Formulation

For reasons of dimensional homogenity, a quadratic formulation of the air flow equation, in which the turbulent and laminar components of flow are separated, is sometimes preferred. This is given by the equation:

$$\Delta P = \alpha Q + \beta Q^2$$

where α and β are empirical constants.

The coefficients α and β may be derived from known values of C and n by using the Power Law to generate flow rates at two pressure values (eg 1 Pa and 50 Pa). Substitution of these two flow rates into the quadratic equation, enable α and β to be determined by simultaneous solution.

Equivalent Leakage Area ELA_4 (4 Pa Representation)

This attempts to represent a leakage value in terms of a physical area at a representative reference pressure. It is used extensively in the United States where it forms the basis of a simplified infiltration and ventilation model. It is based on the orifice flow equation in which the discharge coefficient is assumed to be unity.

ELA_4 is given by the Equation:

$$ELA_4 = Q_4 \sqrt{\frac{\rho}{8}}$$

where

ELA_4 = Equivalent Leakage Area at 4 Pa (m^2),

Q_4 = air flow rate at 4 Pa ($m^3.s^{-1}$), and

ρ = air density ($kg.m^{-3}$).

ELA_4 may be evaluated from the C and n coefficients using the relation:

$$ELA_4 = C4^{n-0.5}\sqrt{\frac{\rho}{2}}$$

where flow has been calculated at a reference pressure of 4 Pa.

Equivalent Leakage Area ELA_{10} (10 Pa Representation)

In Canada, a 10 Pa reference pressure is used in the ELA_{10} calculation because Q_{10} can always be measured directly when conducting fan pressurisation tests. A more representative discharge coefficient of 0.61 is normally also applied in place of the unity values used in the 4 Pa formulation. Thus in this instance ELA_{10} is given by:

$$ELA_{10} = \frac{Q_{10}}{0.61}\sqrt{\frac{\rho}{20}}$$

where

Q_{10} = air flow rate at 10 Pa ($m^3.s^{-1}$).

Comparison of Coefficients

In the table below α and β (of the quadratic formulation) have been evaluated by simultaneous solution from example values of C and n, for two different sets of pressures: 1 Pa and 4 Pa; 1 Pa and 10 Pa. Two reference pressures are necessary for this conversion because the quadratic and Power Law approaches only agree at three different pressures at most (including zero pressure), except when either $\alpha = 0$ or $\beta = 0$. For the example conversion from C and n to ELA_4 and ELA_{10}, the density of air has been assumed to be equal to 1.21 kg.m^{-3}.

C/(m^3.s^{-1}.Pa^{-n})	n		α	β	ELA_4 (C_d = 1.00)/(cm^2)	ELA_{10} (C_d = 0.61)/(cm^2)
0.2×10^{-3}	0.66	1,4 Pa	3.0×10^3	10.1×10^6	1.9	3.7
		1,10 Pa	3.3×10^3	8.3×10^6		

To predict air flow through openings, it is therefore crucial to have information on flow characteristics. The air leakage data presented in this report are based on the use of C and n values. All other representations of flow may be derived from these C and n values.

Flow Exponents

A wide spread in values of flow coefficient within the range of validity of 0.5 to 1.0 was observed. In some instances there was scatter beyond this range, but these were still included in the regression analysis. In general, the flow exponent increased in value with airtightness but a marked difference in characteristics between 'joint' leakage and 'porous' surface leakage was observed. These differences are depicted in Figures 1.3(a) and 1.3(b) respectively. The majority of flow exponents for leakage openings at joints or material interfaces were found to be within ±0.1 of their mean value, 0.6. On the other hand, the exponent for porous surfaces varied between 0.5 and unity, showing a clear correlation with airtightness.

The curves presented in Figure 1.3 were used in the averaging of flow exponent for the component leakage data tables. Flow exponents for crack and joints between components were based on the average value of data depicted in Figure 1.3 (a), while flow exponents for air leakage across surfaces were based on data shown in Figure 1.3 (b).

The equations for the linear regression lines fitted to the data in the respective cases are:

(a) for cracks and joints, $n = 0.58 - 0.05 \log_{10} C$, and

(b) for porous surfaces, $n = 0.63 - 0.13 \log_{10} C$.

Data sources for Figure 1.3:

(a) #116, #1116, #1405, #1449, #2708, #2722, #5152, BRE Unpublished

(b) #86, #142, #176, #311, #787, #2702, #3800, #3880, BRE Unpublished

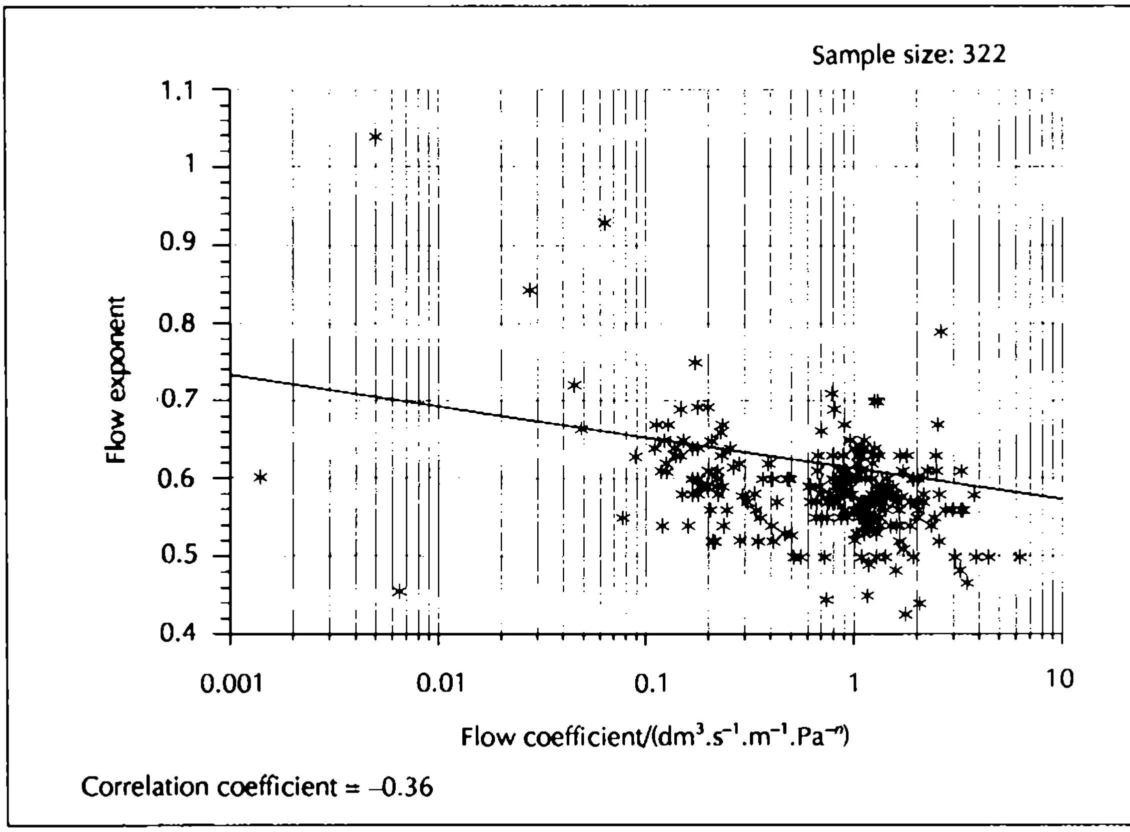


Figure 1.3 (a) Flow per Unit Length of Crack

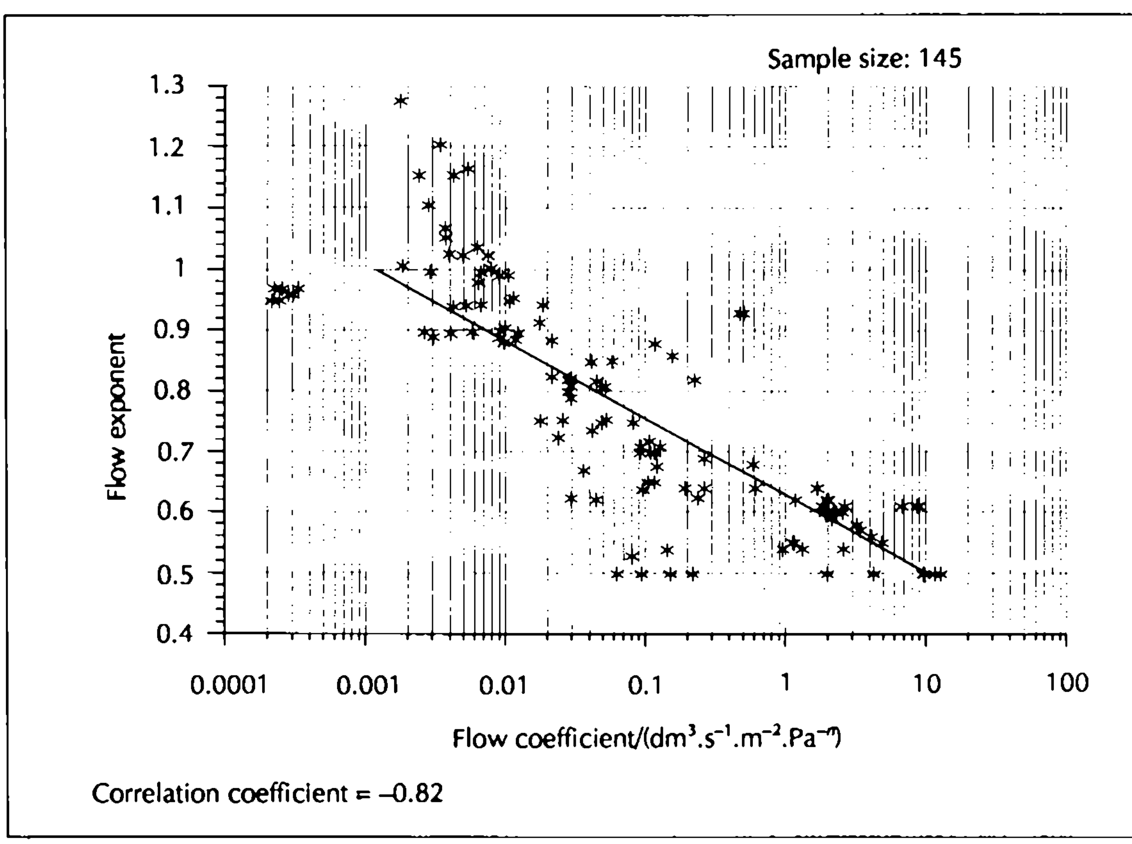


Figure 1.3 (b) Flow per Unit Surface Area

1.2 Component Air Leakage

1.2.0 Introduction (to The Component Leakage Characteristics Data Tables)

Tables of data are presented for the following components:

- windows,
- doors,
- component/wall interfaces,
- wall construction, ceilings and floors,
- ceiling/wall/floor interfaces,
- wall/wall interfaces,
- penetrations (service pipes,outlets etc.),
- roofing,
- fireplaces and flues, and
- trickle ventilators and vents.

The volume flow rate through the building components described in the tables are related to the pressure difference across them by using the Power Law (see Section 1.1.5), expressed with a flow coefficient, C and a flow exponent, n. All results are for *field test* experiments unless they are explicitly stated as originating from laboratory tests.

Table entries emphasized in **bold type** are those which have a sample size greater than or equal to 5 items, an arbitrary level.

Flow Coefficients

Flow coefficients are normalised to give flow (expressed in units of $dm^3.s^{-1}.m^{-1}.Pa^{-n}$) per unit length of crack in all cases except:

(i) wall, ceiling, floor and roofing constructions, for which flows are normalised by surface area ($dm^3.s^{-1}.m^{-2}.Pa^{-n}$),

(ii) flow through fireplaces is normalised to flow per unit flue area ($dm^3.s^{-1}.m^{-2}.Pa^{-n}$),

(iii) measured data given here for trickle ventilators are limited to indicating flow with the vents closed relative to flow with the vent open, and

(iv) flow coefficients for roller doors are expressed per unit surface area of door ($dm^3.s^{-1}.m^{-2}.Pa^{-n}$).

Mean Values

Any mean values of the flow coefficients, which have been used in the compilation of these data tables from the sources, are geometric mean values. (e.g. when the median has been interpolated between two known values). The justification is that in this case the geometric mean preserves the form of the flow equation i.e. for two equations describing the flow characteristics of a type of crack from different experiments,

$$Q_1 = K_1\,\Delta P^{n_1} \text{ and } Q_2 = K_2\,\Delta P^{n_2},$$

the geometric mean, Q_g is given by

$$Q_g = (Q_1\,Q_2)^{0.5} = (K_1\,\Delta P^{n_1})^{0.5}\,(K_2\,\Delta P^{n_2})^{0.5} = (K_1\,K_2)^{0.5}\,\Delta P^{0.5(n_1+n_2)}.$$

Hence the geometric mean of the air flow rate is proportional to the geometric mean of the flow coefficients, $(K_1\,K_2)^{0.5}$ and also to the pressure difference raised to the power of the arithmetic mean of the flow exponents, $0.5(n_1 + n_2)$.

Flow Exponents

All flow exponents for data expressed *per unit length of crack* have been taken as 0.6, due to the low correlation coefficient observed with linear regression of flow coefficients with flow exponents. (Shown in Figure 1.3(a).) For data normalised *by surface area,* the calculated linear regression line was used to determine an associated flow exponent for each flow coefficient (which is shown in Figure 1.3(b)). This was considered acceptable because of the good correlation observed between the two quantities. These exponents are given in the data tables for the relevant items.

Conversion of Data

In some cases certain assumptions had to be made in order to convert the data to Power Law form:

(i) the flow exponent was taken to be 0.66 in all cases in which another value was not supplied,

(ii) the discharge coefficient C_d was assumed to equal 0.6 for data to which the Orifice Equation (see Section 1.1.5) applied and no other value was given, or

(iii) the air temperature was assumed to be uniform at 20°C, resulting in an air density of 1.21 kg.m^{-3} at a pressure of 1 atmosphere.

Quartiles

The lower quartile, median and upper quartile values of a sample of numerical data are those values below which respectively 25%, 50% and 75% of the distribution lie. For those components for which the sample size was found to be equal to two, the lower quartile was taken to equal the lesser of the two flow coefficients, whilst the upper quartile was assigned the value of the greater. The median was interpolated from the magnitudes of the two coefficients by determining their geometric mean. A similar convention was followed for components with a sample size of three items, except that no interpolation was necessary in order to find their median average. For samples consisting of more than three items, the usual definitions were applied to deduce the respective quartiles, except that as previously indicated the geometric mean was used for interpolating between values.

1.2.1 Windows

Window data represented the most widely available of published information. Data summaries are based on a total of 180 data items. These data are presented in units of $dm^3.s^{-1}$ per metre length of openable perimeter at a pressure difference of 1 Pa. Leakage values do not include air leakage between the frame and wall (see Section 1.2.3).

Window data are categorised into three generic forms. These are:

- casement or hinged windows which compress against the frame when closed,
- sliding windows (including sash) which move within horizontal or vertical channels or tracks, and
- louvre windows.

Airtightness Standards are summarised in Table 1.1 and measured data are summarised in Table 1.2. Distributions for weatherstripped and non-weatherstripped examples, (field data and laboratory data) are also illustrated in Figure 1.4.) The median value, based on field data, for weatherstripped windows is 0.14, with upper and lower quartiles of 0.25 and 0.082 respectively. A much broader distribution is observed for non weatherstripped examples. The median, upper and lower quartiles are 0.40, 0.88, and 0.20 respectively. For comparison purposes, the flow coefficients for 0.5 mm and 1.0 mm width cracks (both with assumed discharge coefficient of 0.61 and air density equal to 1.21 $kg.m^{-3}$) and representative flow coefficients for a range of airtightness Standards are also presented. This shows that most test results are leakier than current Standards but represent gaps of under 0.5 mm. Laboratory test data showed similar characteristics to field data but without an extended tail.

Table 1.1 Standards, Recommendations and Legal Codes of Practice – Windows

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
Belgium STS 52.0	Building Height 0-10 m	3.00 $m^3.h^{-1}.m^{-1}$ at 100 Pa	0.040 $dm^3.s^{-1}.m^{-1}$
	Building Height 10-18 m	3.00 $m^3.h^{-1}.m^{-1}$ at 100 Pa	0.040 $dm^3.s^{-1}.m^{-1}$
	Building Height >18 m	2.00 $m^3.h^{-1}.m^{-1}$ at 100 Pa	0.027 $dm^3.s^{-1}.m^{-1}$
Canada CAN 3-A440-M84	A1 Low Rise Buildings (<3 storeys, <600 m^2)	2.79 $m^3.h^{-1}.m^{-1}$ at 75 Pa	0.045 $dm^3.s^{-1}.m^{-1}$
	A2 Medium to High Rise Buildings	1.65 $m^3.h^{-1}.m^{-1}$ at 75 Pa	0.027 $dm^3.s^{-1}.m^{-1}$
	A3 High Performance, Institutional & Commercial	0.55 $m^3.h^{-1}.m^{-1}$ at 75 Pa	0.009 $dm^3.s^{-1}.m^{-1}$
	Fixed	0.25 $m^3.h^{-1}.m^{-1}$ at 75 Pa	0.004 $dm^3.s^{-1}.m^{-1}$
	Storm (Max)	8.35 $m^3.h^{-1}.m^{-1}$ at 75 Pa	0.134 $dm^3.s^{-1}.m^{-1}$
	Storm (Min)	5.00 $m^3.h^{-1}.m^{-1}$ at 75 Pa	0.080 $dm^3.s^{-1}.m^{-1}$
Denmark DS-418	Assumed Value (When True Value Not Known)	0.50 $dm^3.s^{-1}.m^{-1}$ at 30 Pa	0.053 $dm^3.s^{-1}.m^{-1}$

Table 1.1 Standards, Recommendations and Legal Codes of Practice – Windows (cont'd)

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
Finland SFS 3304	Class 1 (Max)	0.50 $m^3.h^{-1}.m^{-2}$ at 50 Pa	0.011 $dm^3.s^{-1}.m^{-2}$
	Class 2 (Min)	0.50 $m^3.h^{-1}.m^{-2}$ at 50 Pa	0.011 $dm^3.s^{-1}.m^{-2}$
	Class 2 (Max)	2.50 $m^3.h^{-1}.m^{-2}$ at 50 Pa	0.053 $dm^3.s^{-1}.m^{-2}$
	Class 3 (Min)	2.50 $m^3.h^{-1}.m^{-1}$ at 50 Pa	0.053 $dm^3.s^{-1}.m^{-1}$
France NF P20 302	A1	20-60 $m^3.h^{-1}.m^{-2}$ at 100 Pa	0.266-0.798 $dm^3.s^{-1}.m^{-2}$
	A2	7-20 $m^3.h^{-1}.m^{-2}$ at 100 Pa	0.093-0.266 $dm^3.s^{-1}.m^{-2}$
	A3	<7 $m^3.h^{-1}.m^{-2}$ at 100 Pa	<0.093 $dm^3.s^{-1}.m^{-2}$
Germany DIN 18055	A Building Height 0-8 m Above Grade	6.00 $m^3.h^{-1}.m^{-1}$ at 50 Pa	0.126 $dm^3.s^{-1}.m^{-1}$
	B-D Building Height > 8 m Above Grade	3.00 $m^3.h^{-1}.m^{-1}$ at 50 Pa	0.063 $dm^3.s^{-1}.m^{-1}$
Italy UNI 7979	A1	8.00 $m^3.h^{-1}.m^{-1}$ at 50 Pa 31.00 $m^3.h^{-1}m^{-2}$ at 50 Pa	0.168 $dm^3.s^{-1}.m^{-1}$ 0.651 $dm^3.s^{-1}.m^{-2}$
	A2	4.00 $m^3.h^{-1}.m^{-1}$ at 50 Pa 13.00 $m^3.h^{-1}.m^{-2}$ at 50 Pa	0.084 $dm^3.s^{-1}.m^{-1}$ 0.273 $dm^3.s^{-1}.m^{-2}$
	A3	1.40 $m^3.h^{-1}.m^{-1}$ at 50 Pa 4.80 $m^3.h^{-1}.m^{-2}$ at 50 Pa	0.029 $dm^3.s^{-1}.m^{-1}$ 0.101 $dm^3.s^{-1}.m^{-2}$
Netherlands NEN 3661	Building Height up to 15 m (Normal Exposure)	2.50 $dm^3.s^{-1}.m^{-1}$ at 75 Pa	0.145 $dm^3.s^{-1}.m^{-1}$
	Building Height 15-40 m (Normal Exposure)	2.50 $dm^3.s^{-1}.m^{-1}$ at 150 Pa	0.092 $dm^3.s^{-1}.m^{-1}$
	Building Height 40-100 m (Normal Exposure)	2.50 $dm^3.s^{-1}.m^{-1}$ at 300 Pa	0.058 $dm^3.s^{-1}.m^{-1}$
	Building Height up to 15 m (Coastal Exposure)	2.50 $dm^3.s^{-1}.m^{-1}$ at 300 Pa	0.058 $dm^3.s^{-1}.m^{-1}$
	Building Height 15-40 m (Coastal Exposure)	2.50 $dm^3.s^{-1}.m^{-1}$ at 300 Pa	0.058 $dm^3.s^{-1}.m^{-1}$
	Building Height 40-100 m (Coastal Exposure)	2.50 $dm^3.s^{-1}.m^{-1}$ at 450 Pa	0.044 $dm^3.s^{-1}.m^{-1}$
New Zealand NZS N4211:1987	Airtight	0.60 $dm^3.s^{-1}.m^{-1}$ at 150 Pa 2.00 $dm^3.s^{-1}.m^{-2}$ at 150 Pa	0.022 $dm^3.s^{-1}.m^{-1}$ 0.073 $dm^3.s^{-1}.m^{-2}$
	Moderate Air Leakage	2.00 $dm^3.s^{-1}.m^{-1}$ at 150 Pa 8.00 $dm^3.s^{-1}.m^{-2}$ at 150 Pa	0.073 $dm^3.s^{-1}.m^{-1}$ 0.293 $dm^3.s^{-1}.m^{-2}$
	Low Air Leakage	4.00 $dm^3.s^{-1}.m^{-1}$ at 150 Pa 17.00 $dm^3.s^{-1}.m^{-2}$ at 150 Pa	0.147 $dm^3.s^{-1}.m^{-1}$ 0.623 $dm^3.s^{-1}.m^{-2}$
Sweden	All Buildings	1.70 $m^3.h^{-1}.m^{-2}$ at 50 Pa 5.60 $m^3.h^{-1}.m^{-2}$ at 300 Pa	0.036 $dm^3.s^{-1}.m^{-2}$ 0.036 $dm^3.s^{-1}.m^{-2}$
	Buildings >8 Storeys	7.90 $m^3.h^{-1}.m^{-2}$ at 500 Pa	0.036 $dm^3.s^{-1}.m^{-2}$
Switzerland SIA 331	Building Height 0-8 m	5.65 $m^3.h^{-1}.m^{-1}$ at 150 Pa	0.056 $dm^3.s^{-1}.m^{-1}$
	Building Height 8-20 m	8.95 $m^3.h^{-1}.m^{-1}$ at 300 Pa	0.056 $dm^3.s^{-1}.m^{-1}$
	Building Height 20-100 m	14.25 $m^3.h^{-1}.m^{-1}$ at 600 Pa	0.056 $dm^3.s^{-1}.m^{-1}$

Table 1.1 Standards, Recommendations and Legal Codes of Practice – Windows (cont'd)

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
United Kingdom BS6375: Part 1: 1989	Openable – Design Wind Pressure (Exposure) <1600 Pa	6.34 $m^3.h^{-1}.m^{-1}$ at 50 Pa	0.133 $dm^3.s^{-1}.m^{-1}$
	Openable – Design Wind Pressure (Exposure) > = 1600 Pa	4.84 $m^3.h^{-1}.m^{-1}$ at 50 Pa	0.102 $dm^3.s^{-1}.m^{-1}$
	Fixed – Design Wind Pressure (Exposure) <1600 Pa	1.00 $m^3.h^{-1}.m^{-1}$ at 200 Pa	0.008 $dm^3.s^{-1}.m^{-1}$
	Fixed – Design Wind Pressure (Exposure) > = 1600 Pa	1.00 $m^3.h^{-1}.m^{-1}$ at 300 Pa	0.006 $dm^3.s^{-1}.m^{-1}$
	Fixed – High Performance	1.00 $m^3.h^{-1}.m^{-1}$ at 600 Pa	0.004 $dm^3.s^{-1}.m^{-1}$
	Openable – High Performance	6.60 $m^3.h^{-1}.m^{-1}$ at 600 Pa	0.02 $dm^3.s^{-1}.m^{-1}$
USA ASHRAE 90-80	All	0.77 $dm^3.s^{-1}.m^{-1}$ at 75 Pa	0.045 $dm^3.s^{-1}.m^{-1}$

Table 1.2 Leakage Characteristics – Windows

Data expressed for each m length of joint	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-1}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
Windows (Weatherstripped)							
Hinged	**0.086**	**(0.6)**	**0.13**	**(0.6)**	**0.41**	**(0.6)**	**29**
Sliding	**0.079**	**(0.6)**	**0.15**	**(0.6)**	**0.21**	**(0.6)**	**19**
Windows (Non-weatherstripped)							
Hinged	**0.39**	**(0.6)**	**0.74**	**(0.6)**	**1.1**	**(0.6)**	**42**
Sliding	**0.18**	**(0.6)**	**0.23**	**(0.6)**	**0.37**	**(0.6)**	**36**
Louvre (expressed per louvre)			0.34	(0.6)			1
Sources: BRE Unpublished, #40, #116, #320, #458, #1116, #1357, #1405, #1449							

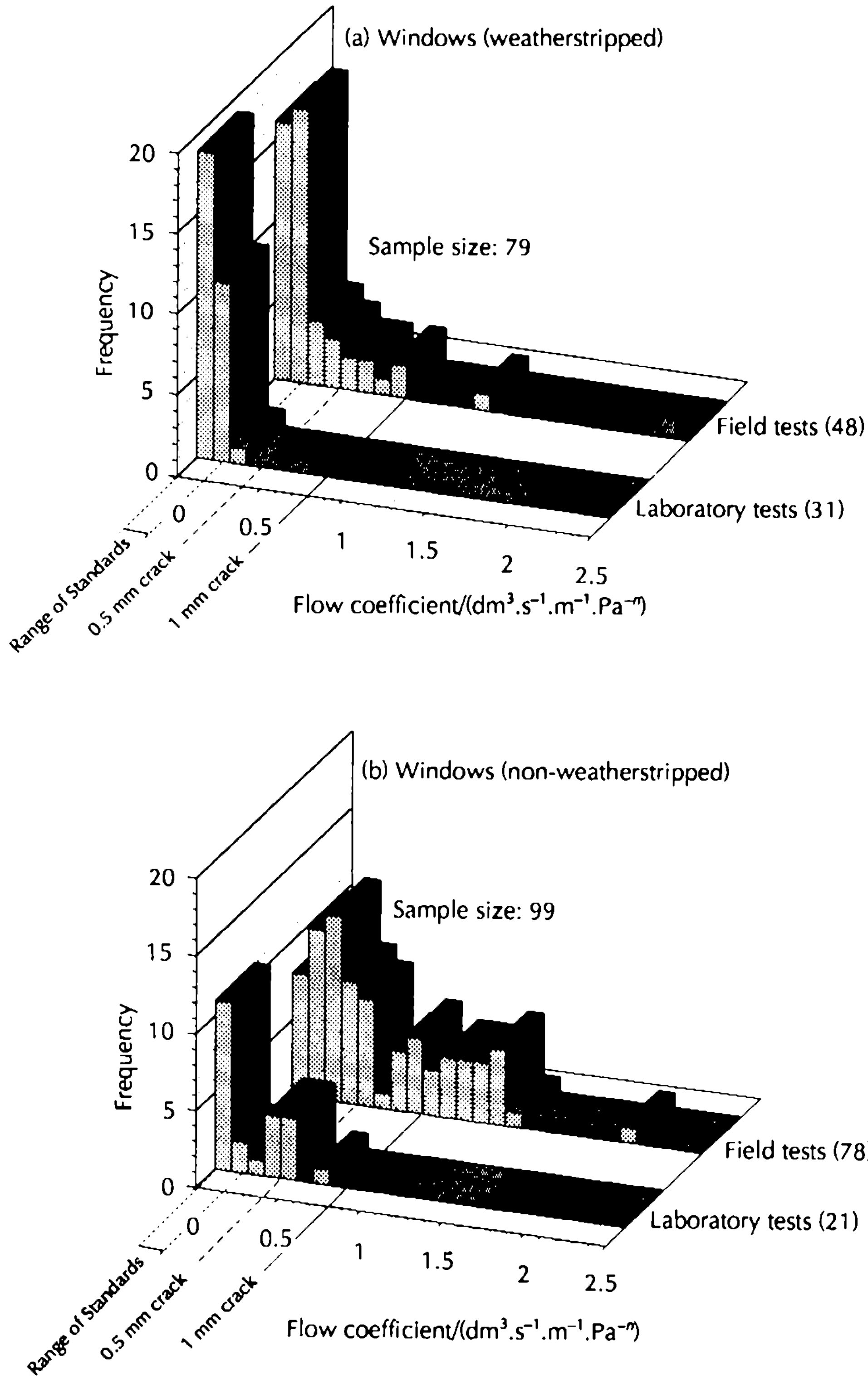


Figure 1.4 Air Leakage Distributions for Windows

1.2.2 Doors

The distribution of measured leakage performance of external doors followed a similar trend to that of windows.

Door categories include:

- hinged,
- sliding, and
- revolving.

Data are presented in $dm^3.s^{-1}.m^{-1}$ of openable crack. Relevant Standards as flow coefficients and exponents are summarised in Table 1.3. Table 1.4 summarises measurement data.

Table 1.3 Standards, Recommendations and Legal Codes of Practice – Doors

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
Canada CGSB 82-GP-2M	Sliding Glass With Aluminium Frame	2.50 $dm^3.s^{-1}.m^{-2}$ at 75 Pa	0.145 $dm^3.s^{-1}.m^{-2}$
Denmark DS-418	Assumed Value (When True Value Not Known)	0.50 $dm^3.s^{-1}.m^{-1}$ at 50 Pa	0.038 $dm^3.s^{-1}.m^{-1}$
USA ASHRAE 90-80	Residential (Sliding Glass)	2.50 $dm^3.s^{-1}.m^{-2}$ at 75 Pa	0.145 $dm^3.s^{-1}.m^{-2}$
	Residential (Entrance – Swinging Doors)	6.35 $dm^3.s^{-1}.m^{-2}$ at 75 Pa	0.367 $dm^3.s^{-1}.m^{-2}$
	Non-Residential	17.00 $dm^3.s^{-1}.m^{-2}$ at 75 Pa	0.984 $dm^3.s^{-1}.m^{-2}$

Table 1.4 Leakage Characteristics - Doors

Data expressed for each m length of joint	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-1}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
External Doors (Weatherstripped)							
Hinged	**0.082**	**(0.6)**	**0.27**	**(0.6)**	**0.84**	**(0.6)**	**15**
Sliding			No data				
Revolving - Laboratory test	1.0	(0.6)	1.5	(0.6)	2.0	(0.6)	4
External Doors (Non-weatherstripped)							
Hinged	**1.1**	**(0.6)**	**1.2**	**(0.6)**	**1.4**	**(0.6)**	**17**
Sliding			0.20	(0.6)			1
Roller Door, per m^2 of surface ($dm^3.s^{-1}.m^{-2}.Pa^{n}$) - Laboratory test	3.3	(0.6)	5.7	(0.6)	10	(0.6)	2
Internal Doors (Non-weatherstripped)	**1.1**	**(0.6)**	**1.3**	**(0.6)**	**2.0**	**(0.6)**	**84**
Loft Hatches (Non-Weatherstripped)	0.64	(0.6)	0.68	(0.6)	0.75	(0.6)	4

Sources: BRE Unpublished, #40, #116, #173,, #1357, #1405, #5848

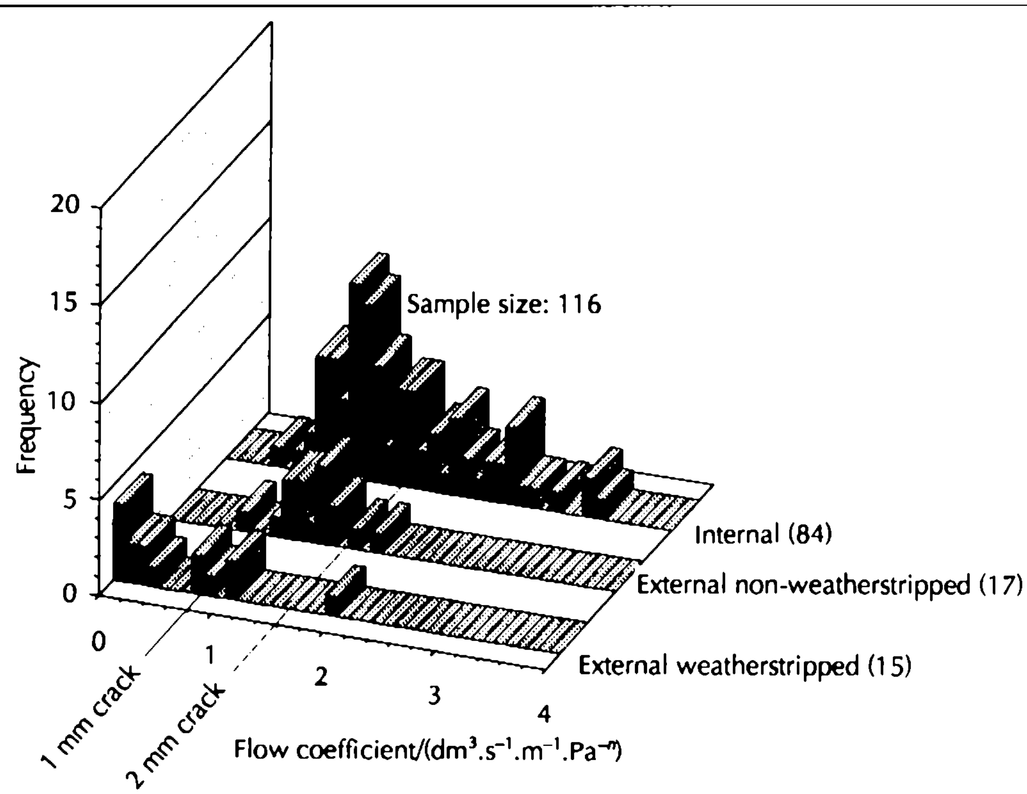


Figure 1.5 Doors (Hinged)

1.2.3 Interface of Window and Door Frames with Walls

A common source of air leakage is between the frame of a component, such as a door or window, and the surface in which it is embedded. Modern caulking techniques provide a means of reducing this leakage but in many instances high rates of air leakage are possible. Deterioration of joints as caulking ages is especially a problem and therefore a survey of components is particularly important. Median values relate to components in good condition. The upper quartile value should be considered for components which have been in extended service, while the lower quartile value should be reserved for only the highest quality of workmanship.

From the limited data available, no significant difference in leakage characteristics was identified between the different construction materials of either the frame or the wall. There were, however, significant differences in performance between caulked and uncaulked components.

While this is potentially, a major source of air leakage, leakage performance Standards have not been identified.

A summary of data is presented for uncaulked and caulked examples in Table 1.5.

Table 1.5 Leakage Characteristics – Wall/Window and Wall/Door Frame

Data expressed for each m length of joint	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-1}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
Caulked joint – Laboratory and field tests	**3.3×10^{-4}**	**(0.6)**	**2.5×10^{-3}**	**(0.6)**	**0.012**	**(0.6)**	**7**
Uncaulked joint – Laboratory and field tests	**0.053**	**(0.6)**	**0.061**	**(0.6)**	**0.067**	**(0.6)**	**5**
Sources: #1357, #1414, #1514, #2964, #5378.							

1.2.4 Wall Construction, Ceilings and Floors

Porous surfaces such as used in the construction of walls, floors, and ceilings provide a further source of air leakage which can have a considerable impact on overall building airtightness. These do not include air vents, air bricks or service penetrations which must be treated separately. Values are presented in terms of flow rate across unit area of material, ie $dm^3.s^{-1}.m^{-2}$. The leakage characteristics of the interfaces between walls, ceilings and floors are covered separately in Section 1.2.5.

Generally, a wall has an inner leaf, an insulation layer and an outer leaf. Normally, the inner leaf is of higher airtight construction than the outer leaf and insulation layer. The airtightness performance of a wall is then dominated by the quality of the inner leaf construction.

Existing standards on the performance of these components are limited. A value for the Netherlands is presented in Table 1.6. Leakage characteristics based on measured data are presented in Table 1.7. The distribution of the data presented in Table 1.7, for suspended timber floors is shown in Figure 1.6, whilst the (airtightness) distribution of exterior (bare) concrete block walls is given in Figure 1.7.

It should be noted that the data referenced to Wouters (1987) in Table 1.7 includes experimental data measured by H. Hens and others at the Katholicke Universiteit Leuven (Laboratorium Bouwfysica), Belgium between 1981-85.

Table 1.6 Standards, Recommendations and Legal Codes of Practice – Walls, Ceilings and Floors

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
Netherlands Building Decree. Issued December 16, 1991	Flooring	20 x 10^{-6} $m^3.s^{-1}.m^{-2}$ at 1 Pa	0.020 $dm^3.s^{-1}.m^{-2}$

Table 1.7 Leakage Characteristics – Walls, Ceilings and Floors

Data expressed for each m^2 of surface. Includes joints	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-2}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
Brick (bare) – Laboratory and Field Tests	**0.022**	**(0.84)**	**0.043**	**(0.80)**	**0.094**	**(0.76)**	**5**
Brick (plastered)	0.016	(0.86)	0.018	(0.85)	0.021	(0.84)	3
Brick (wall board panelling) – Laboratory test	0.010	(0.88)	0.042	(0.81)	0.18	(0.72)	2
Cladding (ungasketed)	0.010	(0.88)	0.032	(0.82)	0.10	(0.76)	2
Cladding (gasketed) – Laboratory test	6.9×10^{-3}	(0.90)	0.012	(0.87)	0.015	(0.86)	3
Concrete block (bare)	**0.082**	**(0.77)**	**0.13**	**(0.74)**	**2.0**	**(0.59)**	**10**
Concrete block (plastered, internal) – Laboratory test	0.021	(0.84)	0.021	(0.84)	0.021	(0.84)	2
Concrete panels (pre cast)	**0.050**	**(0.80)**	**0.11**	**(0.75)**	**0.12**	**(0.74)**	**6**
Concrete panels (pre cast, gasketed) – Laboratory test			0.026	(0.83)			1
Metal panels (walls)	0.076	(0.77)	0.090	(0.76)	0.13	(0.74)	3
Curtain walling	0.089	(0.76)	0.12	(0.74)	0.14	(0.74)	3
Plaster board (ceiling)	0.042	(0.81)	0.11	(0.75)	0.20	(0.72)	3
Fibre board (ceiling)			0.094	(0.76)			1
Timber panel (with wall board)	**0.27**	**(0.70)**	**0.52**	**(0.67)**	**2.7**	**(0.58)**	**6**
Timber panel (with air barrier) – Laboratory test			0.066	(0.78)			1
Timber floor (suspended)	**0.11**	**(0.75)**	**0.15**	**(0.74)**	**0.45**	**(0.67)**	**15**
Sources: #40, #86, #91, #142, #176, #177, #214, #311, #597, #1357, #3880, #5746, Wouters (1987), Brunelli (1969), BRE Unpublished.							

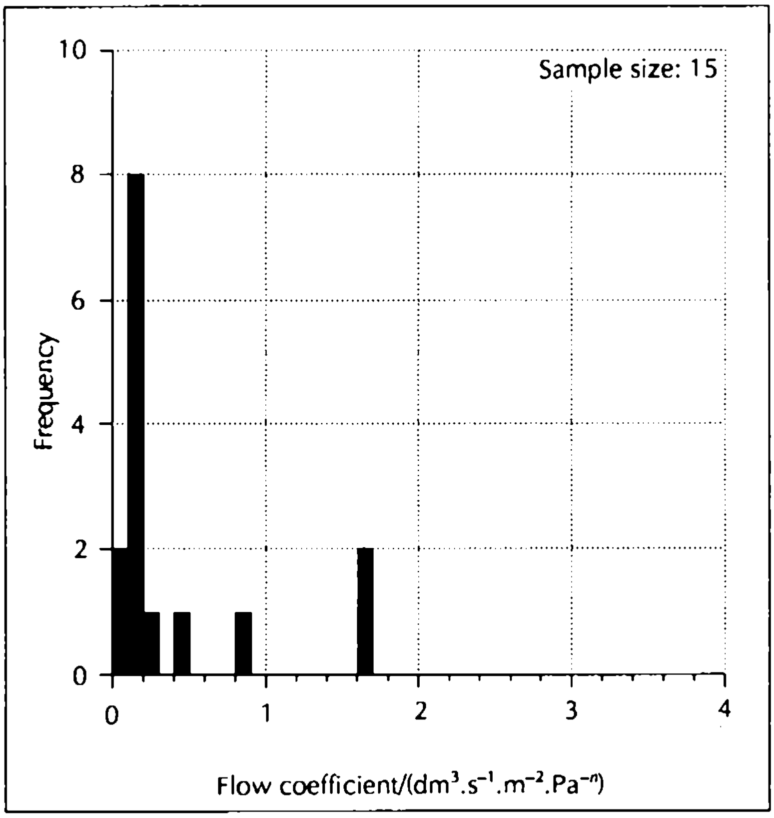


Figure 1.6 Floors – Suspended Timber

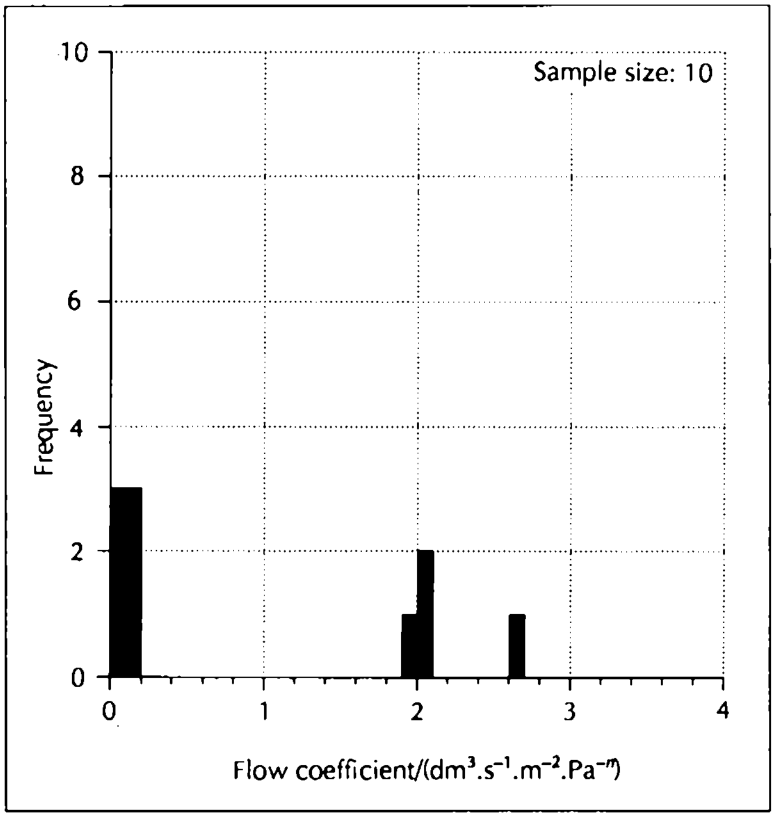


Figure 1.7 Exterior Walls – Concrete Block (Bare)

1.2.5 Ceiling/Wall/Floor Interfaces

Cracks and gaps at the interfaces between walls, ceilings and floors provide a further source of air leakage. Examples for different types of construction are illustrated in Figure 1.8. Inadequate attention to sealing or caulking can result in significant air infiltration through these interfaces. Allowance must be made wherever a component penetrates the inner leaf of construction into the insulation layer or beyond. While potentially a major source of air leakage, data are very limited and Standards have not been traced. The measurement data presented are based on 22 samples derived from four countries. Leakage distributions for these components are tabulated in Table 1.8. Data are presented in units of $dm^3.s^{-1}.m^{-1}$ length of joint.

It is important to undertake a survey of visible gaps and cracks. Performance is influenced by age during which time openings occur through general movement and settling. It is suggested that upper quartile values should be considered for buildings of greater than 2-3 years, although this has yet to be verified.

Table 1.8 Leakage Characteristics – Wall to Floor/Ceiling Joints

Data expressed for each m length of joint		Lower Quartile		Median		Upper Quartile		Sample Size
		$dm^3.s^{-1}.m^{-2}.Pa^{-n}$						
Wall Material	Ceiling Material	*C*	*(n)*	*C*	*(n)*	*C*	*(n)*	
Caulked:								
Masonry	Timber/Fibre Board			No data				
Masonry/ Concrete	Concrete	5.0×10^{-3}	(0.6)	0.024	(0.6)	0.11	(0.6)	2
Timber – Laboratory test	**Timber/Fibre Board**	$\mathbf{6.6 \times 10^{-3}}$	**(0.6)**	**0.011**	**(0.6)**	**0.015**	**(0.6)**	**9**
Timber	Concrete	0.052	(0.6)	0.083	(0.6)	0.11	(0.6)	4
Uncaulked:								
Masonry/ Concrete	Timber/Fibre Board	0.45	(0.6)	0.49	(0.6)	0.53	(0.6)	2
Masonry	Concrete			No data				
Timber	**Timber/Fibre Board**	**0.008**	**(0.6)**	**0.023**	**(0.6)**	**0.030**	**(0.6)**	**5**

Sources: #1105, #1261, #1357, #1607, #5693.

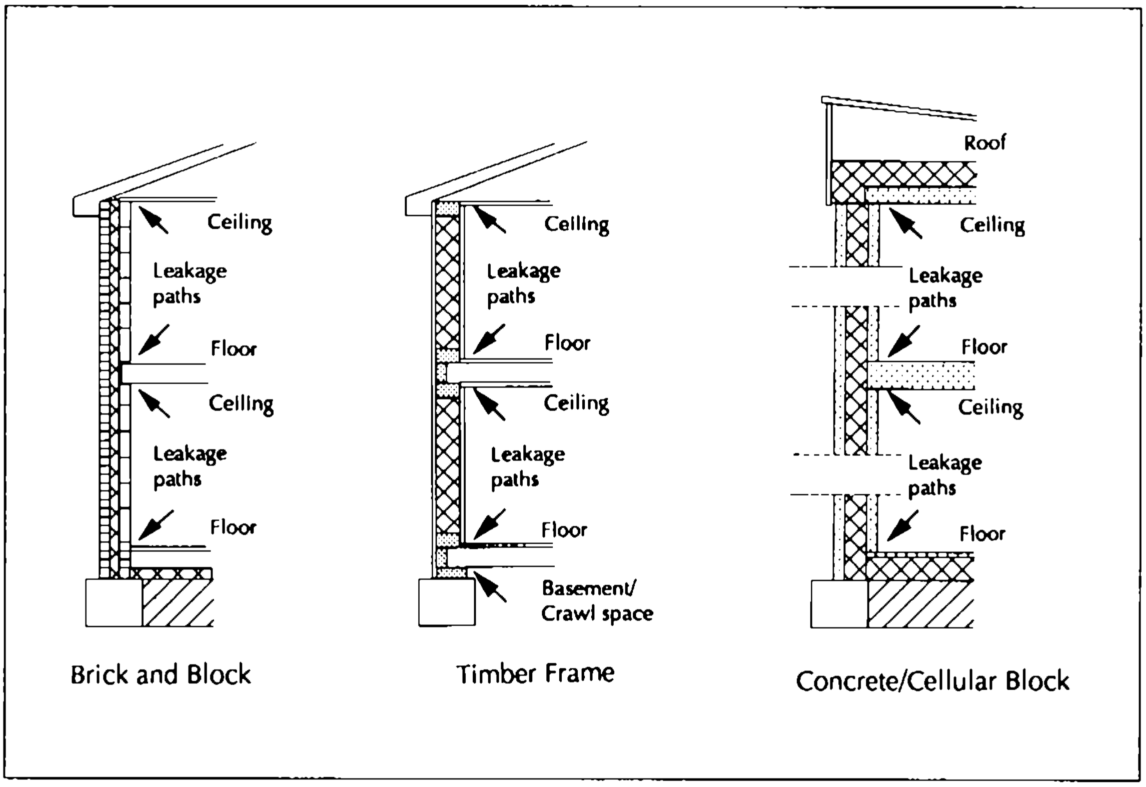


Figure 1.8 Floor/Wall/Ceiling Joints

1.2.6 Wall to Wall Interfaces

Certain wall constructions have joints at each corner, which are potential sources of air leakage. Types of construction include timber-framed and also various types of panel construction. On the other hand, brick or block type construction are of interleaved type and do not present a continous interface. A leakage allowance must be made wherever a wall to wall joint is formed. Examples of measured data are presented in Table 1.9. Figure 1.9 shows the distribution of flow coefficients for caulked wall to wall joints.

Table 1.9 Leakage Characteristics – Wall to Wall Joints

Data expressed for each m length of joint	Lower Quartile	Median	Upper Quartile	Sample Size
	$dm^3.s^{-1}.m^{-1}.Pa^{-n}$			
	C (n)	C (n)	C (n)	
Caulked:				
Timber/Timber – Laboratory test	**6.7×10^{-4} (0.6)**	**1.6×10^{-3} (0.6)**	**3.4×10^{-3} (0.6)**	**40**
Masonry/Timber		No data		
Uncaulked:				
Timber/Timber		No data		
Masonry/Timber		No data		
Sources: #1105, #5378.				

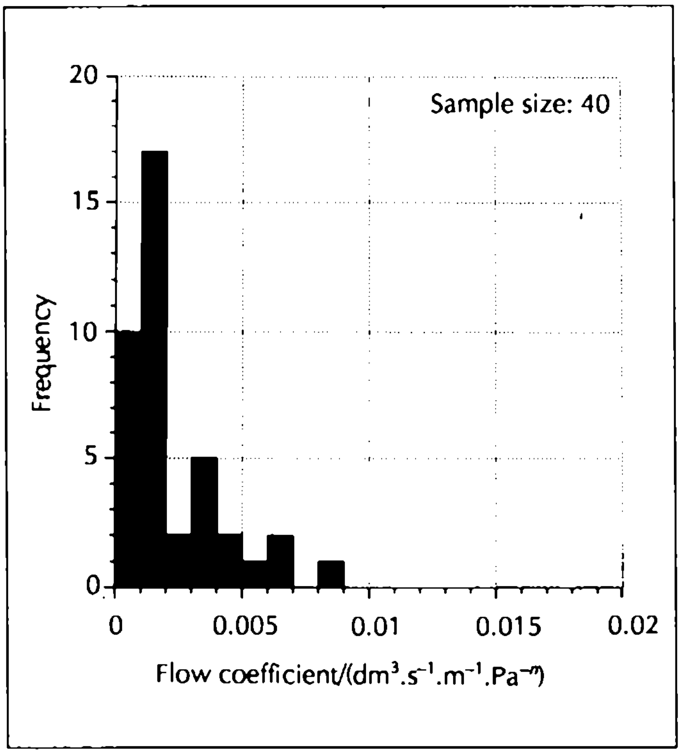


Figure 1.9 Wall (Timber) to Wall (Timber) Joints – Caulked

1.2.7 Penetrations

Many structural elements and components penetrate the inner leaf of a construction thus creating a leakage opening. The leakage resulting from poorly sealed penetrations can be estimated from the surface area of opening. Smaller gaps can be inferred from available measurement data summarised in Table 1.10. Pipe and conduit penetrations, especially, can be very leaky. In these instances (gaps greater than .5 mm) the surface area of opening should be measured and the leakage characteristics inferred from the orifice flow equation given in Section 1.1.5. Data should only be applied to components that penetrate the inner leaf of the building.

Data presented in this section are expressed in terms of $dm^3.s^{-1}.m^{-1}$ length of circumference of penetration.

Table 1.10 Leakage Characteristics – Penetrations

Data expressed for each m length of perimeter joint	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-2}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
Discharge pipes	1.1	(0.6)	1.2	(0.6)	1.4	(0.6)	2
Sealed spiral ducts	0.027	(0.6)	0.14	(0.6)	0.78	(0.6)	2
Vent			0.80	(0.6)			1
Pipes – Laboratory Test	0.63	(0.6)	0.74	(0.6)	0.84	(0.6)	3
Sources: BRE Unpublished, #1104, #1294, #5693.							

1.2.8 Roofing

The data presented in this Section refers to roofing located directly over an occupied space. Examples include shopping malls, factories and warehouses. Typically, roofing material is especially permeable to air. Data are presented in terms of $dm^3.s^{-1}.m^{-2}$ of surface and includes the cracks and gaps between individual tiles or roofing elements. These measurement results do not apply to the interface between the roof and wall which must be determined by applying the data presented in Table 1.11.

Table 1.11 Leakage Characteristics – Roofing

Data expressed for each m^2 of surface. Includes joints	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-2}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
Shingles (roofing)	0.60	(0.66)	0.70	(0.65)	1.1	(0.63)	3
Tiles (roofing)	**2.1**	**(0.59)**	**2.3**	**(0.58)**	**4.0**	**(0.55)**	**9**
Metal (roofing	**0.49**	**(0.67)**	**0.63**	**(0.66)**	**0.98**	**(0.63)**	**6**
Sources: #1529, #3880.							

1.2.9 Fireplaces and Flues

Fire-places and flues represent a significant source of air leakage. Table 1.12 presents typical leakage data for chimneys fitted with and without dampers.

Table 1.12 Leakage Characteristics – Chimneys

Data expressed for each m² of chimney flue area	Lower Quartile		Median		Upper Quartile		Sample Size
	$dm^3.s^{-1}.m^{-2}.Pa^{-n}$						
	C	*(n)*	*C*	*(n)*	*C*	*(n)*	
Fireplace opening bare – Laboratory and field tests	670	(0.5)	750	(0.5)	790	(0.5)	3
Pegboard baffle (Sealed) – Laboratory tests			300	(0.5)			1
Pegboard baffle (Unsealed) – Laboratory tests			410	(0.5)			1
Plywood baffle (Unsealed) – Laboratory test	180	(0.5)	180	(0.5)	180	(0.5)	2
Sources: BRE Unpublished, #1259.							

1.2.10 Trickle Ventilators

Air grilles and air bricks are too numerous to present general measurement information. In the first instance it is recommended that manufacturers' specifications are used. If none are available then the leakage performance of opened vents should be based on total openable area using the orifice flow equation given in Section 1.1.5. Measurement data have been used to estimate the difference in air leakage performance between open vents and closed vents. When a closed vent shows visible signs of leakage then the upper quartile value should be used. The lower quartile value should be applied only to well constructed vents with good sealing. Most modern grilles are expected to have a much tighter specification than even the lower quartile value given here. For instance the Belgian standard NBN D50-001 requires that the ratio is less than 0.03.

Data for estimating the leakage characteristics of closed vents are presented in Table 1.13.

Table 1.13 Leakage Characteristics (expressed by the ratio of 'closed' flow to 'open' flow) – Trickle Ventilators

	Lower Quartile	Median	Upper Quartile	Sample Size
Trickle Ventilators – Laboratory test	**0.06**	**0.08**	**0.23**	**8**
To determine the flow characteristics of a closed trickle ventilator when its 'open' flow is given by size $Q = C\Delta P^n$, multiply by value given above, to give e.g. $Q = 0.06\ C\Delta P^n$, the flow equation of the trickle ventilator when the vents are closed.				
Data Source: BRE Unpublished				

1.3 Example

An averagely constructed two storey building of insulated cavity brick construction has internal floor dimensions of 8 m x 6 m and a ceiling height of 2.8 m on each storey. The ground floor is of solid concrete construction which is perfectly sealed to the interior brick leaf. The ceilings are of plaster board construction and the interior walls are plastered and painted. The ceiling to wall joints are uncaulked. The floor of the upper storey is of suspended timber construction which only penetrates the inner leaf of each 8 m wall.

The upper storey ceiling is penetrated by:

(i) a non-weatherstripped roof hatch of dimension 1.0 m x 1.0 m, and

(ii) a service pipe of 200 mm diameter.

Each of the 8 m walls is penetrated by:

(i) a door of dimension 2 m x 1 m on the lower storey,

(ii) a window frame of dimension 1.0 m x 1.5 m on each storey, and

(iii) a window frame of dimension 1.0 m x 1.0 m on each storey.

Each of the 6 m walls is penetrated by:

(i) a window frame of dimension 1.0 m x 1.0 m on each storey.

The large window frames each have:

(i) 2 x side hung openers of dimension 1.0 m x 0.5 m, and

(ii) 1 x top hung opener of dimension 0.25 m x 0.5 m.

The small window frames each have:

(i) 1 x side hung opener of dimension 1.0 m x 0.5 m, and

(ii) 1 x top hung opener of dimension 0.25 m x 0.5 m.

All windows and doors are of timber construction with weatherstripped opening sections. Door and window frame to wall joints are uncaulked.

An estimation of the air change rate of this building at an inside/outside pressure difference of 50 Pa is given in Table 1.14, for each of three possibilities:

The building is of:

(i) high construction standard (lower quartiles),

(ii) good construction (medians), or

(iii) poor construction quality (upper quartiles).

The net (internal) building volume approximately equals 269 m^3.

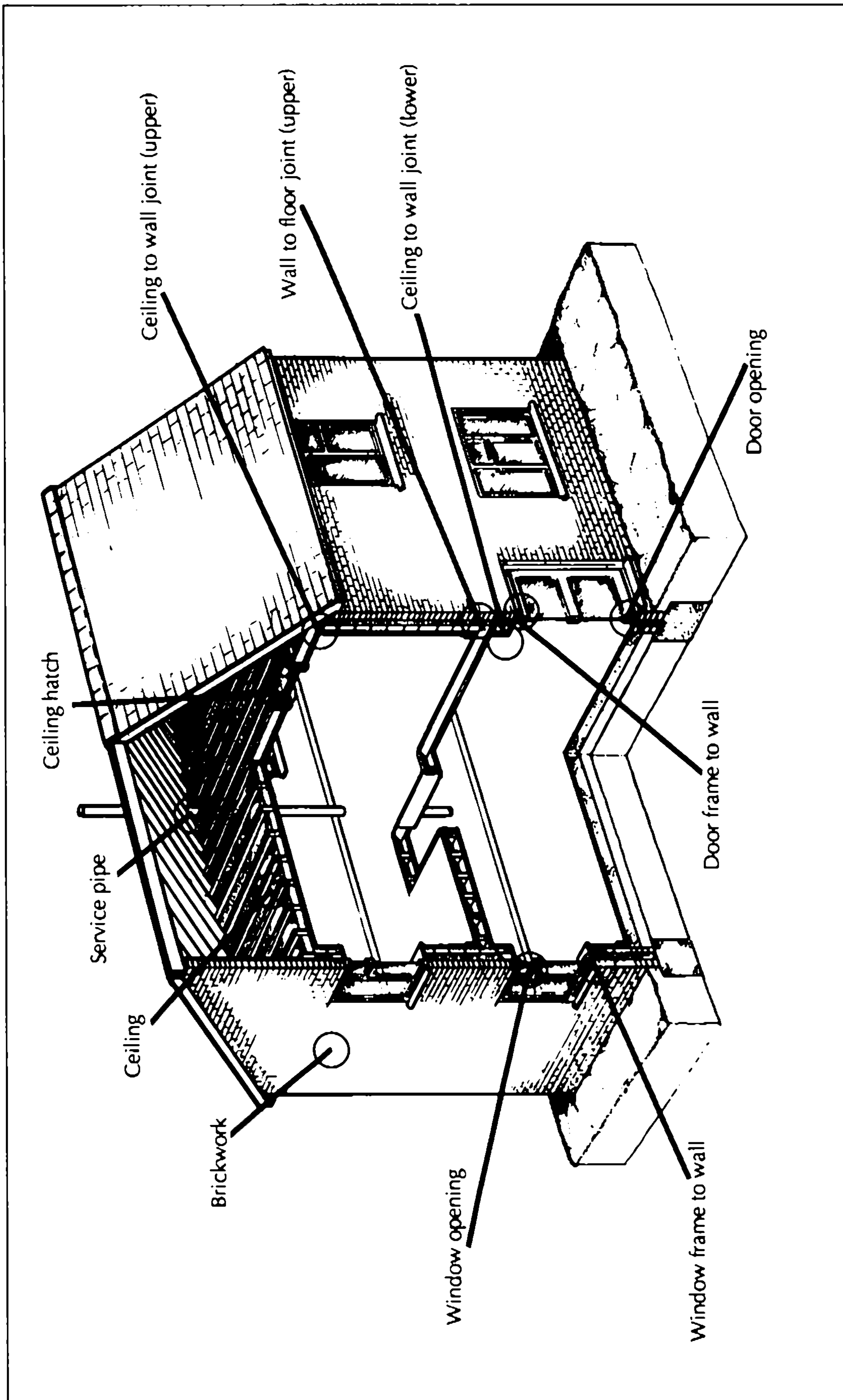


Figure 1.10 Location of Leakage Paths Described in the Worked Example

Table 1.14

Component	Dimension /m^2	Lower quartile: C /$dm^3.s^{-1}.m^{-2}.Pa^{-n}$	Lower quartile: n	Lower quartile: Leakage at 50 Pa /$m^3.h^{-1}$	Lower quartile: Percentage	Median: C /$dm^3.s^{-1}.m^{-2}.Pa^{-n}$	Median: n	Median: Leakage at 50 Pa /$m^3.h^{-1}$	Median: Percentage	Upper quartile: C /$dm^3.s^{-1}.m^{-2}.Pa^{-n}$	Upper quartile: n	Upper quartile: Leakage at 50 Pa /$m^3.h^{-1}$	Upper quartile: Percentage
Ceiling	59	0.042	0.81	212	10.5	0.11	0.75	439	17.0	0.20	0.72	710	17.9
Brickwork	138.8	0.016	0.86	231	11.5	0.018	0.85	250	9.7	0.021	0.84	281	7.1
	Dimension /m	C /$dm^3.s^{-1}.m^{-1}.Pa^{-n}$	n	Leakage at 50 Pa /$m^3.h^{-1}$	Percentage	C /$dm^3.s^{-1}.m^{-1}.Pa^{-n}$	n	Leakage at 50 Pa /$m^3.h^{-1}$	Percentage	C /$dm^3.s^{-1}.m^{-1}.Pa^{-n}$	n	Leakage at 50 Pa /$m^3.h^{-1}$	Percentage
Service pipe	0.63	0.63	0.60	15.0	0.7	0.74	0.60	17.3	0.7	0.84	0.60	19.9	0.5
Ceiling hatch	4	0.64	0.60	96.5	4.8	0.68	0.60	102	4.0	0.75	0.60	113.0	2.9
Ceiling to wall joint (upper)	32	0.45	0.60	542	26.9	0.49	0.60	590	22.9	0.53	0.60	638	16.1
Ceiling to wall joint (lower)	16	0.45	0.60	271	13.4	0.49	0.60	295	11.4	0.53	0.60	319	8.1
Wall to floor joint (upper)	16	0.45	0.60	271	13.4	0.49	0.60	295	11.4	0.53	0.60	319	8.1
Window frame to wall	52	0.053	0.60	104	5.2	0.061	0.60	120	4.6	0.067	0.60	131	3.3
Door frame to wall	12	0.053	0.60	24.1	1.2	0.061	0.60	27.5	1.1	0.067	0.60	30.1	0.8
Window opening	66	0.086	0.60	214	10.6	0.13	0.60	324	12.5	0.41	0.60	1018	25.7
Door opening	12	0.082	0.60	36.7	1.8	0.27	0.60	122	4.7	0.84	0.60	379	9.6
Total				2018	100			2582	100			3958	100
Air changes per hour at 50 Pa				7.5				9.6				14.7	

Part Two

Whole Building Leakage

Whole Building Leakage

2.1 Overview

2.1.0 Introduction

The infiltration characteristics of a building is ultimately a function of building airtightness. This is the sum of the leakage characteristics of all the cracks and gaps formed during the construction of the building. In theory, building airtightness may be inferred by applying to each leakage path, the leakage data presented in the previous section. An alternative method is to establish the airtightness performance by pressure testing, in which the air flow rate through the building is measured for incremental changes in artificially induced pressure. The relationship between pressure and flow is normally represented by the Power Law Equation. Typically, air leakage is expressed in air changes per hour (ach) at an artificially induced pressure of 50 Pa.

$$\text{Air changes per hour at 50 Pa} = \frac{\text{volume flow rate at 50 Pa } (m^3.h^{-1})}{\text{net (internal) building volume } (m^3)}$$

This approach has formed the basis of an increasing number of airtightness Standards. Knowledge of airtightness may be used to provide guidance on infiltration performance and on the suitability of various ventilation strategies.

2.1.1 Scope of Data

The purpose of this Section is to present an analysis of whole building air leakage, based on measurements in over 2700 buildings, the majority of which are dwellings. The objective has been to identify the construction techniques and materials that contribute to airtightness performance and to tabulate these data in a form that may be used for design and evaluation purposes.

2.1.2 Using The Data

Airtightness data may be used in the prediction of infiltration and ventilation rates in buildings. Two methods are illustrated in Figure 2.1. At the most basic level, various studies have shown that average infiltration may be estimated by dividing the air leakage at 50 Pa by a factor of between 10 and 30. (For more details see #3320 (Dubrul, 1988)). Typically, a value of 20 is often used. Since air infiltration is weather dependent and is also influenced by surrounding obstructions, this factor approach may be far from adequate, except for the most rudimentary of design applications. More detailed estimates of infiltration may be derived by distributing the leakage value of the building either uniformly over the external surface area of the building (walls, roof and ventilated floor spaces) or by using known leakage sites. A single zone or multi-zone flow network is then established and incorporated into a zonal air flow model, described in #4917 (Liddament, 1986). These models include both weather and shielding parameters, and therefore provide a more accurate basis for calculation. This approach should provide sufficient accuracy for basic ventilation design.

2.1.3 Standards

Improved airtightness has evolved through the implementation of airtightness requirements. This is specifically the case for Sweden, Norway and for Canadian R2000 homes. Current Standards and recommendations relating to airtightness are presented in Figure 2.3 (Limb, 1994). These show that in addition to parts of Scandinavia and North America, Belgium, the Netherlands and Switzerland have now introduced recommended airtightness standards according to ventilation approach. Where requirements exist, design and construction should be in accordance with the relevant requirements.

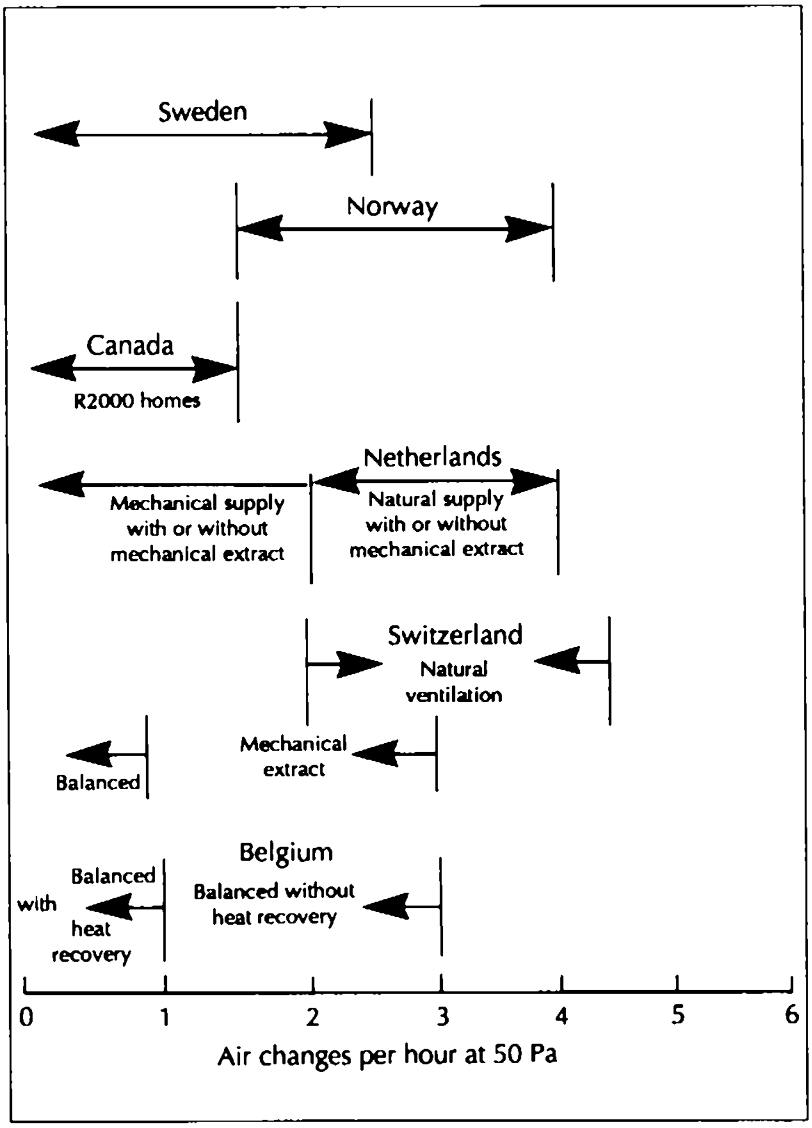


Figure 2.3 Airtightness Recommendations and Standards

2.1.4 Presentation Of Data

This analysis is presented as a series of data sheets which provide a basic leakage value at 50 Pa for a range of generic forms of building construction and type. Factors which tend to increase or decrease the basic leakage value are then listed with suggested correction values. By working through this list, the user can derive an overall leakage value that provides the closest match to the building under consideration. All windows, vents, flues and other purpose provided openings are assumed to be sealed. Allowance for such openings can be made by making reference to the component leakage section.

These are guideline values only. It is important that the user takes into account any other obvious construction defects or parameters before applying the data. Above all, the data should only be applied in the absence of more accurate information. Furthermore, estimates should be verified on completion of construction or retrofit.

Much of the data used in this analysis is based on measurements made in single family and multi-family dwellings. While data from other sources were limited, data sheets for other construction types have been prepared.

Many countries have undertaken airtightness measurements in representative samples of buildings. Typical examples for dwellings are presented in Figure 2.4. Mean values and standard deviations are given in Table 2.1 for the same sets of data on which the distributions shown in Figure 2.4 are based. In almost all cases, the range in airtightness values was found to be far too broad to provide simple guidance on average airtightness. It has therefore been important to identify the individual building characteristics that contributed to airtightness performance and to identify the generic types of construction that display a typical airtightness pattern. As a general rule, buildings tend to be constructed to a higher airtightness specification in severe climatic regions. This is illustrated in Figure 2.5 for regions of Canada, where airtightness is much greater in the severe Prairies Region than in the Pacific Region. The numbers printed after the legends in Figure 2.5 indicate the size of the samples from which the arithmetic means and standard deviations were calculated. These were then used to plot a log-normal distribution curve for each Canadian region.

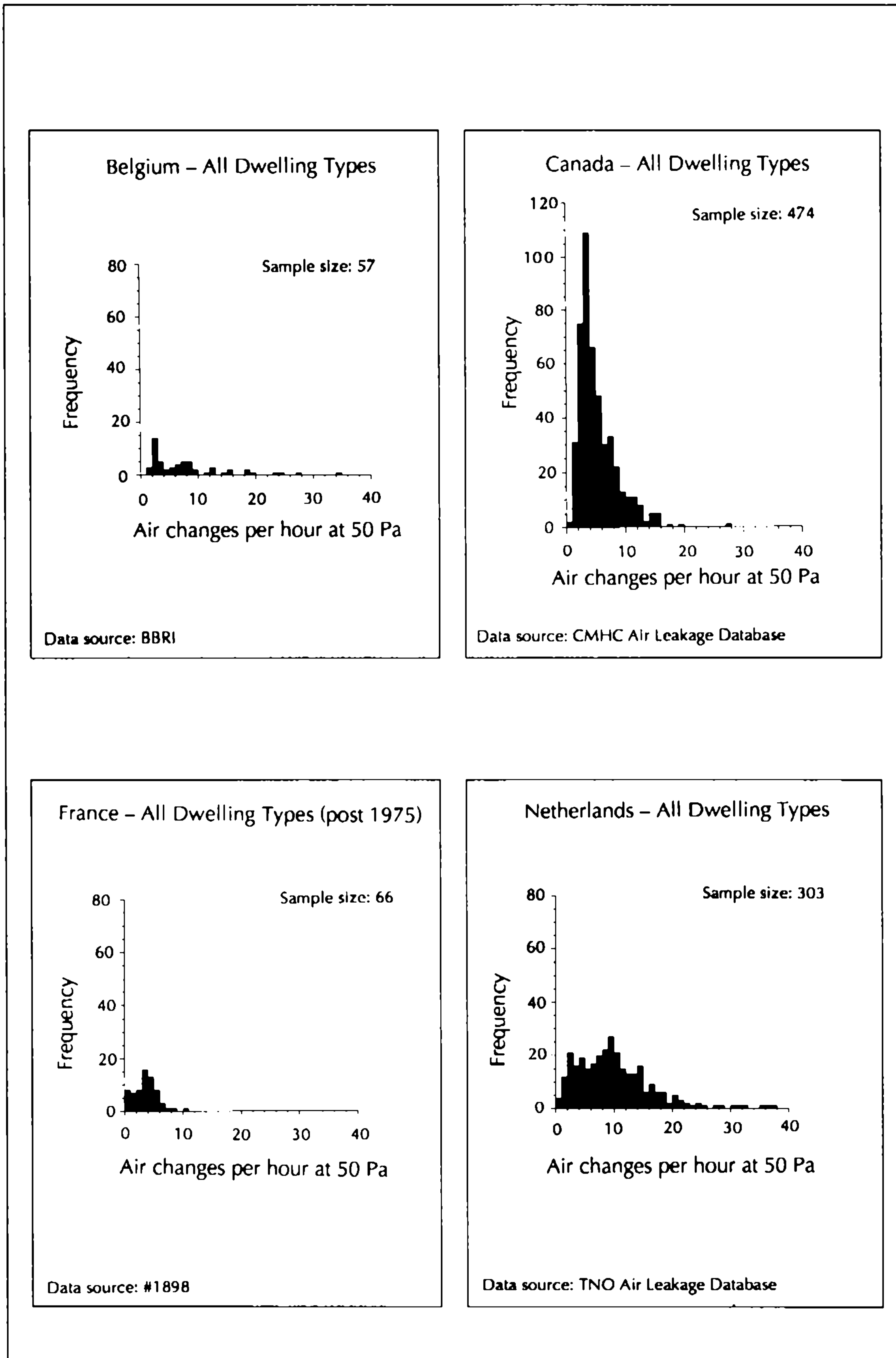


Figure 2.4 Comparison of Whole Building Leakage Values at 50 Pa

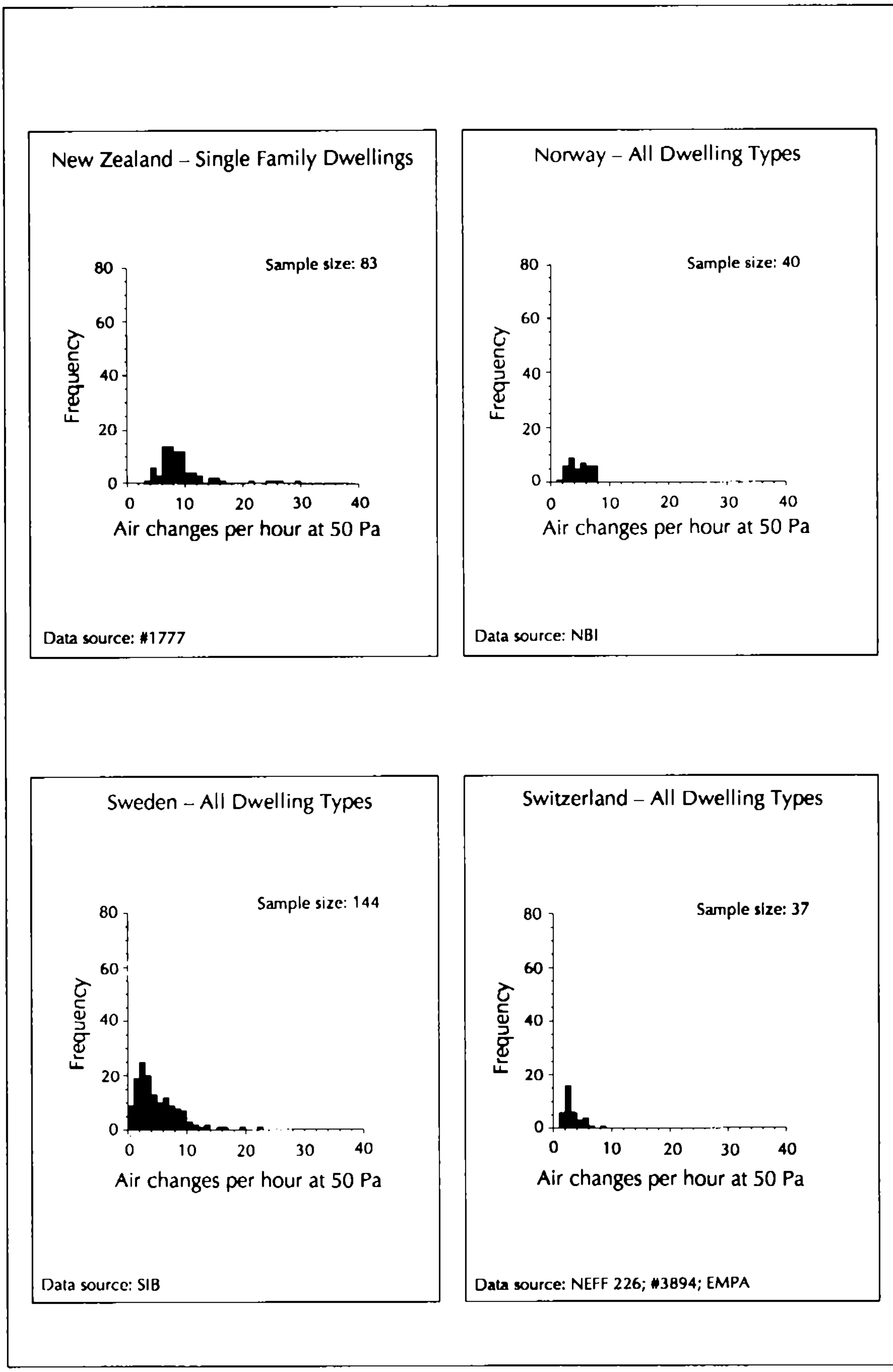


Figure 2.4 Comparison of Whole Building Leakage Values at 50 Pa

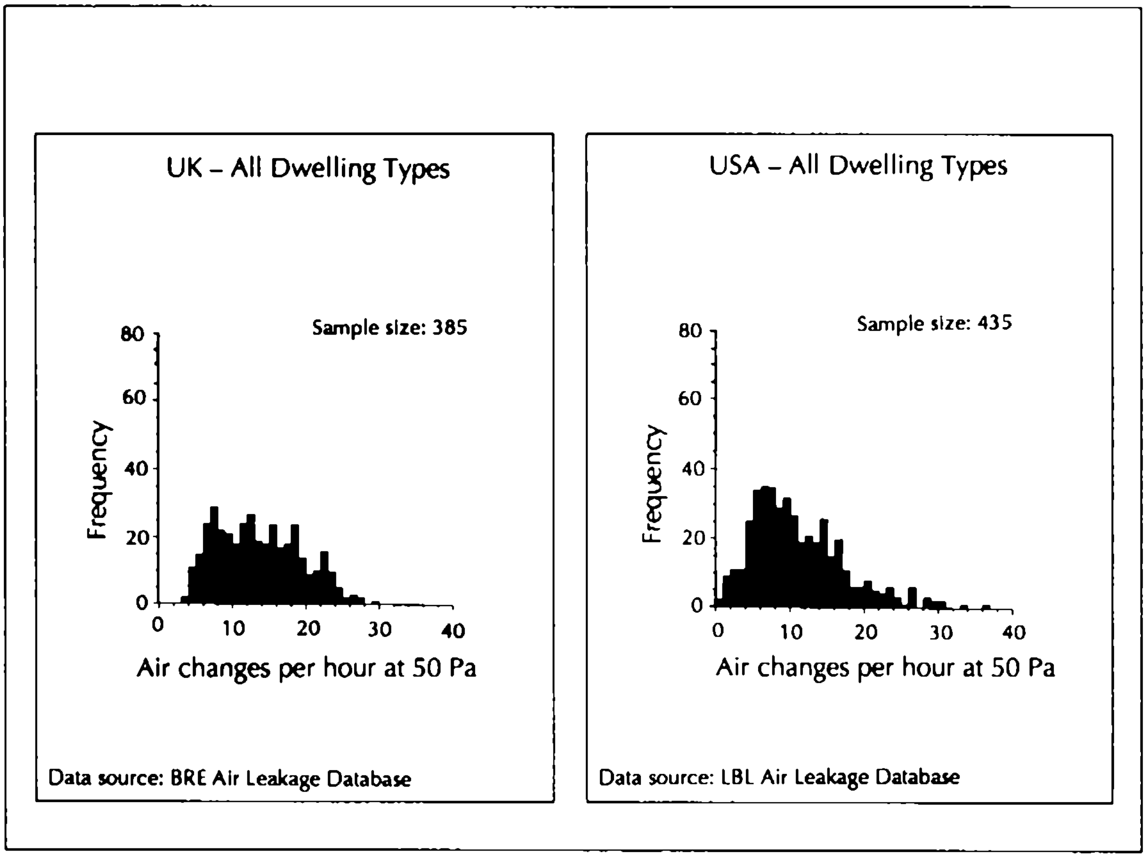


Figure 2.4 Comparison of Whole Building Leakage Values at 50 Pa

Table 2.1

Country	Air changes per hour at 50 Pa		
	Arithmetic mean	Standard deviation	Sample size
Belgium	8.23	7.22	57
Canada	5.31	3.28	474
France	3.59	2.03	66
Netherlands	10.14	6.71	303
New Zealand	9.48	4.86	83
Norway	4.95	1.83	40
Sweden	5.10	3.81	144
Switzerland	3.22	1.48	37
UK	13.62	5.71	385
USA	11.18	6.23	435

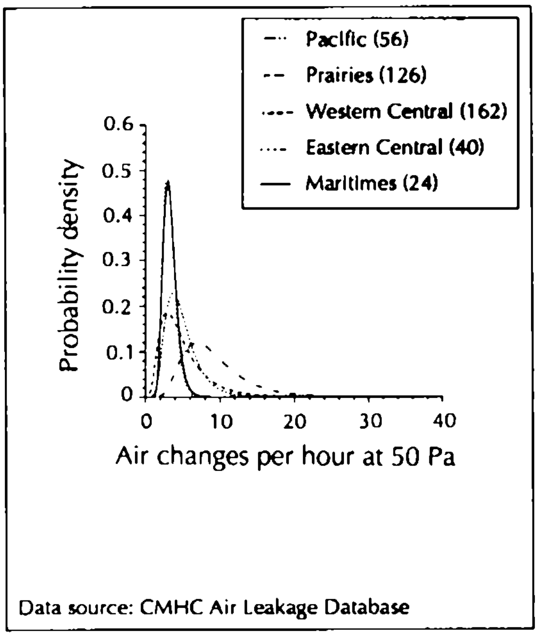
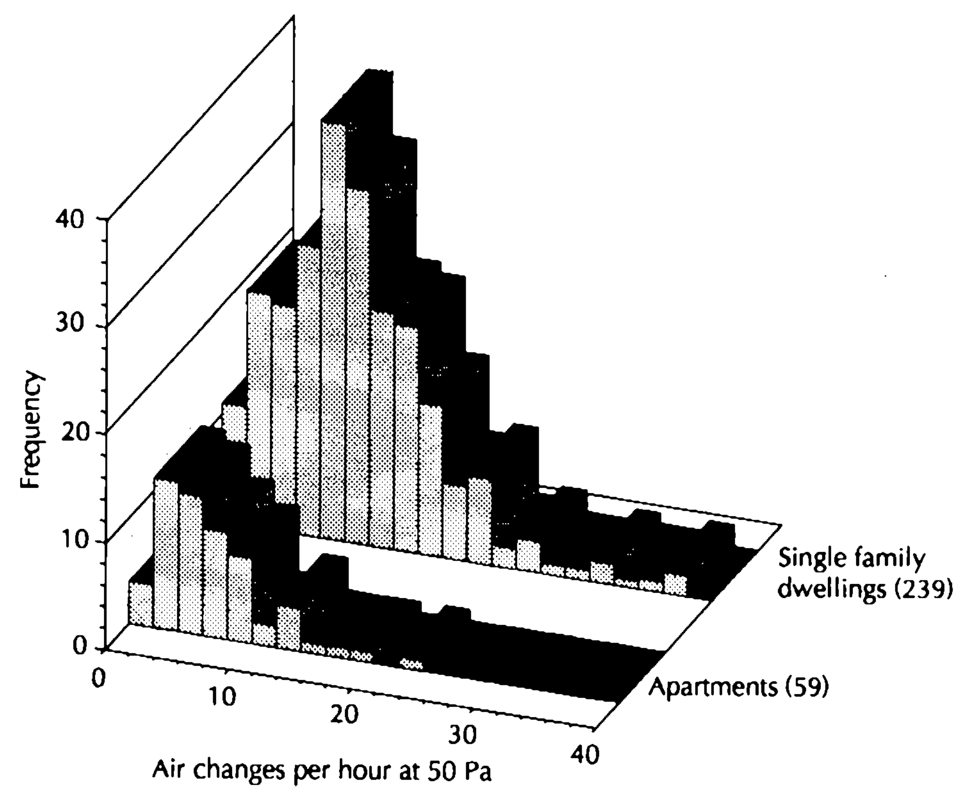


Figure 2.5 Approximate Airtightness Distributions for Regions Across Canada

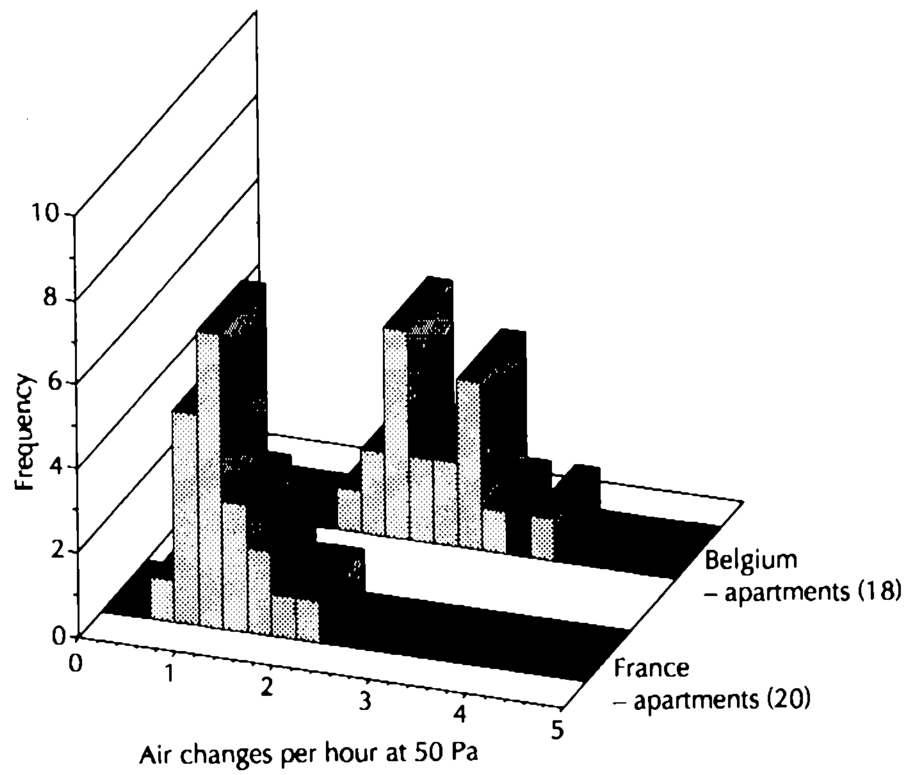
2.1.5 Factors Influencing Airtightness

Airtightness is particularly influenced by the type of construction. A cellular concrete apartment block, for example, in which the main path of leakage is through the front and rear facades, tends to be tighter than a single family dwelling of complex floor plan. An example of Dutch data is presented in Figure 2.6 (i), in which apartment building airtightness is consistently greater than that of the overall airtightness patterns of buildings. The main reason for this difference is that most apartments do not have roof panels, which are normal for single family dwellings.



Data source: TNO Air Leakage Database

Figure 2.6 (i) Comparison of Apartment Building Airtightness with Single Family Dwellings in the Netherlands



Data source: BBRI

Figure 2.6 (ii)

Figure 2.6 (ii) shows an airtightness comparison of two apartment buildings of similar construction type, one in Belgium and the other in France. The data refer to the airtightness of individual dwellings in each building.

On the other hand, timber frame construction can have a very broad range of airtightness, which varies between more than 20 ach at 50 Pa for American 'ranch house' type buildings to less than 1 ach at 50 Pa for Canadian R2000 homes. Much depends on the correct use of an air vapour barrier and on the caulking of joints. In the United Kingdom, relatively high permeabilities can be associated with a highly jointed brick and block construction combined with substantial penetration of the inner cavity by floor joists and service penetrations. Open cellular cavity insulation provides negligible impedance to air movement, while chimney stacks and ventilated suspended floors further contribute to leakiness. While a substantial proportion of UK housing could benefit from improved airtightness, a tradition towards 'adventitious' ventilation means that improvements to purpose provided ventilation would also need to be applied to any retrofit measure.

Building age (year of construction) has some influence on airtightness. Modern buildings constructed to new airtightness Standards have a particular influence, although, for older buildings, the variation is less certain. Examples of building airtightness for dwellings constructed throughout the 20th century are illustrated for the Netherlands and the United Kingdom in Figures 2.7 (i) and 2.7 (ii) below. The numbers printed at the foot of the bars in these figures indicate the size of the samples from which the arithmetic means were calculated. The standard deviations of each data class are also presented in the figures.

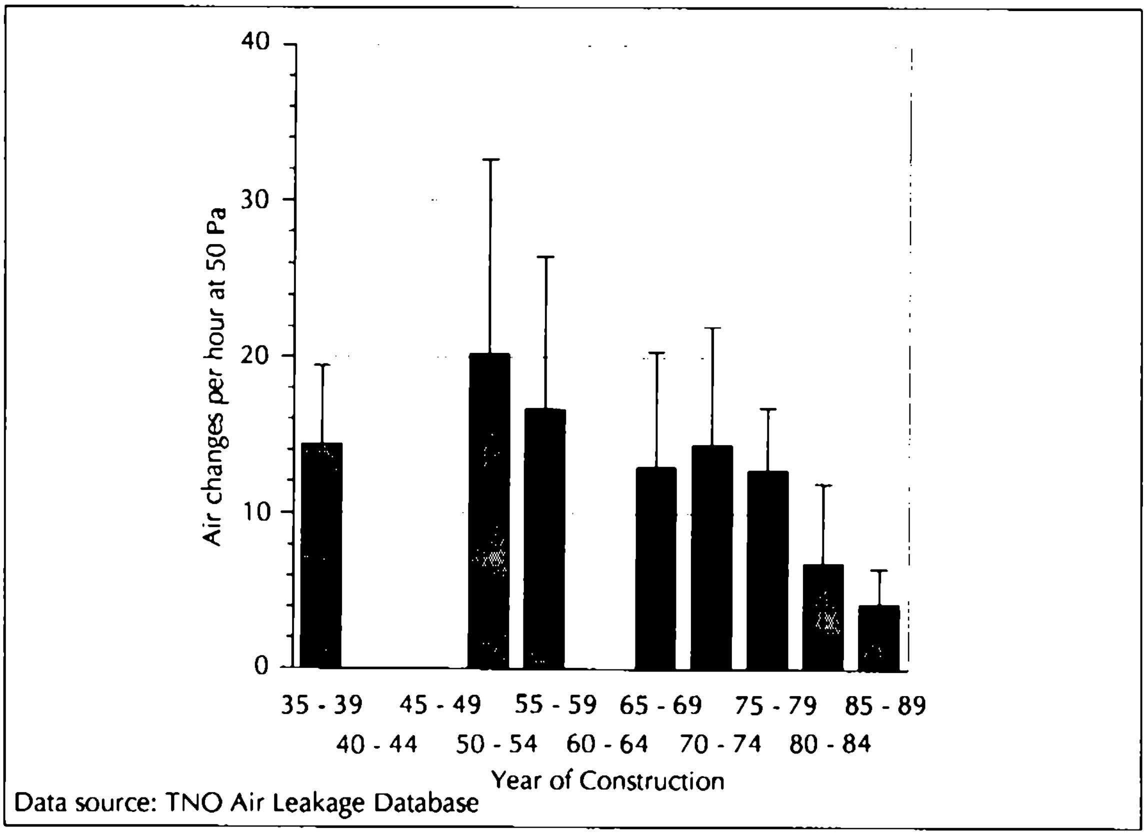


Figure 2.7 (i) Netherlands – All Dwelling Types

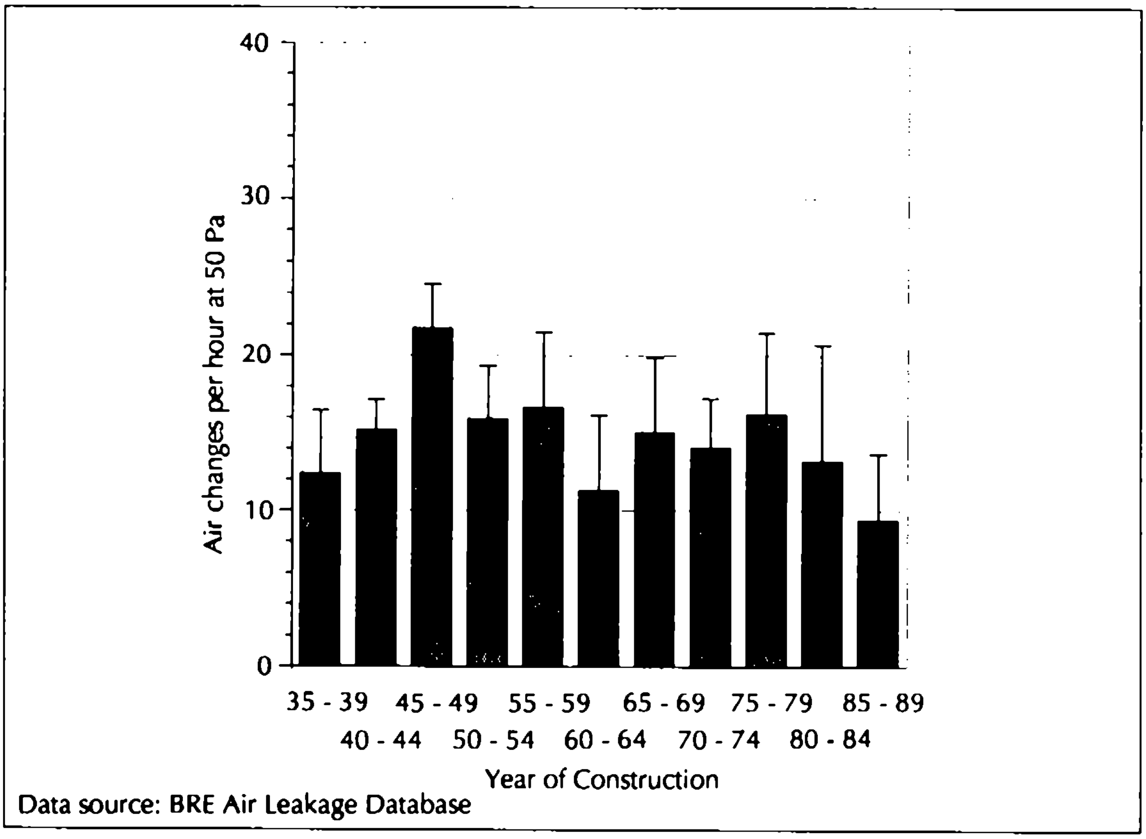
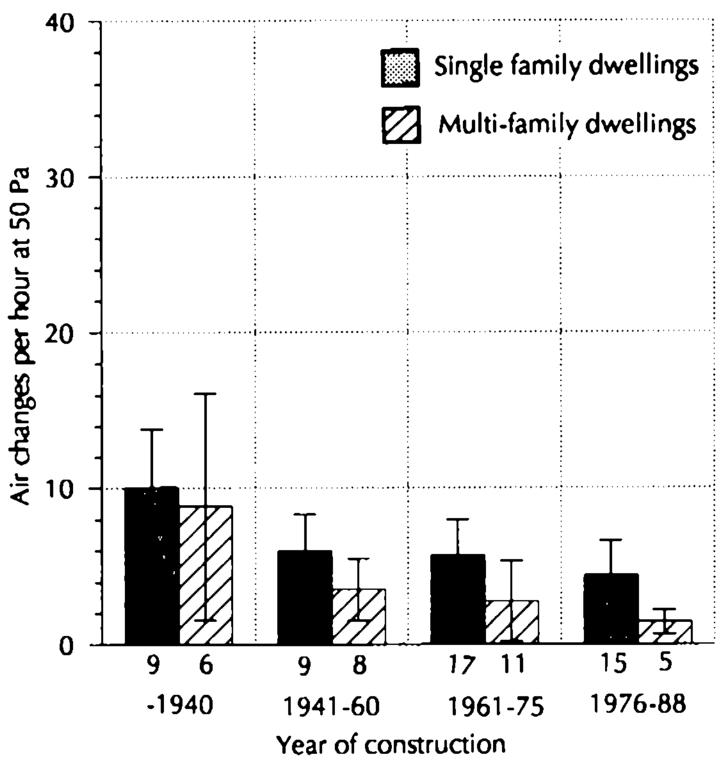


Figure 2.7 (ii) UK – All Dwelling Types

Figure 2.7 (iii), based on Swedish data, additionally compares building age for both single and multi-family dwellings.



Data source: SIB

Figure 2.7 (iii) Sweden – All Dwelling Types

The Generic forms of construction, identified as having a characteristic airtightness performance include:

- timber frame construction (low rise),
- brick and block construction (low rise),
- concrete/curtain wall construction (high rise),
- concrete panel (industrial), or
- metal panel (industrial).

These have been used to form the basis of data sheets.

Within each generic form of construction, wide variations in airtightness are possible. Factors contributing to reduced airtightness include:

- absence of air barrier,
- presence of a ventilated basement or crawl space,
- complex floor plan,
- non-weatherstripped windows and doors,
- unsealed service penetrations,
- basement furnace and/or open flue,
- ducted air system passing through unconditioned space,
- poor join/sealing,
- loading bay doors, and
- age of building.

Other measures contribute to increased airtightness. These include:

- gasketed windows and doors,
- semi-detached (duplex) or centre terrace location,
- plastered or rendered inner walls, and
- gasketed or caulked joints.

'Correction' values to allow for these contributory parameters are presented within Section 2.2.

2.1.6 Characteristic Flow Exponent

A further aspect of importance is the flow exponent, since this can have a marked effect on flow rate as the pressure across an opening increases. Measurements from Canada, Netherlands, New Zealand, UK and USA can be seen in Figure 2.8 (i). Exponents based on data from these sources show no clear correlation and, instead, are normally distributed about a mean value of approximately 0.66. (In this case the actual mean equals 0.65.) The distribution of flow exponents is shown in Figure 2.8 (ii). For this reason a flow exponent of 0.66 has been assumed in all instances.

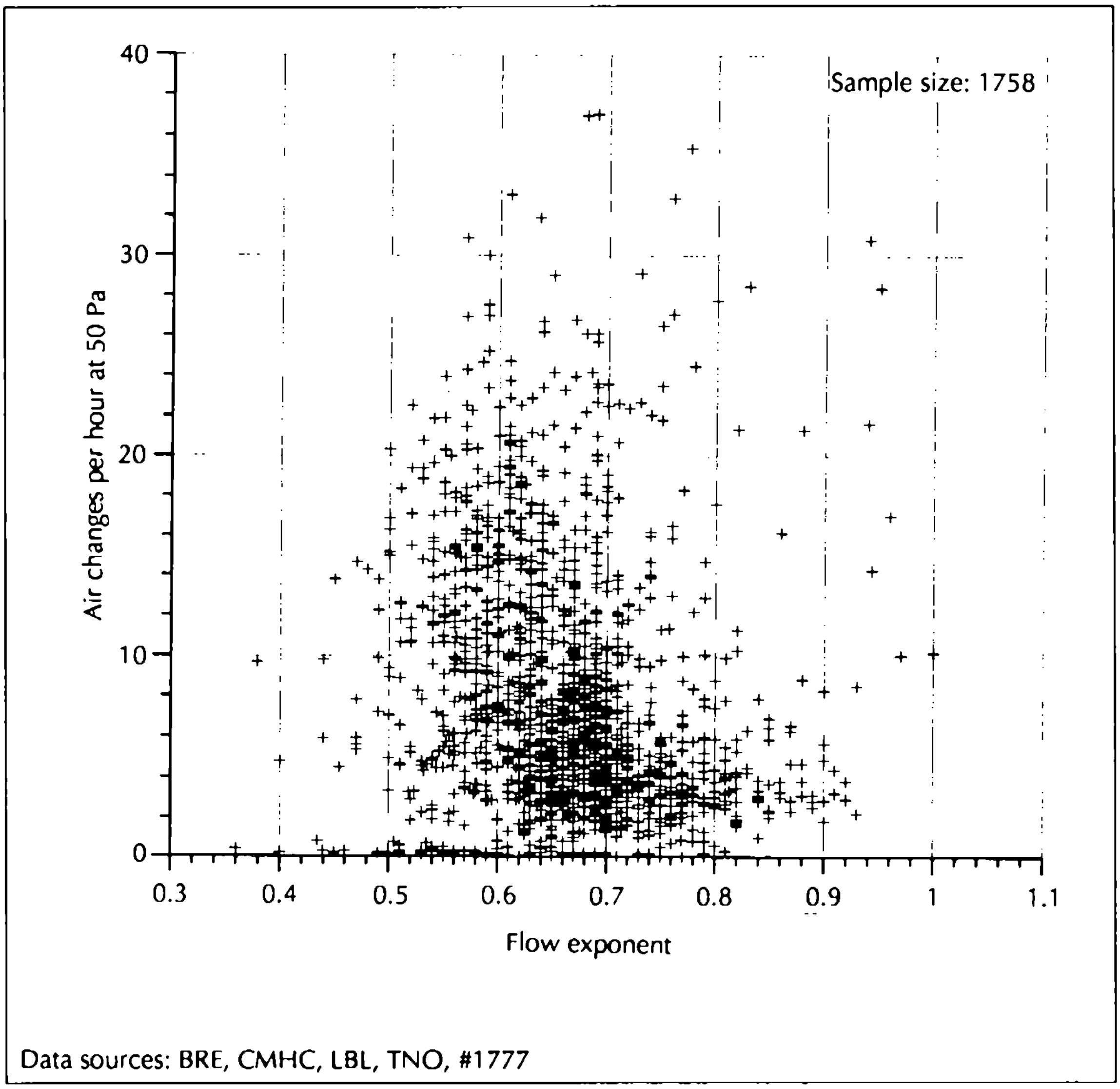


Figure 2.8 (i)

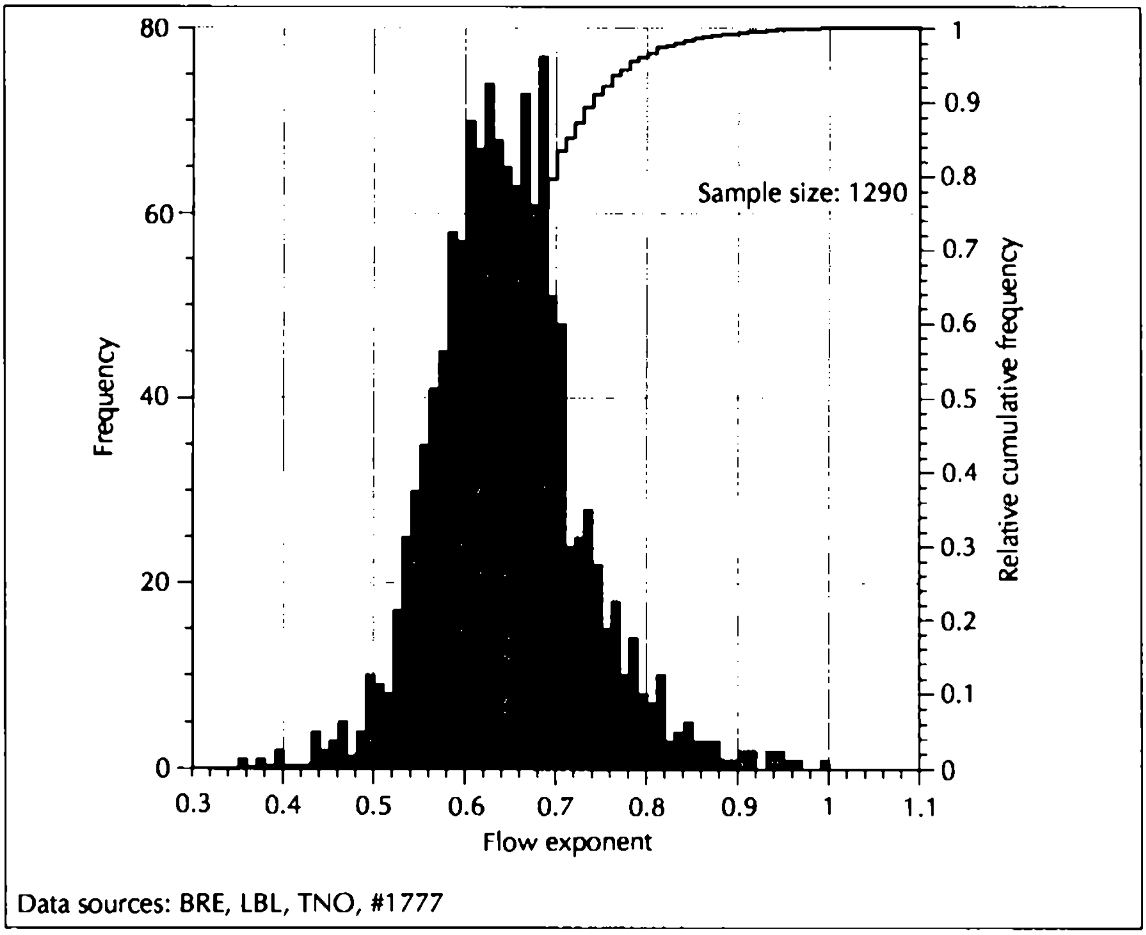

80
60
40
20
0
Frequency
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Flow exponent
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Relative cumulative frequency
Sample size: 1290
Data sources: BRE, LBL, TNO, #1777

Figure 2.8 (ii)

2.2 Whole Building Leakage Data Tables

2.2.0 Using The Data Sheets

Data sheets are presented in Tables 2.2 (i) to 2.2 (v). However, these only provide approximate guidance.

The user should first select a sheet which is most appropriate to the building construction type of interest. For each sheet a representative leakage value at 50 Pa is presented. The user should add and subtract to this airtightness value according to the leakage parameters appropriate to the building as listed in the Table. On completion an estimated leakage value will be derived.

An example is presented in Table 2.2 (vi). It is a semi-detached low-rise building of timber frame construction. The door and window frames are ungasketted, but the windows and doors themselves have been weatherstripped. There is no (polythene) vapour barrier present in the building structure and all service penetrations have been left unsealed. The building has a ducted air circulation system. The ground floor is of solid concrete construction and has a simple rectangular plan. The example indicates that the airtightness of the particular building described could be estimated to equal 8.5 ach.

Table 2.2 (i) Building Type: Timber Frame Insulated Construction, Low Rise

Basic Leakage (at 50 Pa):		3 ach
Additions:		
No Polyethylene Barrier	(+3 ach)	....
Basement/Crawl Space/Suspended Floor	(+1 ach)	....
Complex (Non Rectangular) Floorplan	(+1 ach)	....
Non-weatherstripped Windows and Doors	(+1 ach)	....
Unsealed Service Penetrations	(+1 ach)	....
Basement Furnace/Open Flue	(+1 ach)	....
Ducted Air Circulation System	(+2 ach)	....
Subtractions:		
Semi-Detached (Duplex)	(–0.5 ach)	....
Centre Row/Terrace	(–1 ach)	....
Gasketed Window/Door Frames	(–1 ach)	....
	Total:	....

Other Details (User Supplied):

Flow Exponent, *n*, (0.66)	=
Building Volume	=
Exposed Surface Area	=
Flow Coefficient, *C*, /Unit Area	=

Table 2.2 (ii) Building Type: Brick and Block Construction, Low Rise

Basic Leakage (at 50 Pa):		8 ach
Additions:		
Suspended Floor	(+1 ach)	....
Open Flue	(+1 ach)	....
Complex (Non Rectangular) Floorplan	(+1 ach)	....
Non-weatherstripped Windows and Doors	(+1 ach)	....
Unsealed Service Penetrations	(+1 ach)	....
Subtractions:		
Semi-Detached (Duplex)	(–1 ach)	....
Centre Row/Terrace	(–2 ach)	....
Cavity Wall Insulation	(–1 ach)	....
Plastered/Rendered Walls	(–1 ach)	....
Gasketed Window/Door Frames	(–1 ach)	....
	Total:	....
Other Details (User Supplied):		
Flow Exponent, n, (0.66)	=	
Building Volume	=	
Exposed Surface Area	=	
Flow Coefficient, C, /Unit Area	=	

Table 2.2 (iii) Building Type: Concrete/Curtain Wall Construction, High Rise

Basic Leakage (at 50 Pa):			3 ach
Additions:			
Poor Joint Sealing	(+5 ach)		....
Complex (Non Rectangular) Floorplan	(+1 ach)		....
Non-weatherstripped Windows and Doors	(+1 ach)		....
Unsealed Service Penetrations	(+1 ach)		....
Ducted Air Circulation System	(+2 ach)		....
Subtractions:			
Plastered/Rendered Walls	(–1 ach)		....
Gasketed Window/Door Frames	(–1 ach)		....
		Total:	....
Other Details (User Supplied):			
Flow Exponent, *n*, (0.66)	=		
Building Volume	=		
Exposed Surface Area	=		
Flow Coefficient, *C*, /Unit Area	=		

Table 2.2 (iv) Building Type: Concrete Panel – Industrial

Basic Leakage (at 50 Pa):		10 ach
Additions:		
Poor Joint Sealing	(+5 ach)	....
Complex (Non Rectangular) Floorplan	(+2 ach)	....
Non-weatherstripped Windows and Doors	(+1 ach)	....
Unsealed Service Penetrations	(+3 ach)	....
Ducted Air Circulation System	(+3 ach)	....
Subtractions:		
Plastered/Rendered Walls	(–3 ach)	....
Gasketed Window/Door Frames	(–1 ach)	....
Weatherstripped Loading Doors	(–3 ach)	....
	Total:	....

Other Details (User Supplied):

Flow Exponent, *n*, (0.66)	=
Building Volume	=
Exposed Surface Area	=
Flow Coefficient, *C*, /Unit Area	=

Table 2.2 (v) Building Type: Metal Panel – Industrial

Basic Leakage (at 50 Pa):		12 ach
Additions:		
Poor Joint Sealing	(+5 ach)	....
Complex (Non Rectangular) Floorplan	(+2 ach)	....
Non-weatherstripped Windows and Doors	(+1 ach)	....
Unsealed Service Penetrations	(+3 ach)	....
Ducted Air Circulation System	(+3 ach)	....
Subtractions:		
Plastered/Rendered Walls	(–3 ach)	....
Gasketed Window/Door Frames	(–1 ach)	....
Weatherstripped Loading Doors	(–3 ach)	....
	Total:	....
Other Details (User Supplied):		
Flow Exponent, *n*, (0.66)	=	
Building Volume	=	
Exposed Surface Area	=	
Flow Coefficient, *C*, /Unit Area	=	

Table 2.2 (vi) Building Type: Timber Frame Insulated Construction, Low Rise

Basic Leakage (at 50 Pa):		3 ach
Additions:		
No Polyethylene Barrier	(+3 ach)	+3 ach
Basement/Crawl Space/Suspended Floor	(+1 ach)	
Complex (Non Rectangular) Floorplan	(+1 ach)	
Non-weatherstripped Windows and Doors	(+1 ach)	
Unsealed Service Penetrations	(+1 ach)	+1 ach
Basement Furnace/Open Flue	(+1 ach)	
Ducted Air Circulation System	(+2 ach)	+2 ach
Subtractions:		
Semi-Detached (Duplex)	(–0.5 ach)	–0.5 ach
Centre Row/Terrace	(–1 ach)	
Gasketed Window/Door Frames	(–1 ach)	
	Total:	8.5 ach
Other Details (User Supplied):		
Flow Exponent, *n*, (0.66)	=	
Building Volume	=	
Exposed Surface Area	=	
Flow Coefficient, *C*, /Unit Area	=	

Part Three

Wind Pressure Evaluation

Wind Pressure Evaluation

3.1 Overview

3.1.0 Introduction

The values presented in this section must only be regarded as approximate and therefore, if more accurate design information is required, recourse to specific wind tunnel or full scale measurements will have to be considered. The intention of these data sets is to provide the user with an indication of the range of pressure coefficient values which might be anticipated for various building orientations and for various degrees of shielding.

The data are presented as follows:

Estimation Of Site Wind Velocity

Tables 3.1 and 3.2 contain terrain coefficients for converting wind velocity measured at an open site, at a level of 10 m, to roof height values, recommended by BSI and ASHRAE respectively.

Tables 3.3 and 3.4 contain terrain and shielding coefficients for use in the LBL model.

High Rise

Data depicted in Figures 3.3 (i) to 3.3 (iii) are based on data derived from #441 (Bowen, 1976). They show the distribution of pressure coefficients for a tall building, shielded by surrounding low-rise buildings (of 1/6 of its height). Wind approach angles of 0°, 45° and 90° are included.

Figure 3.4 shows analysis of the data given in #441, presented in #85 (Shaw, 1979). The effect of the height of surrounding shielding can be seen from it.

Figures 3.5 (i) and 3.5 (ii) are based on a sample of unpublished Building Research Establishment (BRE) data, indicating the effect of a lightwell on wind pressure coefficients.

Low Rise

Tables 3.5 (i) to 3.5 (vi) cover low-rise buildings of typically no more than three storeys. Three degrees of shielding are considered. These are:

open countryside – no obstructions – exposed,

rural surroundings – some obstructions – semi-sheltered, and

urban – building surrounded on all sides by obstructions of similar size – sheltered.

Data are presented for each face and for the roof surface, where roof pitch angles of

<10°,

10°-30°, and

>30°.

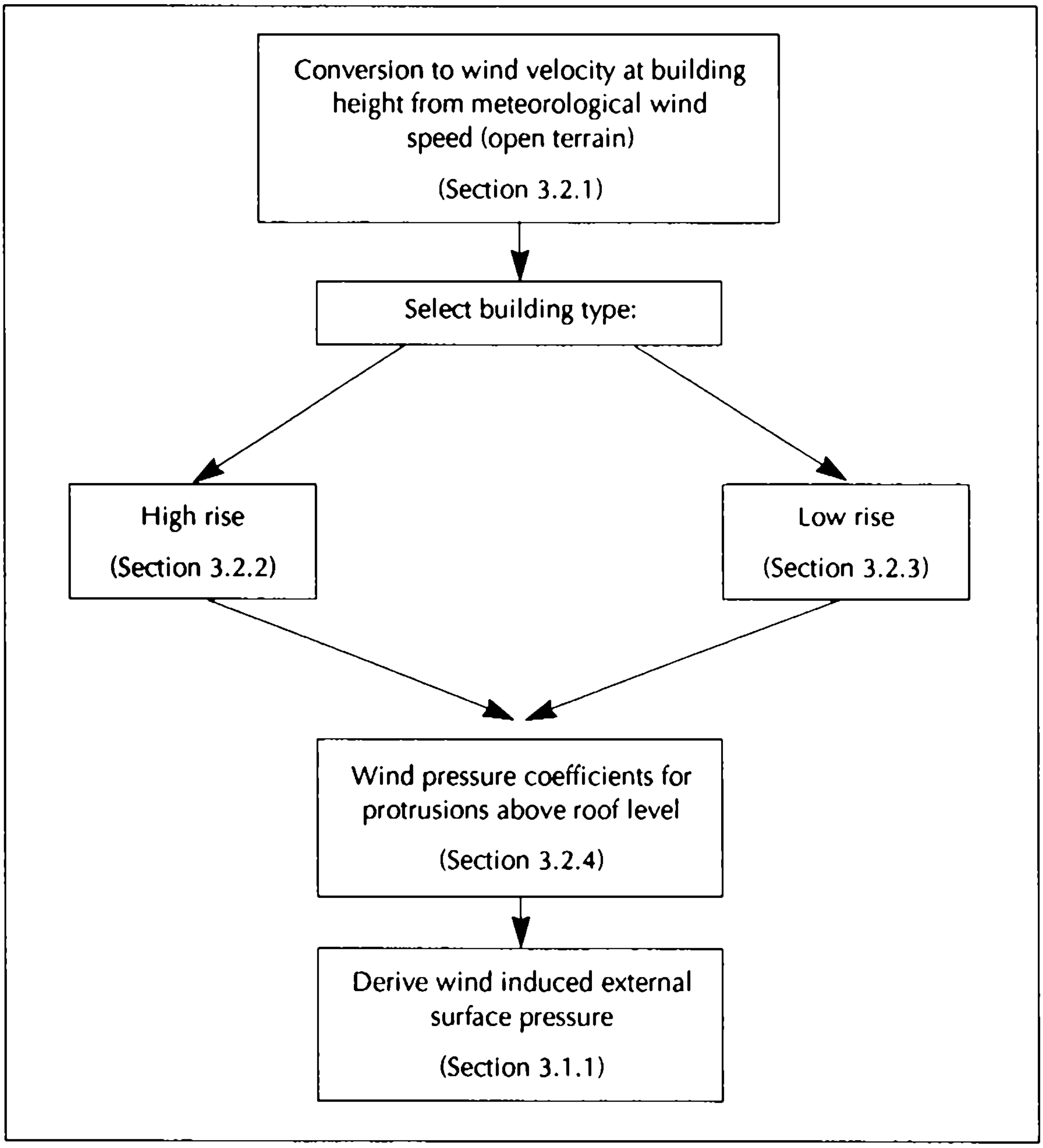
are considered.

Tables 3.5 (i) to 3.5 (iii) cover data for buildings of length to width ratios of 1:1 and Tables 3.5 (iv) to 3.5 (vi) cover data for length to width ratios 2:1.

Above Roof Level

Pressure coefficient data given in Figure 3.6 apply to flue openings situated above roof level. They are for sheltered conditions with a reference wind velocity taken at roof height above ground level.

Figure 3.7 presents a graphical method for the siting of flue openings to prevent back draughting.



3.1.1 Theoretical Outline

For the purpose of determining the airflow through the fabric of a building, it is necessary to know the indoor to outdoor pressure difference. This is partly determined by the action of the wind on the building, so surface pressures due to wind effects on the fabric need to be derived.

Even at a smaller scale than the dimensions of a building, atmospheric wind is very turbulent in nature. Any rough surfaces or sharp edges, around which it passes, result in the formation of dissipative eddies and separation of the air flow currents. This turbulent wind can give rise to transient effects such as flow with rapidly changing velocity (involving both magnitude and direction) and possibly even completely reversing its direction of flow. Thus under certain circumstances, it is feasible that the mean surface pressure vanishes, tending to zero, while the root mean square variation of the surface pressure is actually greater than zero. In this way single-sided infiltration and exfiltration can occur at leakage sites on the building fabric.

The mean surface pressure $\bar{P}$, which acts at a location on a building due to the wind, can be regarded as a linear combination of two reference pressures, one static and the other, dynamic. The static reference pressure is usually taken to be local atmospheric pressure P_{at} in the free stream, above the boundary layer at the building's location. The dynamic reference pressure is conventionally taken to equal the pressure P_r due to the wind, when it is undisturbed by, but at the same height as the building, r.

$$P_r = \frac{1}{2} \rho v_r^2,$$

where

P_r = pressure due to the wind (Pa),

v_r = mean wind velocity at the height of the building (m.s^{-1}),

ρ = air density (kg.m^{-3}).

Making the assumption that local atmospheric pressure remains constant,

$$\bar{P} = P_{at} + C_{\bar{p}} P_r.$$

Substituting for P_r,

$$\bar{P} = P_{at} + C_{\bar{p}} \frac{1}{2} \rho v_r^2,$$

where values of the dimensionless coefficient $C_{\bar{p}}$ are to be determined for different locations on the building. Rearranging this gives

$$C_{\bar{p}} = \frac{\bar{P} - P_{at}}{\frac{1}{2} \rho v_r^2}.$$

The $C_{\bar{p}}$ values are only valid for a particular wind angle, which is expressed relative to the orientation of the building. They also only apply for a particular degree of surrounding shielding. So, for example, in general most of the pressure coefficients for a tall building, in the vicinity of low rise buildings, will be higher than the corresponding ones for a similar tall building, surrounded by buildings of comparable height. In addition they vary according to the spatial separation of nearby obstructions.

Another related wind pressure coefficient can also be defined,

$$C_{p'} = \frac{P'}{\frac{1}{2}\rho v_r^2}$$

where

P' = root mean square variation of the pressure about the mean pressure $\bar{P}$.

P' gives an indication of the deviation from the mean pressure $\bar{P}$ which might be encountered.

For many ventilation rate calculations effects such as single-sided ventilation are neglected. Therefore the coefficient $C_{p'}$ will not be discussed further here, but it is relevant to mention that the degree of surrounding shielding affects the values of $C_{\bar{p}}$ and $C_{p'}$ in different ways. Whilst the effects of shielding can dramatically reduce the mean values of the wind pressure coefficients, the $C_{p'}$ pressure coefficients can remain mostly unaffected.

3.2 Wind Pressure Evaluation Data

3.2.1 Estimation Of Site Wind Velocity From Meteorological Data

It is important to note that the dominating term in the determination of wind induced surface pressure is not the value of the pressure coefficient, but the wind velocity at building height. This is because the pressure varies not linearly but with the square of the velocity. For this reason accurate estimation of site wind velocity from meteorological data is necessary. (Site wind velocity applies to the terrain in which the building is standing.)

In the first instance measured data from a meteorological station must be used to calculate the wind velocity above the boundary layer. However, in general, data concerning free stream velocity above the station can only be extrapolated to the site of interest using wind velocity profile laws and roughness parameters (examples of which are given below), when the free stream is unchanged by the underlying topography. (The relevant location lies within the representative area of the meteorological station.) Otherwise it is necessary to determine the free stream velocity above the building location by wind tunnel studies.

Once the free stream velocity above the building has been derived, then a wind velocity profile law and appropriate roughness parameter can be used to estimate the wind velocity at the building height.

The influence of the terrain roughness depends upon the wind direction. This arises due to the varied terrain types over which the wind might pass, when it originates from different directions. Additionally, in a region without homogeneous topography, there are no areas where a boundary layer can develop fully according to one roughness type. The actual boundary layer has a profile which results from the superposition of the layers resulting from the constituent roughness types.

Two different types of velocity profile are presented below, neither of which are universally applicable:

A *power law* wind velocity profile is sometimes used. This is given by

$$\frac{\bar{v}_z}{\bar{v}_\delta} = \left(\frac{z}{\delta}\right)^a$$

where

z = height above ground (m),

δ = atmospheric boundary layer thickness (m),

$\bar{v}_z$ = mean wind velocity at height z (m.s^{-1}),

$\bar{v}_\delta$ = mean free stream velocity (m.s^{-1}),

a = roughness parameter dependent on terrain. (See Tables 3.1 and 3.2.)

This empirical law can be applied in non-convective conditions, but not in circumstances where the small-scale topography causes local wind accelerations. Consequently any changes in ground height must be gradual for this approach to be valid.

Another estimation approach is to use a *logarithmic* wind velocity profile,

$$\bar{v}_z = \frac{v_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

where

ln (...) denotes the natural logarithm,

z = height above ground (m),

$\bar{v}_z$ = mean wind velocity at height z (m.s^{-1}),

v_* = friction velocity (m.s^{-1}) = $\sqrt{\dfrac{\text{surface drag per unit area}}{\text{density}}}$

κ = the Karman constant (approximately 0.4),

z_0 = the roughness length (m).

Values of z_0 range from about 0.0002 m for the open sea and 0.25 m for rural land with few large obstacles to greater than 2 m in city centres.

It is considered that the logarithmic profile law is only valid for values of z such that $z > 20z_0$. This means that for example, a reference velocity cannot be deduced for a reference height of 10 m in too rough a terrain such as a village (or worse), using this particular law.

In wooded areas or city centres, a *displacement height* d is employed to introduce a datum ground level at 0.5 ... 0.75 of the height of the obstacles. The logarithmic profile then becomes

$$\bar{v}_z = \frac{v_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right)$$

This gives a more realistic description of the wind behaviour above the closely spaced obstructions.

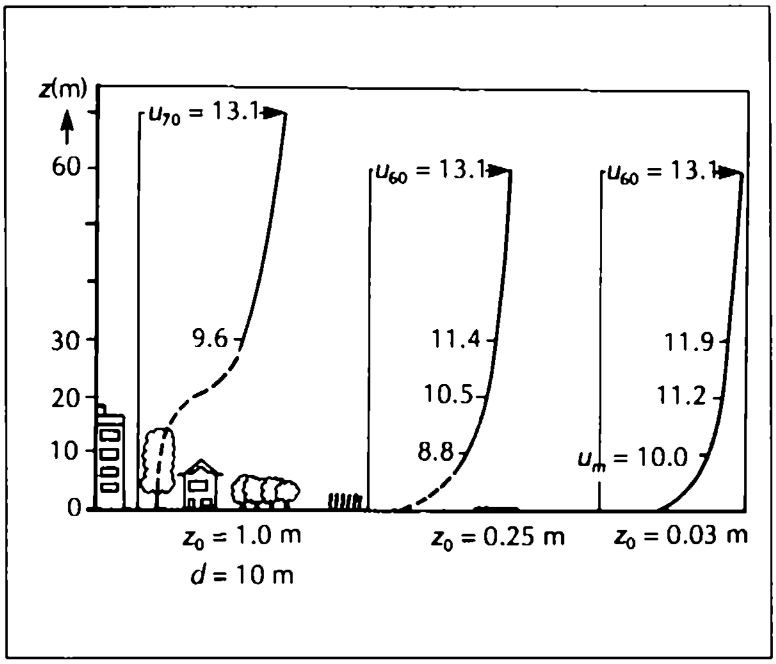


Figure 3.1

Figure 3.1 shows logarithmic velocity profiles for three example roughness lengths (1 m, 0.25 m and 0.03 m). In the first of these, a displacement height of 10 m is used. The free stream velocity at 60 m above (datum) ground level is 13.1 m.s^{-1} in each of the examples.

Based on a power law profile described earlier, BS5925:1991 (British Standards Institution) suggests that in order to estimate wind velocity in a particular terrain from Meteorological Office wind velocity u_{m}, measured at 10 m height in open country, the following conversion may be used:

$v_r \quad = u_m\, K r^a$ where v_r = wind velocity at height r.

The values of the constants K and a, appropriate to the particular surroundings can be found in the following table:

Table 3.1

Terrain	K	a
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33
Source: BS5925:1991.		

These are in good agreement with values given in ASHRAE Fundamentals (1993), except that for cities K and a are assigned the values 0.14 and 0.40 respectively.

Table 3.2

Terrain	*K*	*a*
Airport	0.71	0.15
Suburban	0.32	0.28
Urban	0.14	0.40
Source: ASHRAE Fundamentals (1993).		

The Lawrence Berkeley Laboratory (LBL) Equivalent Leakage Area (ELA) model (#478, #608; Sherman and Grimsrud, 1980) was developed to predict air infiltration rates using the minimum number of model parameters. Therefore precise details were sacrificed in favour of simplicity of use. In particular the wind induced air infiltration rate is calculated from the ELA at 4 Pa, A_o (m^2).

$$Q_w = C' (1-R)^{1/3} v_r A_o \quad (m^3.s^{-1}),$$

where

C' is a dimensionless coefficient whose appropriate value can be found in Table 3.4,

v_r = required site wind velocity ($m.s^{-1}$) at building height r (m) above ground.

$$R = \frac{A_c + A_f}{A_o},$$

where

A_c = ceiling leakage area (m^2),

A_f = floor leakage area (m^2).

v_r is determined from

$$v_r = \frac{v' \left[\alpha \left(\frac{r}{10}\right)^{\gamma}\right]}{\alpha' \left(\frac{r'}{10}\right)^{\gamma'}},$$

where

v' = measured wind velocity at level r' above ground ($m.s^{-1}$),

α', γ' = constants dependent on terrain where v' was measured (see Table 3.3),

α, γ = constants dependent on terrain where building is located (see Table 3.3).

Combining the orifice equation (See Theoretical Outline, 1.1.5) and the defining equation for wind pressure coefficients,

$$Q = A_o \left(2 \frac{\Delta P}{\rho}\right)^{0.5}$$

with the discharge coefficient Cd assumed equal to unity and

$$\Delta P = \frac{1}{2} \rho C_P v_r^2,$$

with the above equation gives,

$$C_p = [C' (1-R)^{1/3}]^2.$$

In other words, C' and R together define an empirical formula to calculate C_p values for use in this simplified model.

Table 3.3

Terrain description	γ	α
Ocean or other body of water with at least 5km of unrestricted expanse.	0.10	1.30
Flat terrain with some isolated obstacles, e.g. buildings or trees well separated from each other	0.15	1.00
Rural areas with low buildings, trees, etc.	0.20	0.85
Urban, industrial or forest areas.	0.25	0.67
Centre of large city, e.g. Manhattan.	0.35	0.47

Table 3.4

Shielding Class	C'	Description
I	0.34	No obstructions or local shielding whatsoever
II	0.30	Light local shielding with few obstructions
III	0.25	Moderate local shielding, some obstructions within two house heights
IV	0.19	Heavy shielding, obstructions around most of perimeter
V	0.11	Very heavy shielding, large obstructions surrounding perimeter within two house heights

The values described above in Tables 3.1-3.4 do not take into account extremes of terrain, for instance mountainous regions such as the Swiss Alps.

Figure 3.2 provides simplistic guidance about when to use data provided for different types of shielding. In reality the situation is much more complicated because each case is unique. Hertig, 1993 (Draft) describes this in more detail and includes a relevant literature survey.

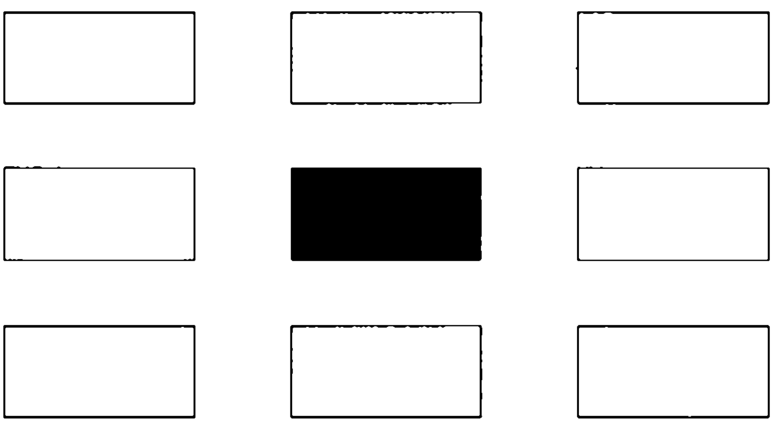
Exposed Building

No surrounding obstructions. This type of building is rarely encountered. Much wind pressure data relates to exposed buildings. Such data are normally inappropriate to infiltration and ventilation studies.

Non Uniform Shielding

Apply exposed wind pressure data only to wind coming from exposed directions.

Uniform Shielding



Building is shielded from all sides by similar structures or other obstructions of equivalent height. This is the most common distribution. Use sheltered wind pressure data.

Figure 3.2 Evaluating Wind Pressure

3.2.2 High Rise Spatially Distributed Wind Pressure Coefficients

The values on the building surfaces in Figures 3.3 (i)-(iii) are based on wind pressure coefficients derived from wind tunnel experiments (#441; Bowen, 1976). They apply to the bounded area into which they have been placed.

The tests were performed on a 1:400 scale model of a tall building with a flat roof, located in a rectangular array of flat-roof low rise buildings of $^1/_6$ its height. These low rise buildings were of the same plan dimensions as the tall building (with width to length ratio 1.5:1) and were placed at a spacing of twice their height. The high rise building had actual dimensions 0.11 m x 0.076 m x 0.23 m (Width x Length x Height). Its height was 91 m to scale.

The wind in the experiment had a simulated boundary layer with a depth of 1.1 m, corresponding to a full scale boundary layer depth of 460 m and a wind velocity profile with a power law exponent equal to 0.43. The reference static pressure was taken as the static pressure at a height of 1.4 m above the base of the model in a measured air flow of 15 $m.s^{-1}$. The wind pressure coefficients of the tall building were referenced to the wind velocity at the same height as the top of the building, but in the undisturbed stream.

Each of the original wind pressure coefficients was positioned at the centre of a rectangle, the area of which was used as a numerical weight in the determination of the coefficients presented in the figures. The pressure coefficients for the new subdivision of the surface (as in the figures) were derived by taking the weighted means of the original wind pressure coefficients which lay within each new rectangle, including the proportional part of any which overlapped. In addition the pressure coefficients in Figures 3.3 (i) and 3.3 (iii) were modified by spatially averaging values either side of the line of symmetry through the building, indicated by dotted lines.

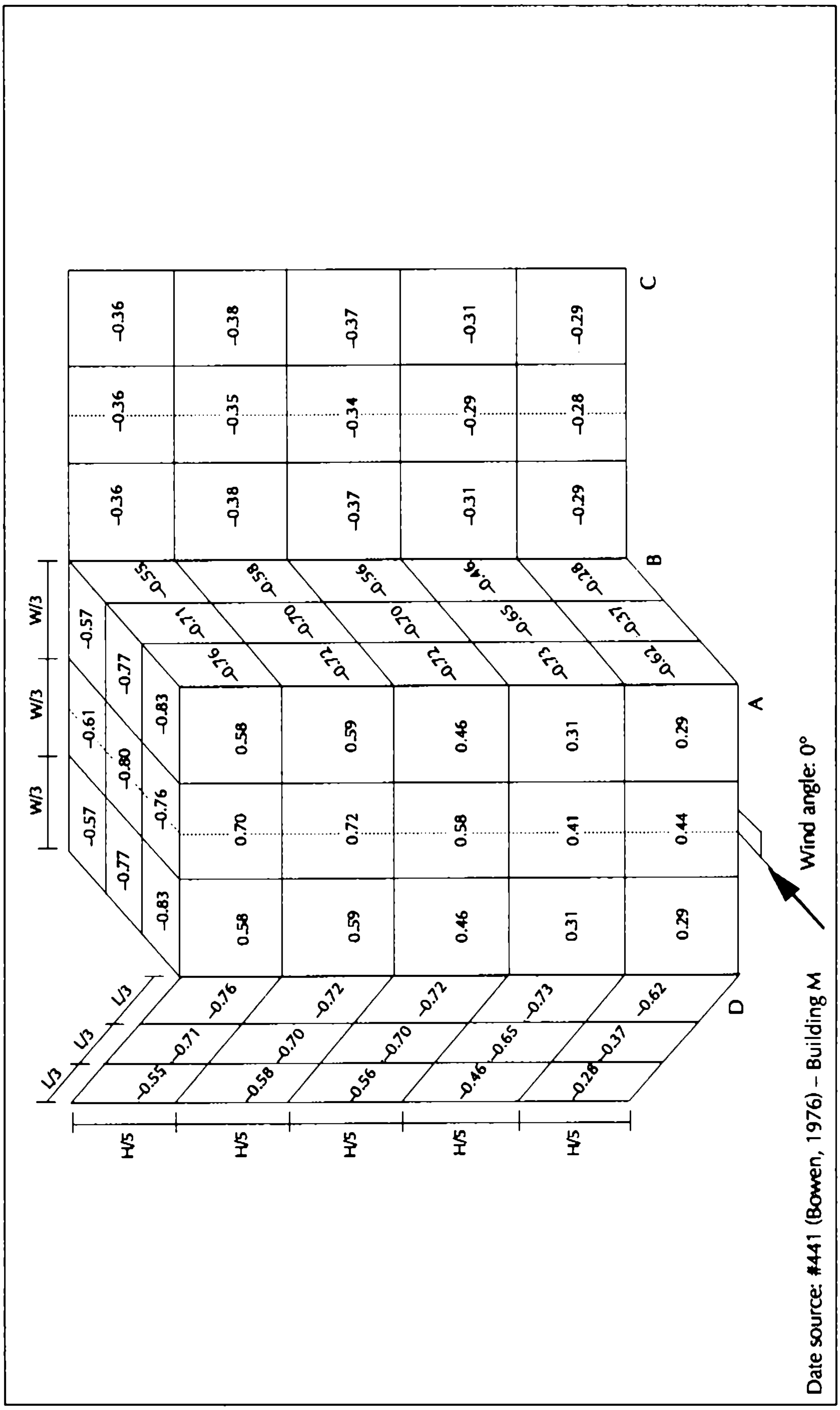
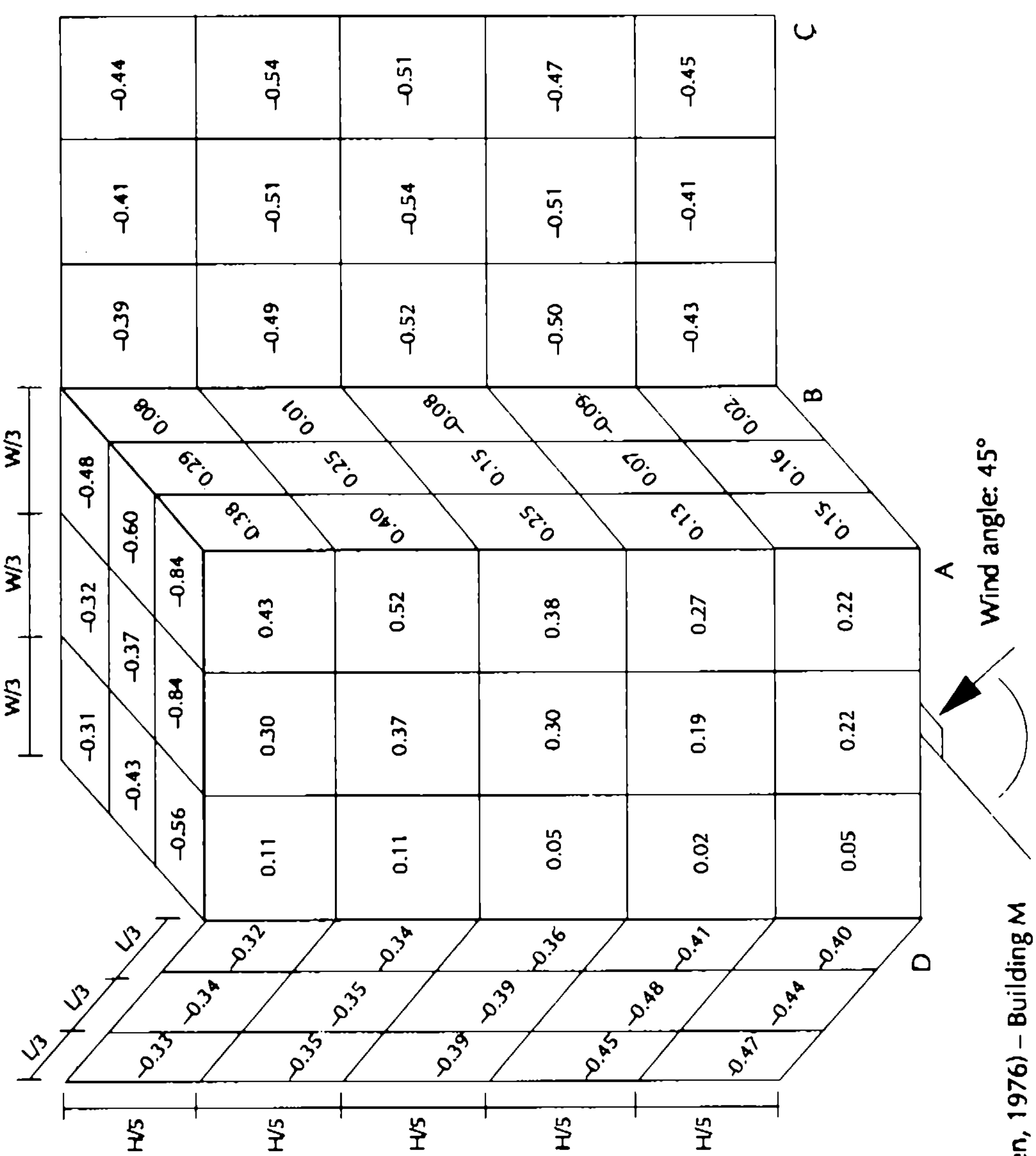
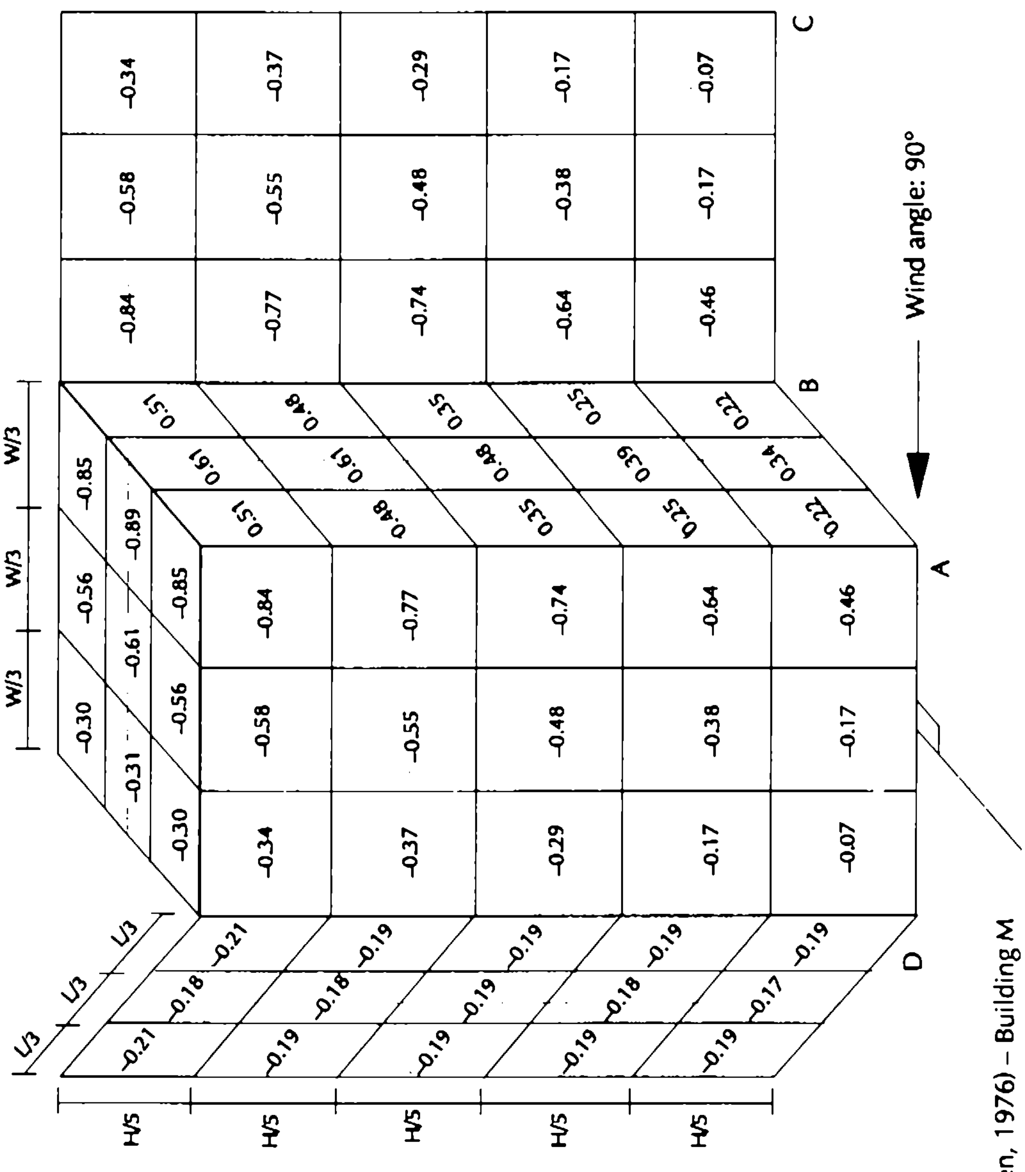

W/3
W/3
W/3
L/3
L/3
L/3
H/5
H/5
H/5
H/5
H/5
A
B
C
D
Wind angle: 0°
Date source: #441 (Bowen, 1976) – Building M

Figure 3.3 (i)



Data source: #441 (Bowen, 1976) – Building M

Figure 3.3 (ii)



Data source: #441 (Bowen, 1976) – Building M

Figure 3.3 (iii)

Figures 3.4 (i) and 3.4 (ii) include curves based on the same data as Figures 3.3 (i) and 3.3 (ii), those indicated by h/H = 1/6. The values of C_{pz} in the figures were calculated by taking the area weighted mean values for each row.

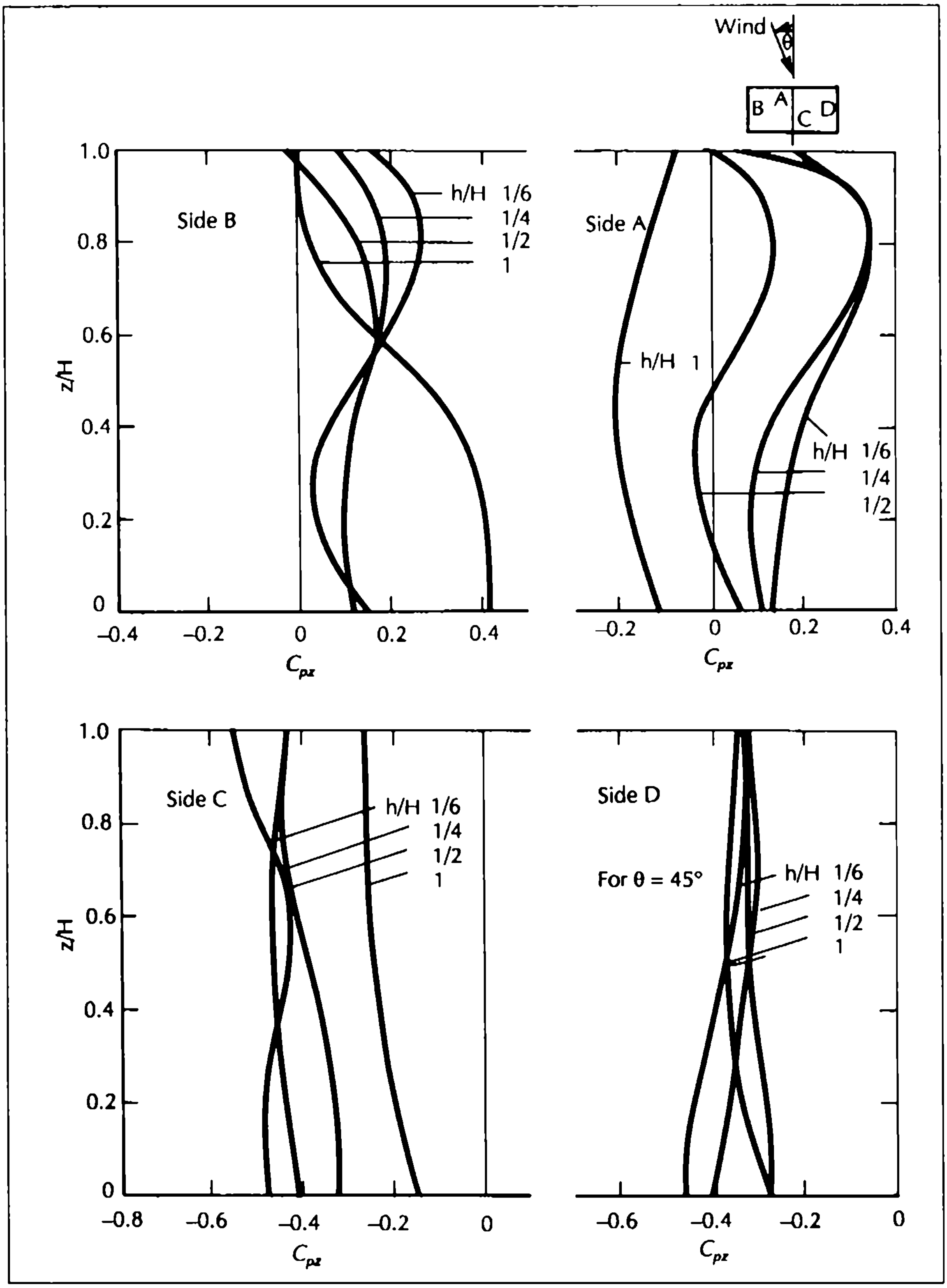


Figure 3.4 (i) Vertical Distribution of Weighted Mean Wind Pressure Coefficients C_{pz}, for Various Surrounding Obstruction Heights (Wind Angle 45°)

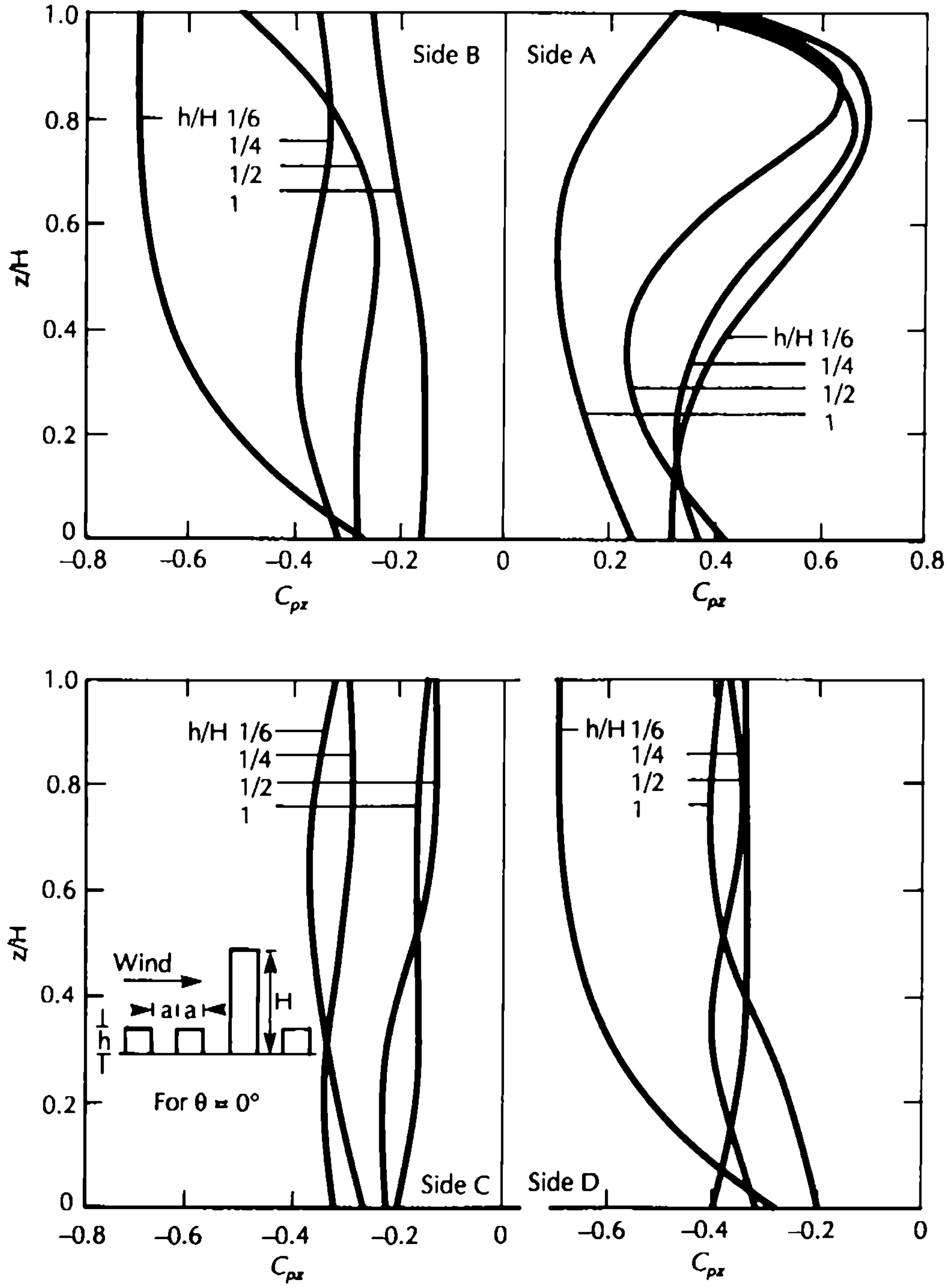


Figure 3.4. (ii) Vertical Distribution of Weighted Mean Wind Pressure Coefficients C_{pz}, for Various Surrounding Obstruction Heights (Wind Angle 0°)

Figures 3.5 (i) and 3.5 (ii) show wind pressure coefficients derived from wind tunnel tests performed on a 1:200 scale model of a tall building with a flat roof and a central lightwell, located in an array of flat-roof low rise buildings. These were of random orientation and $^1/_3$ of the height of the tall building. The high rise building had dimensions 60 m x 50 m x 33 m (Width x Length x Height) to scale. The lightwell measured 30 m x 20 m x 33 m to scale and was completely open to the wind. It was also centrally placed.

The wind pressure coefficients were referenced to the undisturbed wind velocity at the height of the roof. An atmospheric boundary layer was simulated in the wind tunnel and the incoming wind was given a velocity profile with a power exponent of 0.23.

The data on which Figures 3.5 (i) and 3.5 (ii) were based originate from BRE and form only a small sample of a much more extensive data set.

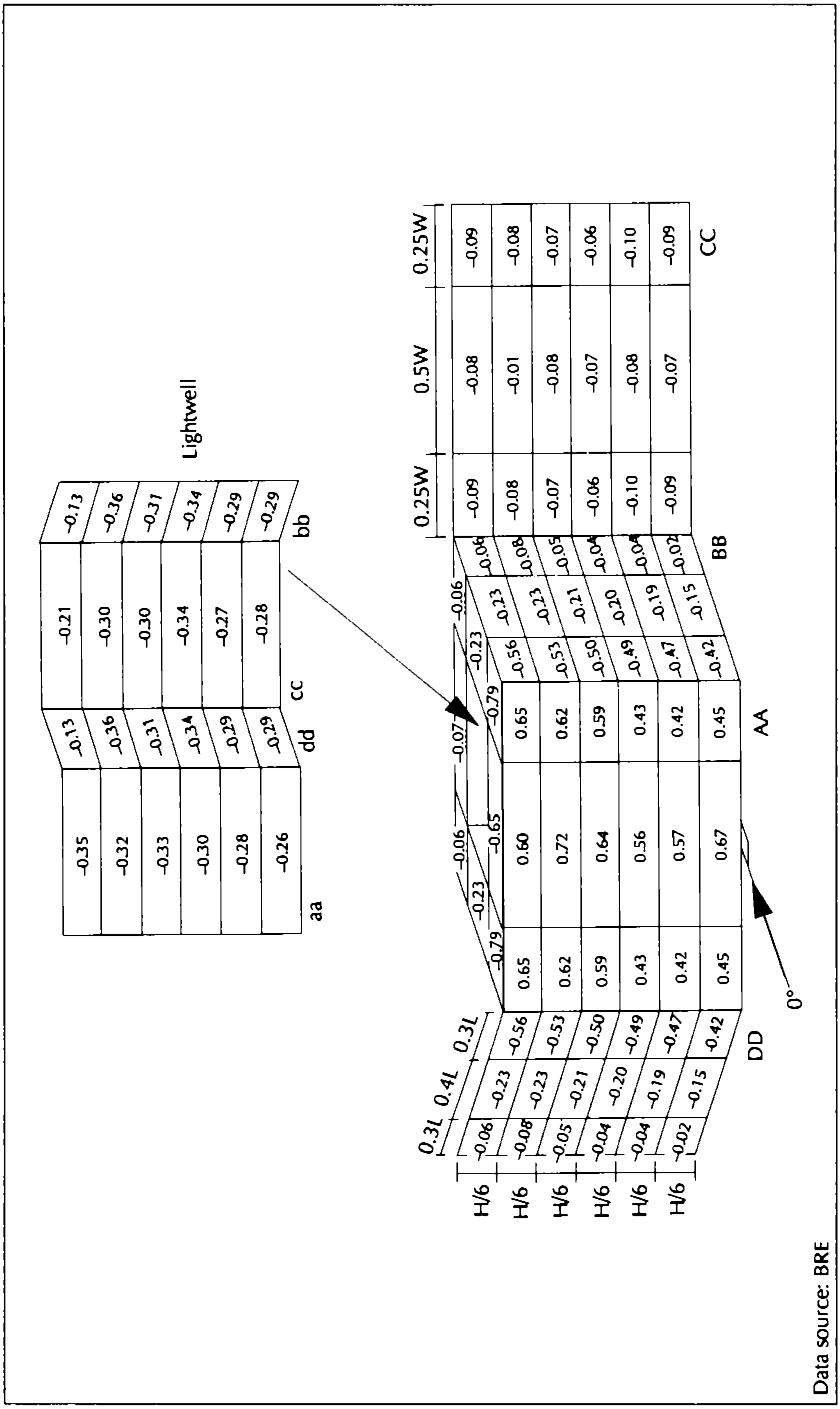
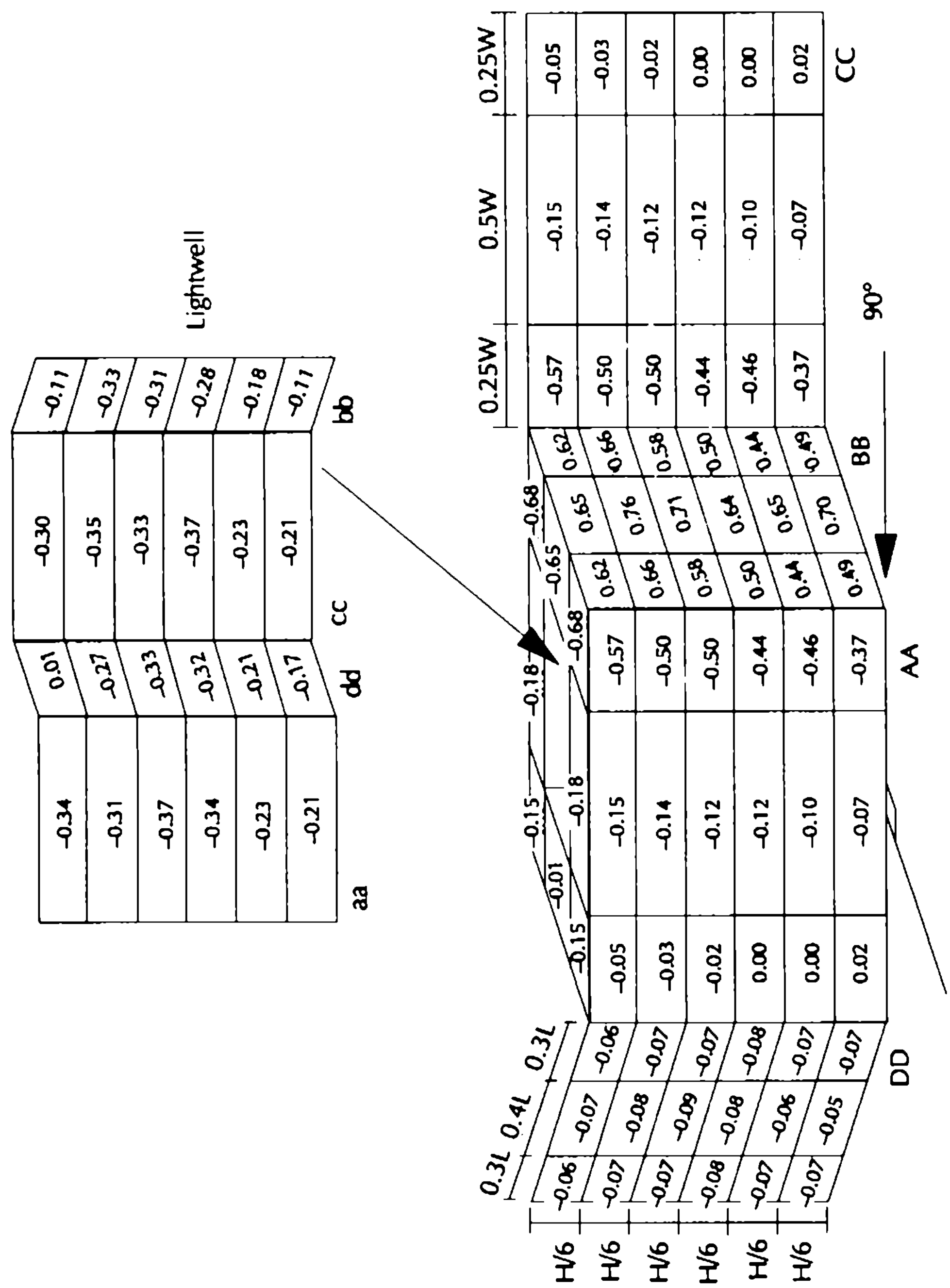


Figure 3.5 (i) Three-Level Office with Lightwell – (surrounded by Low-Rise Buildings)



Data source: BRE

Figure 3.5 (ii) Three-Level Office with Lightwell - (surrounded by Low-Rise Buildings)

3.2.3 Low Rise Single Face Wind Pressure Coefficients

For each shielding condition, the pressure coefficient is expressed as a single value for each face of the building, where the reference height for wind velocity is taken as the building height.

Three types of shielding are covered. These are:

open countryside – no obstructions – exposed,

rural surroundings – some obstructions – semi-sheltered, and

urban – building surrounded on all sides by obstructions of similar size – sheltered.

These tables have been derived from data given in #2077 (Wiren, 1985) and #441 (Bowen, 1976).

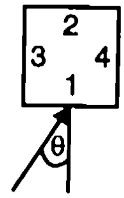
Table 3.5 (i) Wind Pressure Coefficient Data

Low-rise buildings (up to 3 storeys)

Length to width ratio: 1:1

Shielding condition: Exposed

Wind speed reference level: Building height



Wind Angle

Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.7	0.35	–0.5	–0.4	–0.2	–0.4	–0.5	0.35
Face 2		–0.2	–0.4	–0.5	0.35	0.7	0.35	–0.5	–0.4
Face 3		–0.5	0.35	0.7	0.35	–0.5	–0.4	–0.2	–0.4
Face 4		–0.5	–0.4	–0.2	–0.4	–0.5	0.35	0.7	0.35
Roof (<10° pitch)	Front	–0.8	–0.7	–0.6	–0.5	–0.4	–0.5	–0.6	–0.7
	Rear	–0.4	–0.5	–0.6	–0.7	–0.8	–0.7	–0.6	–0.5
Average		–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6
Roof (11-30° pitch)	Front	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5
	Rear	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5
Average		–0.4	–0.5	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5
Roof (>30° pitch)	Front	0.3	–0.4	–0.6	–0.4	–0.5	–0.4	–0.6	–0.4
	Rear	–0.5	–0.4	–0.6	–0.4	0.3	–0.4	–0.6	–0.4
Average		–0.1	–0.4	–0.6	–0.4	–0.1	–0.4	–0.6	–0.4

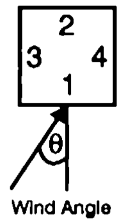
Table 3.5 (ii) Wind Pressure Coefficient Data

Low-rise buildings (up to 3 storeys)

Length to width ratio: 1:1

Shielding condition: Surrounded by obstructions equivalent to half the height of the building

Wind speed reference level: Building height

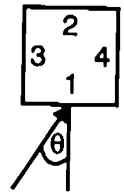


Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.4	0.1	–0.3	–0.35	–0.2	–0.35	–0.3	0.1
Face 2		–0.2	–0.35	–0.3	0.1	0.4	0.1	–0.3	–0.35
Face 3		–0.3	0.1	0.4	0.1	–0.3	–0.35	–0.2	–0.35
Face 4		–0.3	–0.35	–0.2	–0.35	–0.3	0.1	0.4	0.1
Roof (<10° pitch)	Front	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5
	Rear	–0.6	–0.5	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5
Average		–0.6	–0.5	–0.4	–0.5	–0.6	–0.5	–0.4	–0.5
Roof (11-30° pitch)	Front	–0.35	–0.45	–0.55	–0.45	–0.35	–0.45	–0.55	–0.45
	Rear	–0.35	–0.45	–0.55	–0.45	–0.35	–0.45	–0.55	–0.45
Average		–0.35	–0.45	–0.55	–0.45	–0.35	–0.45	–0.55	–0.45
Roof (>30° pitch)	Front	0.3	–0.5	–0.6	–0.5	–0.5	–0.5	–0.6	–0.5
	Rear	–0.5	–0.5	–0.6	–0.5	0.3	–0.5	–0.6	–0.5
Average		–0.1	–0.5	–0.6	–0.5	–0.1	–0.5	–0.6	–0.5

Table 3.5 (iii) Wind Pressure Coefficient Data

Low-rise buildings (up to 3 storeys)

Length to width ratio:	1:1	
Shielding condition:	Surrounded by obstructions equal to the height of the building	
Wind speed reference level:	Building height	



Wind Angle

Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.2	0.05	–0.25	–0.3	–0.25	–0.3	–0.25	0.05
Face 2		–0.25	–0.3	–0.25	0.05	0.2	0.05	–0.25	–0.3
Face 3		–0.25	0.05	0.2	0.05	–0.25	–0.3	–0.25	–0.3
Face 4		–0.25	–0.3	–0.25	–0.3	–0.25	0.05	0.2	0.05
Roof (<10° pitch)	Front	–0.5	–0.5	–0.4	–0.5	–0.5	–0.5	–0.4	–0.5
	Rear	–0.5	–0.5	–0.4	–0.5	–0.5	–0.5	–0.4	–0.5
Average		–0.5	–0.5	–0.4	–0.5	–0.5	–0.5	–0.4	–0.5
Roof (11-30° pitch)	Front	–0.3	–0.4	–0.5	–0.4	–0.3	–0.4	–0.5	–0.4
	Rear	–0.3	–0.4	–0.5	–0.4	–0.3	–0.4	–0.5	–0.4
Average		–0.3	–0.4	–0.5	–0.4	–0.3	–0.4	–0.5	–0.4
Roof (>30° pitch)	Front	0.25	–0.3	–0.5	–0.3	–0.4	–0.3	–0.5	–0.3
	Rear	–0.4	–0.3	–0.5	–0.3	0.25	–0.3	–0.5	–0.3
Average		–0.08	–0.3	–0.5	–0.3	–0.08	–0.3	–0.5	–0.3

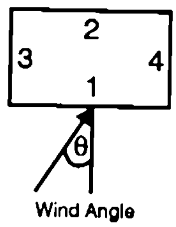
Table 3.5 (iv) Wind Pressure Coefficient Data

Low-rise buildings (up to 3 storeys)

Length to width ratio: 2:1

Shielding condition: Exposed

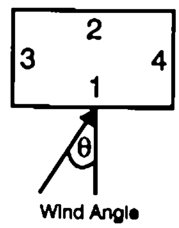
Wind speed reference level: Building height



Location		Wind Angle 0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
Face 2		-0.7	-0.8	-0.5	0.25	0.5	0.25	-0.5	-0.8
Face 3		-0.9	0.2	0.6	0.2	-0.9	-0.6	-0.35	-0.6
Face 4		-0.9	-0.6	-0.35	-0.6	-0.9	0.2	0.6	0.2
Roof (<10° pitch)	Front	-0.7	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.7
	Rear	-0.7	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.7
Average		-0.7	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.7
Roof (11-30° pitch)	Front	-0.7	-0.7	-0.7	-0.6	-0.5	-0.6	-0.7	-0.7
	Rear	-0.5	-0.6	-0.7	-0.7	-0.7	-0.7	-0.7	-0.6
Average		-0.6	-0.65	-0.7	-0.65	-0.6	-0.65	-0.7	-0.65
Roof (>30° pitch)	Front	0.25	0	-0.6	-0.9	-0.8	-0.9	-0.6	0
	Rear	-0.8	-0.9	-0.6	0	0.25	0	-0.6	-0.9
Average		-0.18	-0.45	-0.6	-0.45	-0.18	-0.45	-0.6	-0.45

Table 3.5 (v) Wind Pressure Coefficient Data

Low-rise buildings (up to 3 storeys)



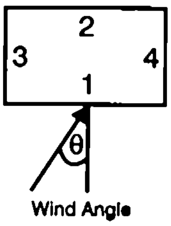
Length to width ratio:	2:1
Shielding condition:	Surrounded by obstructions equivalent to half the height of the building
Wind speed reference level:	Building height

Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.25	0.06	–0.35	–0.6	–0.5	–0.6	–0.35	0.06
Face 2		–0.5	–0.6	–0.35	0.06	0.25	0.06	–0.35	–0.6
Face 3		–0.6	0.2	0.4	0.2	–0.6	–0.5	–0.3	–0.5
Face 4		–0.6	–0.5	–0.3	–0.5	–0.6	0.5	0.4	0.2
Roof (<10° pitch)	Front	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6
	Rear	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6
Average		–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6	–0.6
Roof (11-30° pitch)	Front	–0.6	–0.6	–0.55	–0.55	–0.45	–0.55	–0.55	–0.6
	Rear	–0.45	–0.55	–0.55	–0.6	–0.6	–0.6	–0.55	–0.55
Average		–0.5	–0.6	–0.55	–0.6	–0.5	–0.6	–0.55	–0.6
Roof (>30° pitch)	Front	0.15	–0.08	–0.4	–0.75	–0.6	–0.75	–0.4	–0.08
	Rear	–0.6	–0.75	–0.4	–0.08	0.15	–0.08	–0.4	–0.75
Average		–0.2	–0.4	–0.4	–0.4	–0.2	–0.4	–0.4	–0.4

Table 3.5 (vi) Wind Pressure Coefficient Data

Low-rise buildings (up to 3 storeys)

Length to width ratio:	2:1
Shielding condition:	Surrounded by obstructions equal to the height of the building
Wind speed reference level:	Building height



Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.06	−0.12	−0.2	−0.38	−0.3	−0.38	−0.2	0.12
Face 2		−0.3	−0.38	−0.2	−0.12	0.06	−0.12	−0.2	−0.38
Face 3		−0.3	0.15	0.18	0.15	−0.3	−0.32	−0.2	−0.32
Face 4		−0.3	−0.32	−0.2	−0.32	−0.3	0.15	0.18	0.15
Roof (<10° pitch	Front	−0.49	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
	Rear	−0.49	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
Average		−0.49	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
Roof (11-30° pitch)	Front	−0.49	−0.46	−0.41	−0.46	−0.4	−0.46	−0.41	−0.46
	Rear	−0.4	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
Average		−0.45	−0.46	−0.41	−0.46	−0.45	−0.46	−0.41	−0.46
Roof (>30° pitch)	Front	0.06	−0.15	−0.23	−0.6	−0.42	−0.6	−0.23	−0.15
	Rear	−0.42	−0.6	−0.23	−0.15	−0.06	−0.15	−0.23	−0.6
Average		−0.18	−0.4	−0.23	−0.4	−0.18	−0.4	−0.23	−0.4

3.2.4 Above Roof Level Wind Pressure Coefficients

Figure 3.6 shows the wind pressure coefficient that should be used for those building parts which protrude above roof level (e.g. stack and chimney terminals). Roof angles of 0°, 23° and 30° are included. The pressure coefficient applicable to the uppermost part of the protrusion is the one indicated by the contour line nearest to where the protrusion ends. Figure 3.6 is based on data given in #1302 (Lugtenburg, 1972).

The minimum flue height necessary to avoid back-draughting can be seen in Figure 3.7. It applies to the case of an isolated building, or a building which is sufficiently distant from any surrounding taller buildings. Figure 3.7 is derived from NPR 1088 (Ventilatie van Woongebouwen, Nederlands Normalisatie-instituut) and it is applicable whenever the roof pitch, θ is greater than 23°. The relationship between flue height, h and roof pitch θ is given by

$$h = \left(0.5 + 0.16\ \frac{(\theta - 23^\circ)}{1^\circ}\right) a,$$

where

h is the height above the highest intersection point of the duct with the roof, in metres and must be at least 0.5 m, a is the horizontal distance from the centre of the outlet to the highest point of the roof, in metres, and θ is the pitch of the roof that the duct passes through, in degrees.

If the roof pitch, θ is less than or equal to 23° then the height of the outlet must be at least 0.5 m above the highest intersection point of the duct with the roof, irrespective of its location on the roof.

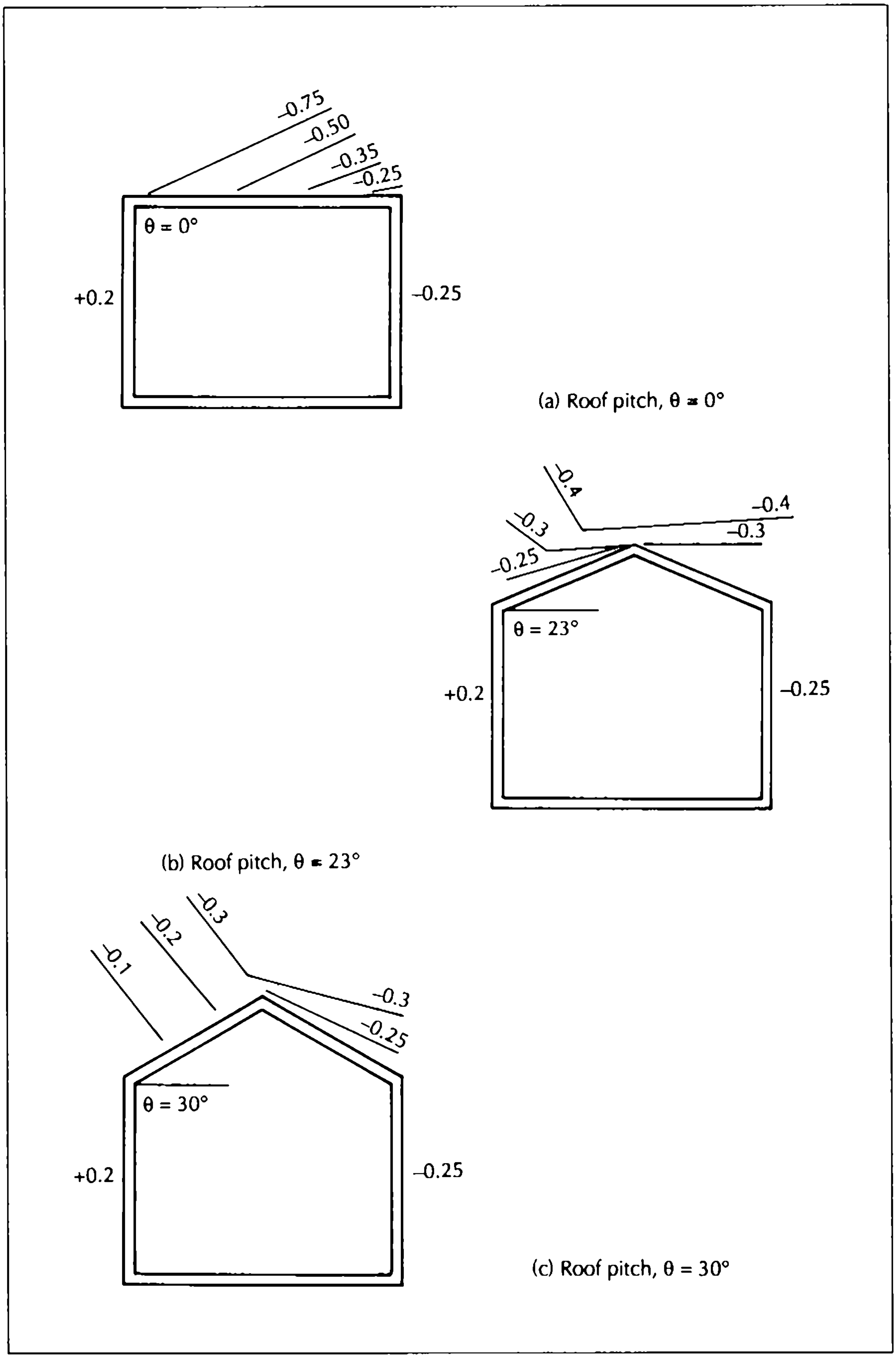


Figure 3.6 Wind Pressure Coefficients for Protrusions above Roof Level

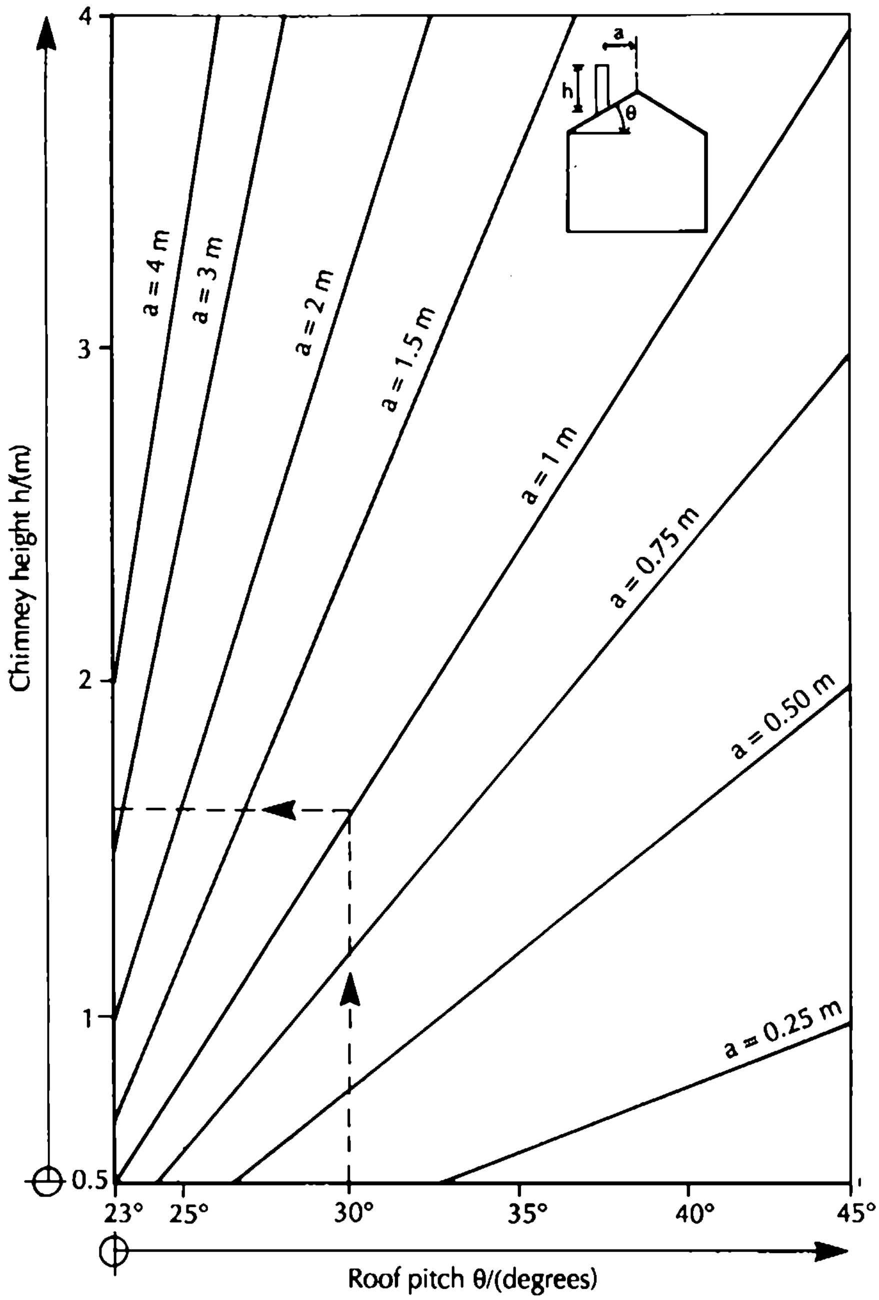


Figure 3.7 Location and Height of the Outlets of Natural Ventilation Ducts to Avoid Back-Draughting

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