

Environmental design

CIBSE Guide A



The rights of publication or translation are reserved.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means without the prior permission of the Institution.

© January 2006 (7th edition) The Chartered Institution of Building Services Engineers London

Issue 2 (January 2007) with corrections to pages 2-29, 2-48, 2-49, 3-11, 3-17, 3-31, 3-32, 5-11, 5-12

Registered charity number 278104

ISBN-10: 1-903287-66-9

ISBN-13: 978-1-903287-66-8

This document is based on the best knowledge available at the time of publication. However no responsibility of any kind for any injury, death, loss, damage or delay however caused resulting from the use of these recommendations can be accepted by the Chartered Institution of Building Services Engineers, the authors or others involved in its publication. In adopting these recommendations for use each adopter by doing so agrees to accept full responsibility for any personal injury, death, loss, damage or delay arising out of or in connection with their use by or on behalf of such adopter irrespective of the cause or reason therefore and agrees to defend, indemnify and hold harmless the Chartered Institution of Building Services Engineers, the authors and others involved in their publication from any and all liability arising out of or in connection with such use as aforesaid and irrespective of any negligence on the part of those indemnified.

Typeset by CIBSE Publications

Printed in Great Britain by Page Bros. (Norwich) Ltd.,
Norwich, Norfolk NR6 6SA

Note from the publisher

This publication is primarily intended to provide guidance to those responsible for the design, installation, commissioning, operation and maintenance of building services. It is not intended to be exhaustive or definitive and it will be necessary for users of the guidance given to exercise their own professional judgement when deciding whether to abide by or depart from it.

Permission to reproduce extracts from the British Standards is granted by BSI. British Standards can be obtained from BSI Customer Services, 389 Chiswick High Road, London W4 4AL. Tel: +44 (0)20 8996 9001. E-mail: cservices@bsi-global.com

Foreword

CIBSE Guide A: *Environmental design* is the premier reference source for designers of low energy sustainable buildings. This edition is the 7th revision and contains significant changes from its predecessor. The contents acknowledge and satisfy the Energy Performance of Buildings Directive and UK legislation, specifically the 2006 Building Regulations Approved Documents L and F. Additionally, the authors have incorporated the latest research and best practice in order to enable environmental design engineers to practise at the forefront of their profession.

The changes made for the 7th revision may briefly be summarised as follows:

Chapter 1: *Environmental criteria for design*: this chapter has been extensively revised to include the adaptive approach and thermal comfort criteria based on the outdoor running mean temperature for offices in both the free running mode (naturally ventilated and mixed mode buildings) and for sealed buildings served by heating and cooling systems. Guidance on overheating criteria has also been included. The health relevant issues associated with environmental design have been transferred to a completely new section (section 8) in order to provide more comprehensive guidance.

Chapter 2: *External design data*: UK dry bulb and wet bulb temperature data have been updated to 2002. New Test Reference Years and Design Summer Years for 14 sites have been identified for which hourly data are available separately. The text in this chapter has also been expanded to include a new section (2.9) giving the latest guidance on future UK climate trends based on UKCIP02 scenarios, and a new section (2.10) on the heat island effect.

Chapter 3: *Thermal properties of building structures*: all the data in this section have been reviewed and updated where necessary to reflect the changes in European and International standards, including test methods for thermal conductivity and thermal transmittance and those related to specification of thermal properties and the calculation of heat transmission. The data for glazed units and windows and for non-steady state properties (admittances etc.) have been reviewed and re-calculated.

Chapter 4: *Ventilation and air infiltration*: the previous edition of Guide A referred only to natural ventilation; this chapter now covers all modes of ventilation. The chapter also specifies minimum ventilation rates to conform to both the revised Approved Document F under the Building Regulations for England and Wales, and the ventilation requirements specified in new European Standards. A new section on empirical data for air infiltration gives design and peak annual average infiltration values for a range of building types and sizes.

Chapter 5: *Thermal response and plant sizing*: this chapter details the design information required to calculate heating and cooling loads and the installed plant capacity. Recognising the iterative nature of the design processes used by practicing engineers, both steady state (manual) calculations using the admittance procedures, and dynamic calculation techniques using computer programs are included in this chapter. The text and data have been comprehensively reviewed and updated. Recommended quality assurance procedures, including the need for a software assessment test for building services design programmes, are also included.

Chapter 6: *Internal heat gains*: this section provides the latest design information on heat emissions from a wide range of internal heat gains to enable designers to use either benchmark values typical of the building and its intended usage, or to make specific estimates where sufficient reliable data are available.

Chapter 7: *Moisture transfer and condensation*: this chapter addresses the widespread concerns amongst clients and building professionals with regard to surface condensation (or, more importantly, mould growth) and also the accumulation of moisture within the structure. The chapter has been expanded to present methods for the prediction of both surface and interstitial condensation and guidelines on how to minimise these problems. The latest British and European Standards methodology and national best practice and the appropriate boundary conditions are also covered.

Chapter 8: *Health issues*: this is a totally new chapter. Its purpose is to advise building service designers and building managers of the health implications of their decisions, and give recommendations for limiting, or preferably avoiding, any adverse health interactions. It has proved impractical to include the full text of this complete and very comprehensive document within this Guide and therefore an abridged version only has been included, with the complete text included on the CD-ROM that accompanies this Guide. Additionally, the complete text is published on the CIBSE website (www.cibse.org) as CIBSE TM 40: *Health issues in building services*.



I would like to express my personal thanks to the individual section authors and their contributors for the many hours of voluntary effort attending meetings, researching, drafting, reading proofs and commenting on not only their own sections but also associated sections in this guide. I would also like to thank the committee secretary, Alan Watson, the editor, Ken Butcher, and Peter Koch for checking and harmonising the symbols and notation used throughout the Guide. My personal thanks are also given to Jacqueline Balian, CIBSE Publishing Director, and to Brian Moss, Chairman of Publications and Research Outputs Delivery Committee (PROD), for their encouragement, support and forbearance during the lengthy gestation period of this 'light' revision.

Finally, I wish to thank all members of our Institution who have provided the section authors, contributors and myself with many useful and constructive suggestions including positive ideas for improving this Guide A revision.

Derrick Braham
Chairman, CIBSE Guide A Steering Committee

Guide A Steering Committee

Derrick Braham (Derrick Braham Associates) (chairman), Brian Anderson (BRE Scotland), David Arnold (Troup Bywaters + Anders), Geoffrey Brundrett, Michael Holmes (Arup), Michael Humphreys (Oxford Brookes University), Geoff Levermore (University of Manchester), Martin Liddament (VEETECH Ltd.), Fergus Nicol (Oxford Brookes University), Chris Sanders (Glasgow Caledonian University), Alan C Watson (CIBSE) (secretary)

Authors, contributors and acknowledgements

Chapter 1: Environmental criteria for design

Principal authors (sections 1.1–1.6)
Michael Humphreys (Oxford Brookes University)
Fergus Nicol (Oxford Brookes University)

Contributors
Jonathan David (CIBSE)
Gay Lawrence Race (CIBSE)

Chapter 2: External design data

Principal authors
Geoff Levermore (University of Manchester)
Tariq Muneer (Napier University)
John Page (consultant)
Chris Sanders (Glasgow Caledonian University)

Contributors
David Chow (Manchester University, School of Mechanical Aerospace and Civil Engineering), Sukumar Natarajan (Manchester University, School of Mechanical Aerospace and Civil Engineering), John Parkinson (Manchester University, School of Mechanical Aerospace and Civil Engineering), Michelle Colley (UKCIP), Mike Hulme (Tyndall Climate Change Research Centre, University of East Anglia), Richard Watkins (Brunel University, School of Engineering and Design)

Acknowledgements
American Society of Heating, Refrigerating and Air-Conditioning Engineers

Chapter 3: Thermal properties of building structures

Principal author
Brian Anderson (BRE Scotland)

Contributors
Sean Doran (BRE Scotland), Kos Mina (BRE Scotland), Gerry Pettit (Concrete Block Association)

Chapter 4: Ventilation and air infiltration

Principal author

Martin Liddament (VEETECH Ltd.)

Chapter 5: Thermal response and plant sizing

Principal author

Michael Holmes (Arup)

Contributors

Chris Britton (Hoare Lea), Foroutan Parand, Daren Robinson (BDSP Partnership), Andrew Wright (De Montfort University), Robert Van Zyl (Cundall Johnson and Partners)

Chapter 6: Internal heat gains

Principal author

David Arnold (Troup Bywaters + Anders)

Chapter 7: Moisture transfer and condensation

Principal author

Chris Sanders (Glasgow Caledonian University)

Chapter 8: Health issues

Chapter 8 consists of extracts from CIBSE TM40: *Health issues in building services*, the full text of which may be found on the CD-ROM that accompanies this Guide. TM40 was prepared by the CIBSE Health Issues Task Group.

CIBSE Health Issues Task Group

Geoffrey Brundrett (consultant) (chairman)

Tim Bowden (Gifford and Partners)

Peter Boyce (Lighting Research Centre, Rensselaer Polytechnic Institute)

Jillian Deans (Dangerous Pathogen Dept., Health and Safety Executive)

Paul Harrison (Cranfield University)

Peter Hoffman (Health Protection Agency)

Stirling Howieson (Centre for Environmental Design and Research, Strathclyde University)

John V Lee (Health Protection Agency)

Geoffrey Leventhall (Consultant)

Shena Powell (Health and Safety Laboratory)

Paul Tearle (Health Protection Agency)

Authors and contributors (1999 edition)

Guide A is a continuing publication and each successive edition relies on material provided for previous editions. The Institution acknowledges the material provided by previous authors and contributors, including: Farshad Alamdari, Brian Anderson, Paul Appleby, Joe Clarke, Vic Crisp, Les Fothergill, Angus Gait, Ian Griffiths, Alan Guy, David Handley, Phil Haves, Greg Hayden, Michael Holmes, Michael Humphreys, Peter Jackman, Ben Keeble, Eric Keeble, Ted King, Geoff Leventhall, Geoff Levermore, Martin Liddament, David Lush, John Moss, Tony Mulhall, Tariq Muneer, Fergus Nicol, Bjarne Olesen, Nigel Oseland, Peter Owens, John Page, Martin Ratcliffe, Gary Raw, Paul Ruffles, Chris Sanders, Jack Siviour, David Spooner, Alexandra Wilson, David Wood, Andrew Wright.

Editor

Ken Butcher

CIBSE Publishing Manager

Jacqueline Balian

Acknowledgement

Crown copyright material is reproduced with the permission of the Controller of HMSO and the Queen's Printer for Scotland under licence number C02W0002935.



Documents

Document Sharing Hub

Contents

1	Environmental criteria for design	1-1
1.1	Introduction	1-1
1.2	Notation	1-1
1.3	Thermal environment	1-3
1.4	Design criteria	1-7
1.5	Other factors potentially affecting comfort	1-13
1.6	The adaptive approach and field-studies of thermal comfort	1-16
1.7	Determination of required outdoor air supply rate	1-18
1.8	Visual environment	1-20
1.9	Acoustic environment	1-25
1.10	Vibration	1-29
1.11	Electromagnetic and electrostatic environment	1-30
	References	1-32
	Appendix 1.A1: Determination of predicted mean vote (PMV)	1-35
	Appendix 1.A2: Measuring operative temperature	1-37
2	External design data	2-1
2.1	Introduction	2-1
2.2	Notation	2-2
2.3	UK cold weather data	2-2
2.4	UK warm weather data	2-6
2.5	Accumulated temperature difference (degree-days and degree-hours)	2-12
2.6	Worldwide weather data	2-15
2.7	Solar and illuminance data	2-22
2.8	Wind data	2-37
2.9	Climate change	2-43
2.10	Heat island effect	2-47
	References	2-50
3	Thermal properties of building structures	3-1
3.1	Introduction	3-1
3.2	Notation	3-2
3.3	Heat losses from buildings	3-3
3.4	Roofs	3-13
3.5	Ground floors and basements	3-13
3.6	Windows	3-20
3.7	Linear thermal transmittance	3-24
3.8	Non-steady state thermal characteristics	3-24
	References	3-25
	Appendix 3.A1: Moisture content of masonry materials	3-27
	Appendix 3.A2: Thermal conductivity and thermal transmittance testing	3-27
	Appendix 3.A3: Heat transfer at surfaces	3-28
	Appendix 3.A4: Seasonal heat losses through ground floors	3-29
	Appendix 3.A5: Application of the combined method to multiple layer structures	3-30
	Appendix 3.A6: Calculation method for admittance, decrement factor and surface factor	3-31
	Appendix 3.A7: Properties of materials	3-33
	Appendix 3.A8: Thermal properties of typical constructions	3-46



4	Ventilation and air infiltration	4-1
4.1	Introduction	4-1
4.2	Role of ventilation	4-2
4.3	Ventilating techniques	4-3
4.4	Ventilating estimation techniques	4-4
4.5	Outline of ventilation and air infiltration theory	4-4
4.6	Assessing natural ventilation and air infiltration rates	4-6
4.7	Estimation methods	4-11
4.8	Airtightness testing	4-19
	References	4-20
5	Thermal response and plant sizing	5-1
5.1	Introduction	5-1
5.2	Notation and glossary of terms	5-3
5.3	Quality assurance	5-6
5.4	Selection of design parameters	5-7
5.5	Calculation methods	5-9
5.6	Steady state models	5-10
5.7	Dynamic models	5-12
5.8	CIBSE cyclic model	5-15
5.9	Airflow modelling	5-27
5.10	Application of CIBSE calculation methods	5-28
5.11	Solar cooling load tables	5-36
	References	5-49
	Appendix 5.A1: Quality assurance in building services software	5-50
	Appendix 5.A2: Overview of calculation methods	5-54
	Appendix 5.A3: Derivation of thermal steady state models	5-57
	Appendix 5.A4: Comparison of thermal steady state models	5-65
	Appendix 5.A5: Equations for determination of sensible heating and cooling loads	5-73
	Appendix 5.A6: Algorithm for the calculation of cooling loads by means of the admittance method	5-77
	Appendix 5.A7: Derivation of solar gain factors	5-85
	Appendix 5.A8: Derivation of factor for intermittent heating	5-95
	Appendix 5.A9: Specification for Reference (dynamic) Model	5-96
6	Internal heat gains	6-1
6.1	Introduction	6-1
6.2	Benchmark values for internal heat gains	6-1
6.3	Occupants	6-2
6.4	Lighting	6-3
6.5	Personal computers and office equipment	6-5
6.6	Electric motors	6-6
6.7	Cooking appliances	6-7
6.8	Hospital and laboratory equipment	6-8
	References	6-8
	Appendix 6.A1: Rate of heat emission from animal bodies	6-9
	Appendix 6.A2: Rate of heat gain from restaurant/cooking equipment	6-10

7	Moisture transfer and condensation	7-1
7.1	Introduction	7-1
7.2	Notation	7-1
7.3	Internal water vapour loads	7-1
7.4	Moisture content of materials	7-2
7.5	Mechanisms of moisture movement	7-3
7.6	Surface condensation and mould growth	7-4
7.7	Inside and outside design conditions	7-7
7.8	Condensation calculations	7-9
7.9	Control of condensation	7-14
	References	7-15
8	Health issues	8-1
8.1	Introduction	8-1
8.2	Thermal conditions for stress	8-1
8.3	Humidity	8-3
8.4	Air quality and ventilation	8-5
8.5	Visual environment	8-11
8.6	Electromagnetic effects	8-13
8.7	Noise and vibration	8-14
	References	8-15
Index		I-1

1 Environmental criteria for design

1.1 Introduction

1.1.1 Comfort

Comfort has been defined as ‘that condition of mind that expresses satisfaction with the ... environment’⁽¹⁾.

The indoor environment should be designed and controlled so that occupants’ comfort and health are assured. There are individual differences in perception and subjective evaluation, resulting in a base level of dissatisfaction within the building population. This dissatisfaction may be with a specific aspect of the environment or may be general and non-specific. The aim of design should be to minimise this dissatisfaction as far as is reasonably practicable.

The environmental factors considered here include the thermal, visual and acoustic conditions, indoor air quality, electromagnetic fields and static electricity. It is not practicable to formulate a single index that quantifies the individual’s response to all these factors, and there may be additive or synergistic effects resulting from interactions among a number of them. For example irritant contaminants, such as formaldehyde, become more noticeable at low air humidity⁽²⁾.

Therefore, it is necessary to specify measurable limits or ranges for each of the environmental factors, making allowance, where possible, for any interactions that might occur.

1.1.2 Health aspects

See also chapter 8: *Health issues*.

The constitution of the World Health Organisation defines good health as ‘a state of complete physical, mental and social well-being, not merely the absence of disease and infirmity’. While for most people this may be an ideal rather than reality, it indicates that the indoor environment should be managed in such a way as to promote health, not merely to avoid illness.

In some cases occupants experience symptoms which may not be obviously related to a particular cause, but which become less severe or disappear when they leave a particular environment. These symptoms, such as nausea, mucosal dryness or irritation, runny nose, eye problems, headaches, skin problems, heavy head and flu-like symptoms, may be quite severe and lead to reduced productivity or absenteeism. If a significant proportion of occupants experience these symptoms then, by definition⁽³⁾, the occupants are suffering from ‘sick building syndrome’.

It is likely that the cause of sick building syndrome is multi-factorial. Researchers have identified a statistically significant correlation between symptom prevalence and many different and unrelated factors. It would appear that if environmental conditions are within the ranges suggested in this Guide then the risk of occupant dissatisfaction and sick building syndrome is reduced, though not eliminated.

1.2 Notation

1.2.1 Symbols

The symbols used within this section are defined as follows.

A	Total area of internal surfaces (ceiling, floor, windows and walls) (m^2)
A_w	Net glazed area of window (m^2)
C_p	Concentration of pollutant (ppm)
C_p^v	Concentration of pollutant by volume ($\text{mg}\cdot\text{m}^{-3}$)
C_{pi}	Limit of concentration of pollutant in indoor air (ppm)
C_{po}	Concentration of pollutant in outdoor air (ppm)
DF	Average daylight factor (%)
DR	Draught rating (%)
E_v	Ventilation effectiveness
f_{cl}	Ratio of the area of clothed human body to that of unclothed human body
H	Heat transfer ratio: $h_c / (h_c + h_r)$
h_c	Convective heat transfer coefficient at body surface ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)
h_r	Radiative heat transfer coefficient at body surface ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)
I_{cl}	Thermal resistance of clothing ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$)
M_a	Activity level (met)
M_p	Molar mass of pollutant ($\text{kg}\cdot\text{mole}^{-1}$)
P^p	Pollutant emission rate ($\text{L}\cdot\text{s}^{-1}$)
p_s	Partial water vapour pressure in air surrounding the body (Pa)
Q	Outdoor air supply rate ($\text{L}\cdot\text{s}^{-1}$)
Q'	Reduced outdoor air supply rate to control intermittent pollution ($\text{L}\cdot\text{s}^{-1}$)
Q_c	Outdoor air supply rate to account for total contaminant load ($\text{L}\cdot\text{s}^{-1}$)
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied
R_a	Area-weighted average reflectance of interior surfaces (ceiling, floor, windows and walls)
T	Diffuse transmittance of glazing material including effects of dirt
T_u	Turbulence intensity (%)
t_p	Duration of release of pollutant(s)
V	Volume of space (m^3)
v	Air speed ($\text{m}\cdot\text{s}^{-1}$)

v_{SD}	Standard deviation of air speed ($\text{m}\cdot\text{s}^{-1}$)
α	Angle in degrees subtended, in the vertical plane normal to the window, by sky visible from centre of window (degree)
α_{rm}	Constant related to running mean temperature
θ_{ai}	Indoor air temperature ($^{\circ}\text{C}$)
θ_{com}	Comfort temperature ($^{\circ}\text{C}$)
θ_{ed}	Daily mean outdoor temperature ($^{\circ}\text{C}$)
θ_c	Operative temperature ($^{\circ}\text{C}$)
θ_{on}	Operative temperature at thermal neutrality ($^{\circ}\text{C}$)
θ_r	Mean radiant temperature ($^{\circ}\text{C}$)
θ_{rm}	Exponentially weighted running mean of the daily mean outdoor temperature ($^{\circ}\text{C}$)
θ_{sc}	Surface temperature of clothing ($^{\circ}\text{C}$)
Φ_c	Heat loss by convection from surface of clothed body (W)
Φ_e	Heat loss by evaporation from surface of clothed body (W)
Φ_k	Heat flow by conduction from surface of clothed body (W)
Φ_m	Metabolic rate per m^2 of body surface (W)
Φ_{rad}	Heat loss by radiation from surface of clothed body (W)
Φ_{re}	Heat exchange by evaporation in respiratory tract (W)
Φ_{rc}	Heat exchange by convection in respiratory tract (W)
Φ_s	Body heat storage (W)
Φ_w	Rate of performance of external work (W)

Note: in compound units, the abbreviation 'L' has been used to denote 'litre'.

1.2.2 Thermal comfort: annotated definitions of main thermal parameters

For the purposes of this Guide, the following terminology is adopted.

Indoor air temperature (θ_{ai})

The dry bulb temperature of the air in the space.

Mean radiant temperature (θ_r)

The uniform surface temperature of a radiantly black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space. (see BS EN ISO 7726⁽⁴⁾ for derivation). (Note: if the surface temperatures of the internal surfaces of the enclosure are unequal, mean radiant temperature varies throughout the enclosure and depends upon the posture and orientation of the occupant.)

Relative air speed (v_r)

The net mean air speed across the body. For sedentary occupancy, v_r is taken as the room air movement only (v). For people in motion it will take account of the speed of their movement in addition to the mean room air speed.

Humidity

The humidity of room air expressed in absolute terms, i.e. moisture content (mass of water vapour per unit mass of

dry air ($\text{kg}\cdot\text{kg}^{-1}$) or vapour pressure (partial pressure of water vapour (Pa)).

Relative humidity

The ratio of vapour pressure to saturation vapour pressure at same dry bulb temperature, expressed as a percentage (% RH).

Percentage saturation

The ratio of moisture content to moisture content of saturated air at same dry bulb temperature, expressed as a percentage (% sat). (Note: at ambient air temperatures and humidities the difference between relative humidity and percentage saturation is small and may be ignored.)

Clo

The unit for thermal insulation of clothing⁽⁵⁾, where 1 clo = $0.155 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$. A clothing ensemble that approximates to 1 clo consists of underwear, blouse/shirt, slacks/trousers, jacket, socks and shoes.

Met

The unit used to express the physical activity of humans is the met⁽⁶⁾, where 1 met = $58.2 \text{ W}\cdot\text{m}^{-2}$. One met is approximately the metabolic rate of a person seated at rest. The average body surface area for adults is about 1.8 m^2 , therefore 1 met is equivalent to approximately 100 W of total heat emission.

Operative and dry resultant temperatures

In previous editions of this Guide, dry resultant temperature was used as a temperature index for moderate thermal environments. In concept it is identical to the 'operative temperature' (θ_c) which is used in both International Standards⁽⁷⁾ and ANSI/ASHRAE⁽¹⁾ standards. In the interests of international consistency of nomenclature, the CIBSE has decided to replace the term 'dry resultant temperature' with the term 'operative temperature'. This entails no change of substance.

The operative temperature (θ_c), like the dry resultant temperature, combines the air temperature and the mean radiant temperature into a single value to express their joint effect. It is a weighted average of the two, the weights depending on the heat transfer coefficients by convection (h_c) and by radiation (h_r) at the clothed surface of the occupant.

The operative temperature is defined as:

$$\theta_c = H \theta_{ai} + (1 - H) \theta_r \quad (1.1)$$

where θ_c is the operative temperature ($^{\circ}\text{C}$), θ_{ai} is the indoor air temperature ($^{\circ}\text{C}$), θ_r is the mean radiant temperature ($^{\circ}\text{C}$), H is the ratio $h_c / (h_c + h_r)$ and $(1 - H)$ is the ratio $h_r / (h_c + h_r)$ where h_c and h_r are the surface heat transfer coefficients by convection and by radiation respectively ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$).

Researchers have differed in their estimates of the values of these heat transfer coefficients, and hence of the value of H . In this Guide the value of $\sqrt{(10 v)}$, where v is the air speed ($\text{m}\cdot\text{s}^{-1}$) is retained for the ratio of h_c to h_r (as for dry resultant temperature in previous editions), and so:

$$\theta_c = \frac{\theta_{ai} \sqrt{(10 v)} + \theta_r}{1 + \sqrt{(10 v)}} \quad (1.2)$$

At indoor air speeds below $0.1 \text{ m}\cdot\text{s}^{-1}$, natural convection is assumed to be equivalent to $v = 0.1$, and equation 1.2 becomes:

$$\theta_c = 1/2 \theta_{ai} + 1/2 \theta_r \quad (1.3)$$

Operative temperature approximates closely to the temperature at the centre of a painted globe of some 40 mm diameter, see Appendix 1.A2. A table-tennis ball is a suitable size, and may be used to construct a globe thermometer appropriate for indoor spaces⁽⁸⁾.

In well insulated buildings that are predominantly heated by convective means, the difference between air and the mean radiant temperatures (and hence between the air and operative temperatures) is small.

Note: from the presence of the air speed in the equation 1.2, it has sometimes been assumed that operative temperature fully allows for the effect of air speed on the occupant. This is not so. Increased air movement has two related effects: (1) it alters the ratio $h_c / (h_c + h_r)$, thus potentially altering operative temperature, and (2) it alters the absolute value of the combined heat transfer coefficient ($h_c + h_r$) between the clothed surface and the enclosure. Thus the surface temperature of the occupant requires for its estimation both the operative temperature and the air speed.

1.3 Thermal environment

1.3.1 Factors affecting thermal comfort

A person's sensation of warmth is influenced by the following main physical parameters, which constitute the thermal environment:

- air temperature
- mean radiant temperature
- relative air speed
- humidity.

Besides these environmental factors there are personal factors that affect thermal comfort:

- metabolic heat production
- clothing.

It is also required that there be no local discomfort (either warm or cold) at any part of the human body due to, for example, asymmetric thermal radiation, draughts, warm or cold floors, or vertical air temperature differences.

Table 1.1 Thermal sensation scale⁽¹⁾

Index value	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

1.3.1.1 Temperature

The room air temperature and radiant temperature may be combined as the operative temperature. Temperature is usually the most important environmental variable affecting thermal comfort. A change of three degrees will change the response on the scale of subjective warmth (Table 1.1⁽¹⁾) by about one scale unit for sedentary persons. More active persons are less sensitive to changes in room temperature. Guidance on temperatures suitable for various indoor spaces in heated or air conditioned buildings is given in Table 1.5 and, for unheated spaces in buildings in warm weather, in Table 1.7.

1.3.1.2 Air movement and draughts

The cooling effect of air movement is well known. If this cooling is not desired, it can give rise to complaints of draught. The temperature of the moving air is not necessarily that of the room air nor that of the incoming ventilation air but will generally lie between these values. It should also be noted that people are more tolerant of air movement if the direction of the air movement varies.

Where air speeds in a room are greater than $0.15 \text{ m}\cdot\text{s}^{-1}$ the operative temperature should be increased from its 'still air' value to compensate for the cooling effect of the air movement. Suitable corrections are given in Figure 1.1. The figure applies to sedentary or lightly active people. Alternatively, the influence of mean relative air speed can be calculated using the PMV index, as described in section 1.3.2. Note that air speeds greater than about $0.3 \text{ m}\cdot\text{s}^{-1}$ are probably unacceptable except in naturally ventilated buildings in summer when higher air speeds may be desirable for their cooling effect.

The relative air speed over the body surface increases with activity. A correction can be estimated where activity level (M_a) exceeds 1 met by adding $0.3 \times (M_a - 1)$ to the air speed relative to a stationary point. For example, for a person whose activity is equivalent to 1.8 met in a room in which the air speed is $0.1 \text{ m}\cdot\text{s}^{-1}$, the relative air speed over that person's body is: $0.1 + 0.3 (1.8 - 1) = 0.34 \text{ m}\cdot\text{s}^{-1}$. This assumes that the direction of the airflow is at random. At higher air speeds, where airflow may be mono-directional, the relative air speed will depend on the direction of travel of the person.

However, studies⁽⁹⁾ have shown that dissatisfaction due to draught is not only a function of mean air speed and local air temperature, but also of fluctuations of air speed. It has been suggested that people are particularly sensitive if air speeds fluctuate at a frequency in the range 0.3–0.6 Hz⁽¹⁰⁾

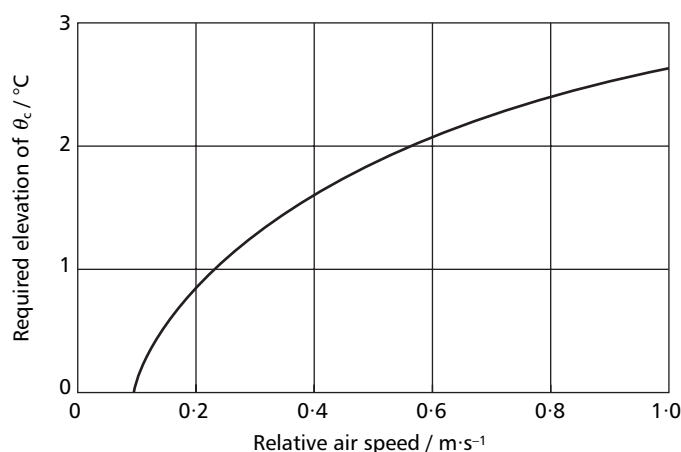


Figure 1.1 Correction to operative temperature (θ_e) to take account of air movement

Fluctuations in air speed may be described by the standard deviation of the air speed (v_{SD}), or the turbulence intensity (T_u) which is defined as the ratio of standard deviation of the air speed to the mean air speed, i.e.:

$$T_u = 100 (v_{SD} / v) \quad (1.4)$$

where T_u is the turbulence intensity (%), v_{SD} is the standard deviation of the air speed ($\text{m}\cdot\text{s}^{-1}$) and v is the mean air speed ($\text{m}\cdot\text{s}^{-1}$). There is debate about the magnitude of the effect of turbulence on the sensation of draught^(11–13). One estimate of the effect is incorporated in the draught rating (DR), see below.

For air conditioned and mechanically ventilated buildings, the draught rating (DR), expressed as a percentage, is given by⁽⁷⁾:

$$DR = (34 - \theta_{ai}) (v - 0.05)^{0.62} (0.37 v T_u + 3.14) \quad (1.5)$$

where DR is the draught rating (%) and θ_{ai} is the indoor air temperature ($^{\circ}\text{C}$). (For air speeds less than $0.05 \text{ m}\cdot\text{s}^{-1}$, take $v = 0.05 \text{ m}\cdot\text{s}^{-1}$; for calculated DR values greater than 100%, use DR = 100%.)

A draught rating of more than 15% is taken to be unacceptable⁽⁹⁾. Figure 1.2⁽⁷⁾ shows solutions for equation 1.5 for DR = 15% based on light, mainly sedentary, activity (i.e. 1.2 met). Each line on the graph shows the limits of acceptable temperature and velocity for a given turbulence intensity. For example, if the temperature of the air passing over the body is 23°C and the turbulence intensity is 60%, the draught rating criterion of 15% corresponds to an air speed of $0.14 \text{ m}\cdot\text{s}^{-1}$. However if the turbulence intensity is only 10%, the limiting velocity for comfort is $0.23 \text{ m}\cdot\text{s}^{-1}$.

In the main body of most rooms, away from supply air jets, the turbulence intensity is usually between 30% and 50%.

1.3.1.3 Humidity

Humidity has little effect on feelings of warmth unless the skin is damp with sweat. For sedentary, lightly clothed people moisture may become apparent as operative temperatures rise above $26\text{--}28^{\circ}\text{C}$. Thus, for most practical purposes, the influence of humidity on warmth in

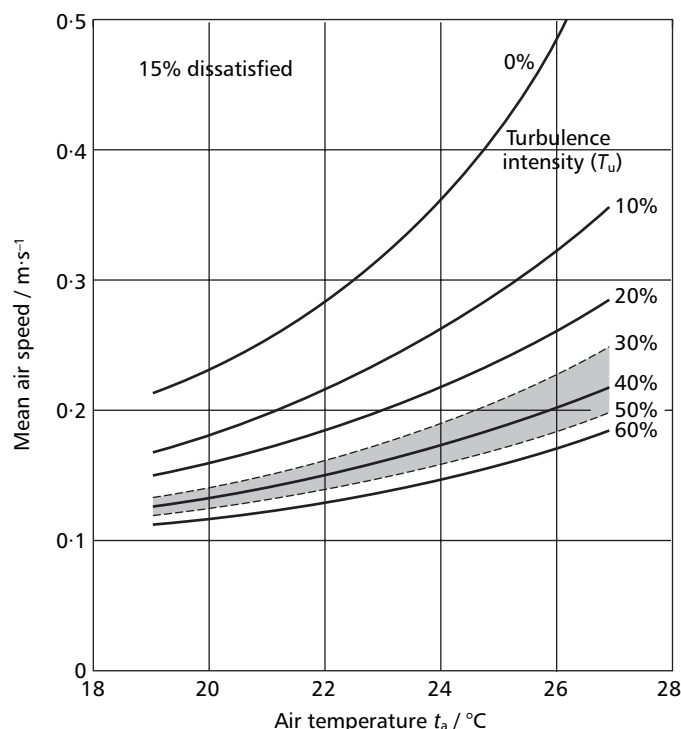


Figure 1.2 Combinations of mean air speed, air temperature and turbulence intensity for a draught rating of 15%⁽²²⁾; data from climate chamber experiment at 20, 23 and 26°C , 15 minute exposures, subjects adjusted clothing for comfort; the data apply to people comfortable had the air been still; people who are feeling cold may complain of draught even in still air (reproduced from BS EN ISO 7730⁽⁷⁾ by permission of the British Standards Institution)

moderate thermal environments may be ignored⁽¹⁴⁾ and humidity in the range 40–70 % RH is generally acceptable⁽¹⁵⁾. However, humidity may be important in the context of microbiological growth, the preservation of artefacts and the reduction of static electricity⁽¹⁶⁾, see section 8.3.3.

High room humidity may occur through a combination of evaporation from moisture sources and poor ventilation, and/or high outdoor humidity, see chapter 7: *Moisture transfer and condensation*. Bathrooms and kitchens are particularly prone.

For the purposes of designing air conditioning systems, a maximum room relative humidity of 60% within the recommended range of summer design operative temperatures would provide acceptable comfort conditions for human occupancy and minimise the risk of mould growth and house dust mites. Condensation should be avoided within buildings on surfaces that could support microbial growth or be stained or otherwise damaged by moisture. This may be achieved by ensuring that, where possible, surfaces are above the dew-point of the adjacent air.

If possible, at the design temperatures normally appropriate to sedentary occupancy, the room humidity should be above 40% RH. Lower humidity is often acceptable for short periods. Humidity of 30% RH or below may be acceptable but precautions should be taken to limit the generation of dust and airborne irritants and to prevent static discharge from occupants. Note that for heated-only buildings in the UK, the humidity can remain below 40% RH during periods of sustained cold weather.

Shocks due to static electricity (see section 8.3.3) are unlikely with humidities above 40% RH or at lower humidities if precautions are taken in the specification of materials and equipment to prevent the build-up of static electricity.

1.3.1.4 Clothing

Clothing worn by people indoors is modified by the season and outdoor weather, as well as by the indoor thermal environment. During the summer months typical clothing ensembles in commercial premises may consist of lightweight dresses or trousers, short or long-sleeved shirts or blouses, and occasionally a suit jacket or sweater. Without jacket or sweater, these ensembles have clothing insulation values ranging from 0.35 to 0.6 clo (see definition in section 1.2.2).

During winter, people wear thicker, heavier ensembles, usually with more layers. A typical indoor winter ensemble would have an insulation value of 0.8 to 1.0 clo, although recent studies of office workers found values generally at the lower end of this range⁽¹⁷⁾.

Clothing insulation values for typical clothing ensembles are given in Table 1.2^(1,5). The insulation provided by other clothing ensembles may be estimated by summing the insulation values for individual garments, see Table 1.3⁽⁷⁾.

The wearing or otherwise of an article of clothing is equivalent in its effect on subjective feelings of warmth to raising or lowering the operative temperature. Table 1.3 shows these equivalencies, which may be used to modify the design temperature ranges given in Table 1.5 (page 1-8).

The clothing insulation provided by an individual garment consists of the effective resistance of the material from which the garment is made plus the thermal resistance of the air layer trapped between the clothing and the skin. If the thickness of this layer is reduced, e.g. by air movement or change in posture, then the thermal resistance of the air layer is reduced leading to a reduction in the overall insulation provided by the clothing. In addition, body movement such as walking can lead to a pumping action in loose clothing that forces cool air between the skin and the surrounding clothing. Therefore, factors other than the thermal resistance of the clothing, e.g. looseness of fit, also affect the clo value. The value of clothing insulation of an ensemble, if estimated from Tables 1.2 or 1.3 is not precise, but will usually be within 20%.

For sedentary occupants, the insulating properties of the chair will affect thermal comfort, see footnotes to Tables 1.2 and 1.3.

1.3.1.5 Metabolic heat production

Metabolic heat production is largely dependent on activity. Table 1.4^(1,6,7) gives metabolic rates for specific activities. For most people, daily activity consists of a mixture of specific activities and/or a combination of work and rest periods. A weighted-average metabolic rate may be used, provided that the activities frequently alternate, i.e. several times per hour.

Table 1.2 Thermal insulation values for typical clothing ensembles for work and daily wear; these values were determined by measurement on a standard thermal mannequin (adapted from ANSI/ASHRAE 55-2004⁽¹⁾ and BS ISO 9920⁽⁵⁾)

Description	Insulation level / clo
Underpants plus:	
— shirt (short sleeves), lightweight trousers, light socks, shoes	0.5
— shirt, lightweight trousers, socks, shoes	0.6
— boiler suit, socks, shoes	0.7
— shirt, trousers, socks, shoes	0.75
— shirt, boiler suit, socks, shoes	0.8
— shirt, trousers, jacket, socks, shoes	0.85
— shirt, trousers, smock, socks, shoes	0.9
Underwear (short sleeves/legs) plus:	
— tracksuit (sweater and trousers), long socks, training shoes	0.75
— shirt, trousers, jacket or sweater, socks, shoes	1.0
— shirt, trousers, boiler suit, socks, shoes	1.1
— shirt, trousers, jacket, insulated jacket, socks, shoes	1.25
— boiler suit, insulated jacket and trousers, socks, shoes	1.4
— shirt, trousers, jacket, insulated jacket and trousers, socks, shoes	1.55
— shirt, trousers, jacket, quilted jacket and overalls, socks, shoes	1.85
— shirt, trousers, jacket, quilted jacket and overalls, socks, shoes, cap, gloves	2.0
Underwear (long sleeves/legs) plus:	
— shirt, trousers, pullover, jacket, socks, shoes	1.3
— insulated jacket and trousers, insulated jacket and trousers, socks, shoes	2.2
— insulated jacket and trousers, quilted parka, quilted overalls, socks, shoes, cap, gloves	2.55
Bra and pants plus:	
— T-shirt, shorts, light socks, sandals	0.3
— petticoat, stockings, lightweight dress (with sleeves), sandals	0.45
— stockings, blouse (short sleeves), skirt, sandals	0.55
— petticoat, stockings, dress, shoes	0.7
— petticoat, shirt, skirt, thick socks (long), shoes	0.8
— shirt, skirt, sweater, thick socks (long), shoes	0.9
— shirt, trousers, jacket, socks, shoes	1.0
— blouse (long sleeves), long skirt, jacket, stockings, shoes	1.1
Pyjamas (long sleeves/legs), bath robe, slippers (no socks)	0.95

Notes:

- (1) For sedentary persons, an allowance should be made for the insulating effect of the chair, i.e. 0.15 clo for an office chair (corresponding to a temperature change of 0.9 K) and 0.3 clo for an upholstered armchair (corresponding to a temperature change of 1.8 K)
- (2) Guidance on the clo-values of a wider range of ensembles, including some non-Western forms of dress, may be found in BS EN ISO 9920⁽⁵⁾

For example, the average metabolic rate for a person typing for 50% of the time, filing while seated for 25% of the time and walking on the level for 25% of the time will be: $(0.5 \times 1.1) + (0.25 \times 1.2) + (0.25 \times 1.6) = 1.25$ met.

For people dressed in normal casual clothing ($I_{cl} = 0.5 - 1.0$ clo), a rise in activity of 0.1 met corresponds to a possible reduction of approximately 0.6 K in the design operative temperatures given in Table 1.5. A greater reduction is possible for heavily clad people.

For example, a seated person with an activity level equivalent to 1.0 met who experiences optimum comfort at 24 °C would find 22.8 °C better when carrying out filing for a period (1.2 met).

Table 1.3 Thermal insulation values for typical garments and corresponding reduction in acceptable operative temperature for sedentary occupants (adapted from BS EN ISO 7730⁽⁷⁾)

Description	Insulation level / clo	Corresponding change in operative temperature / K
Underwear:		
— briefs/underpants	0.03	0.2
— underpants (long legs)	0.10	0.6
— singlet	0.04	0.2
— T-shirt	0.09	0.5
— vest (long sleeves)	0.12	0.7
— bra	0.01	0.06
Shirts/blouses:		
— short sleeve	0.15	0.9
— light blouse (long sleeves)	0.15	0.9
— lightweight (long sleeves)	0.20	1.2
— mediumweight (long sleeves)	0.25	1.5
— flannel shirt (long sleeves)	0.30	1.8
Trousers:		
— shorts	0.06	0.4
— lightweight	0.20	1.2
— mediumweight	0.25	1.5
— flannel	0.28	1.7
Skirts/dresses:		
— light skirt (summer)	0.15	0.2
— heavy skirt (winter)	0.25	1.5
— light dress (short sleeves)	0.20	1.2
— winter dress (long sleeves)	0.40	2.4
Boiler suit	0.55	3.3
Sweaters/pullovers:		
— sleeveless waistcoat	0.12	0.7
— thin	0.20	1.2
— medium	0.28	1.7
— thick	0.35	2.1
Jackets:		
— light (summer)	0.25	1.5
— medium	0.35	2.1
— smock	0.30	1.8
Highly insulative:		
— overall/ski suit	0.90	5.4
— trousers	0.35	2.1
— jacket	0.40	2.4
— sleeveless body-warmer	0.20	1.2
Outdoor clothing:		
— coat	0.60	3.6
— jacket	0.55	3.3
— parka	0.70	4.2
— heavyweight overalls	0.55	3.3
Miscellaneous:		
— ankle socks	0.02	0.1
— thick ankle socks	0.05	0.3
— thick long socks	0.10	0.6
— stockings	0.03	0.2
— shoes (thin soles)	0.02	0.1
— shoes (thick soles)	0.04	0.2
— boots	0.10	0.6
— gloves	0.05	0.3

Note: for sedentary persons, an allowance should be made for the insulating effect of the chair, i.e. 0.15 clo for an office chair (corresponding to a temperature change of 0.9 K), and 0.3 clo for an upholstered armchair (corresponding to a temperature change of 1.8 K)

Table 1.4 Typical metabolic rate and heat generation per unit area of body surface for various activities^(1,5,7)

Activity	Metabolic rate / met	Heat generation / W·m ⁻²
Resting:		
— sleeping	0.7	41
— reclining	0.8	46
— seated, quiet	1.0	58
— standing, relaxed	1.2	70
Walking (on level):		
— 0.9 m·s ⁻¹	2.0	116
— 1.3 m·s ⁻¹	2.6	151
— 1.8 m·s ⁻¹	3.8	221
Office work:		
— reading, seated	1.0	58
— writing	1.0	58
— typing	1.1	64
— filing, seated	1.2	70
— filing, standing	1.4	81
— lifting/packing	2.1	122
Occupational:		
— cooking	1.4–2.3	81–134
— house cleaning	1.7–3.4	99–198
— seated, heavy limb movement	2.2	128
— machine sawing	1.8	105
— light machine work	1.6–2.0	93–116
— heavy machine work	3.0	175
— handling 50 kg bags	4.0	233
Leisure:		
— dancing (social)	1.4–4.4	82–256
— callisthenics/exercise	3.0–4.0	175–233
— tennis (singles)	3.6–4.0	210–233
— basketball	5.0–7.6	291–442
— wrestling (competitive)	7.0–8.7	407–506

Note: average surface area of an adult human body is about 1.8 m²

Care must be used when applying Table 1.4 due to uncertainties in measuring metabolic rates and in defining the tasks. It is reasonably accurate (i.e. $\pm 20\%$) for engineering purposes for well-defined activities with $M_a < 1.5$. However, for poorly defined activities with $M_a > 3.0$ the error may be as high as $\pm 50\%$.

1.3.2 Heat balance model of thermal comfort: predicted mean vote (PMV) and predicted percentage dissatisfied (PPD)

The human thermo-regulatory system attempts to maintain a deep-body temperature of about 37 °C. When this temperature is exceeded, the body initiates heat control mechanisms, e.g. dilation of peripheral blood vessels and sweating. In response to cold, the body instigates constriction of peripheral blood vessels, changes in muscular tone, erection of body hair and shivering. The thermo-regulatory system can maintain the appropriate deep-body temperature in a wide range of combinations of activity level and environmental variables.

The heat balance of the human body may be written as:

$$\Phi_m - \Phi_w = \Phi_{rc} + \Phi_{re} + \Phi_k + \Phi_r + \Phi_c + \Phi_e + \Phi_s \quad (1.6)$$

where Φ_m is the metabolic rate (W), Φ_w is the rate of performance of external work (W), Φ_{rc} is the rate of heat exchange

by convection in the respiratory tract ($\dot{Q}_{re}$), $\dot{Q}_{re}$ is the heat exchange by evaporation in the respiratory tract ($\dot{Q}_{re}$), $\dot{Q}_k$ is the heat flow by conduction from the surface of the clothed body ($\dot{Q}_k$), $\dot{Q}_r$ is the heat loss by radiation from the surface of the clothed body ($\dot{Q}_r$), $\dot{Q}_c$ is the heat loss by convection from the surface of the clothed body ($\dot{Q}_c$), $\dot{Q}_e$ is the heat loss by evaporation from the skin ($\dot{Q}_e$) and $\dot{Q}_s$ is the body heat storage ($\dot{Q}_s$).

In steady state conditions $\dot{Q}_s$ would be zero but this does not necessarily mean that a comfortable thermal state is achieved. It is also necessary for skin temperatures and sweat rates to be neither too high nor too low, their values for comfort depending on the metabolic rate^(18,19). Steady state conditions never truly exist, because the relation to the thermal environment is one of dynamic interaction, and comfort conditions based on the steady state are therefore approximate.

The 'predicted mean vote' (PMV) combines the influence of air temperature, mean radiant temperature, air movement and humidity with that of clothing and activity level into one value on a thermal sensation scale, see Table 1.1. The PMV is the predicted mean value of the 'votes' of a large group of persons, exposed to the same environment, and with identical clothing and activity.

Appendix 1.A1 gives an equation for PMV derived by Fanger⁽⁹⁾ and the listing (in BASIC) of a computer program for solution of the equation, based on that given in BS EN ISO 7730⁽⁷⁾. Solutions to this equation in tabular form, based on 50% saturation, are given in BS EN ISO 7730.

People are thermally dissimilar. Where a group of people is subject to the same environment, it will normally not be possible to satisfy everyone at the same time. The aim, therefore, is to create optimum thermal comfort for the whole group, i.e. a condition in which the highest possible percentage of the group is thermally comfortable.

As the individual thermal sensation votes will be scattered around the mean predicted value (i.e. PMV), it is useful also to predict the percentage of people who would be dissatisfied, taken as those who would vote $> +1$ or < -1 on the sensation scale. The predicted percentage dissatisfied (PPD) attempts to do this and is obtained from the PMV using the following equation⁽⁷⁾:

$$PPD = 100 - 95 \exp [-(0.03353 PMV^4 + 0.2179 PMV^2)] \quad (1.7)$$

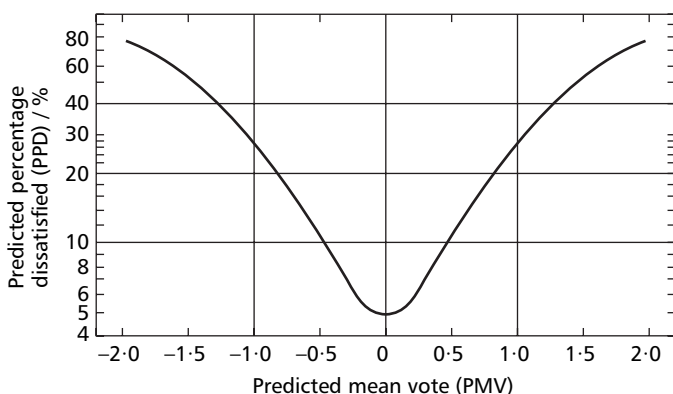


Figure 1.3 PPD as a function of PMV

The predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV) is shown in Figure 1.3. It applies to a large group of people in the same thermal environment and with identical clothing and activity level. Alternatively it may be interpreted as the notional probability that a randomly chosen person, having that clothing and activity, would experience discomfort in that thermal environment. Since PPD assumes uniform clothing, and people are often free to choose their clothing for comfort, there will normally be less discomfort than that predicted by the PPD. PPD is a function of PMV and is seriously affected by any error in the estimation of PMV.

1.3.3 Discrepancies between field-study findings and the PMV/PPD index

The PMV/PPD index is a mathematical model of human thermal physiology, calibrated against the warmth sensations reported by people during experiments in climate-controlled spaces. The index has not always been found to agree with the sensations reported by people in the circumstances of daily life, as obtained during field studies of thermal comfort⁽²⁰⁻²²⁾. Reasons for these differences are diverse and not fully understood. In general, people are found to be more tolerant of diversity in ordinary circumstances than would have been predicted from the PMV/PPD model. The greatest systematic discrepancies occur when indoor temperature is warm and outdoor temperatures are high⁽²³⁾, when PMV predicts that people would be warmer than has been found in practice, and in this circumstance empirical results from field-studies should be preferred.

1.4 Design criteria

1.4.1 General

Table 1.5 gives general guidance and recommendations on suitable winter and summer temperature ranges (together with outdoor air supply rates, filtration grades, maintained illuminances and noise ratings) for a range of room and building types. The operative temperature* ranges correspond to a predicted mean vote (PMV) of ± 0.25 , see section 1.3.2, and assume the clothing insulation and metabolic rates indicated. From these values adjustments can be made for the circumstance that the clothing and activity differ from those assumed in Table 1.5 (see Tables 1.3 and 1.4). The temperature ranges may be widened by approximately 1 °C at each end if a PMV of ± 0.5 (i.e. PPD of 10%) is acceptable.

Guidance on adapting these general recommendations to other situations is given in various sections and Table 1.6 indicates which section should be consulted for further guidance on any given design parameter.

Spaces occupied only briefly, such as bathrooms, toilets, halls and landings are outside the scope of PMV/PPD

* Operative temperature can be measured using a globe thermometer (see Appendix 1.A2), typically with a globe diameter of 0.1 m. Do not place PMV from direct sun. Temperatures can vary within a space, so readings should be taken in several places.

because the thermal steady state is not normally reached. It is often convenient for their resultant temperatures to be similar to those of adjoining spaces.

The summer comfort temperatures given in Table 1.5 apply to air conditioned buildings. Higher temperatures may be acceptable if full air conditioning is not present, and guidance on this may be found in section 1.4.2, with a detailed discussion of the adaptive approach in section 1.6.

The Fuel and Electricity (Heating) (Control) Order 1974⁽²⁴⁾ and the Fuel and Electricity (Heating) (Control)

(Amendment) Order 1980⁽²⁵⁾ prohibit the use of fuels or electricity to heat premises above 19 °C. This does not mean that the temperature in buildings must be kept below 19 °C but only that fuel or electricity must not be used to raise the temperature above this level. In Table 1.5, for some applications, the recommended winter design temperatures exceed 19 °C. In these cases, it is assumed that the recommended temperatures can be maintained by contributions from heat sources other than the heating system. These may include solar radiation, heat gains from lighting, equipment and machinery and heat gains from the occupants themselves.

Table 1.5 Recommended comfort criteria for specific applications

Building/room type	Winter operative temp. range for stated activity and clothing levels*			Summer operative temp. range (air conditioned buildings†) for stated activity and clothing levels*			Suggested air supply rate / (L.s ⁻¹ per person) unless stated otherwise	Filtration grade‡	Maintained illuminance¶ / lux	Noise ratings§ (NR)
	Temp. / °C	Activity / met	Clothing / clo	Temp. / °C	Activity / met	Clothing / clo				
Airport terminals:										
— baggage reclaim	12–19 ^[1]	1.8	1.15	21–25 ^[1]	1.8	0.65	10 ^[2]	F6–F7	200	45
— check-in areas ^[3]	18–20	1.4	1.15	21–23	1.4	0.65	10 ^[2]	F6–F7	500 ^[4]	45
— concourse (no seats)	19–24 ^[1]	1.8	1.15	21–25 _[1]	1.8	0.65	10 ^[2]	F6–F7	200	45
— customs area	18–20	1.4	1.15	21–23	1.4	0.65	10 ^[2]	F6–F7	500	45
— departure lounge	19–21	1.3	1.15	22–24	1.3	0.65	10 ^[2]	F6–F7	200	40
Art galleries — see <i>Museums and art galleries</i>										
Banks, building societies, post offices:										
— counters	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F6–F7	500	35–40
— public areas	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F5–F7	300	35–45
Bars/lounges	20–22	1.3	1.0	22–24	1.3	0.65	10 ^[2]	F5–F7	100–200 ^[5]	30–40
Bus/coach stations — see <i>Railway/coach stations</i>										
Churches	19–21	1.3	1.15	22–24	1.3	0.65	10 ^[2]	G4–F6	100–200	25–30
Computer rooms ^[6]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F7–F9	300	35–45
Conference/board rooms	22–23	1.1	1.0	23–25	1.1	0.65	10 ^[2]	F6–F7	300/500 ^[7]	25–30
Drawing offices	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F7	750	35–45
Dwellings:										
— bathrooms	20–22	1.2	0.25	23–25	1.2	0.25	15 L·s ⁻¹	G2–G4 (extract) ^[8]	150 ^[4]	—
— bedrooms	17–19	0.9	2.5	23–25	0.9	1.2	0.4–1 ACH to control moisture ^[8]	G2–G4	100 ^[4]	25
— hall/stairs/landings	19–24 ^[1]	1.8	0.75	21–25 ^[1]	1.8	0.65	—	—	100	—
— kitchen	17–19	1.6	1.0	21–23	1.6	0.65	60 L·s ⁻¹	G2–G4 (extract) ^[8]	150–300	40–45
— living rooms	22–23	1.1	1.0	23–25	1.1	0.65	0.4–1 ACH to control moisture ^[8]	G2–G4	50–300	30
— toilets	19–21	1.4	1.0	21–23	1.4	0.65	> 5 ACH	G2–G4	100 ^[4]	—
Educational buildings:										
— lecture halls ^[9]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	G4–G5	500 ^[10]	25–35
— seminar rooms	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	G4–G5	300 ^[10]	25–35
— teaching spaces ^[9]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	G4–G5	300 ^[10]	25–35
Exhibition halls	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	G3–G4	300	40
Factories:										
— heavy work	11–14 ^[11]	2.5	0.85	— ^[12]	—	—	— ^[13]	Depends on use	— ^[14,15]	50–65
— light work	16–19	1.8	0.85	— ^[12]	—	—	— ^[13]	Depends on use	— ^[14,15]	45–55
— sedentary work	19–21	1.4	1.0	21–23	1.4	0.65	— ^[13]	Depends on use	— ^[14,15]	45
Fire/ambulance stations:										
— recreation rooms	20–22	1.3	1.0	22–24	1.3	0.65	10 ^[2]	F5	200	35–40
— watchroom	22–23	1.1	1.0	24–26	1.1	0.65	10 ^[2]	F5	200	35–40

Table 1.5 Recommended comfort criteria for specific applications — *continued*

Building/room type	Winter operative temp. range for stated activity and clothing levels*			Summer operative temp. range (air conditioned buildings†) for stated activity and clothing levels*			Suggested air supply rate / (L.s ⁻¹ per person) unless stated otherwise	Filtration grade‡	Maintained illuminance¶ / lux	Noise ratings§ (NR)
	Temp. / °C	Activity / met	Clothing / clo	Temp. / °C	Activity / met	Clothing / clo				
Garages:										
— parking	—	—	—	—	—	—	6 ACH (extract)	—	75/300	55
— servicing	16–19	1.8	0.85	—	—	—	—	G2–G3	300/500	45–50
General building areas:										
— corridors	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	— ^[16]	100	40
— entrance halls/lobbies	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	— ^[16]	100/200 ^[4]	35–40
— kitchens (commercial)	15–18	1.8	1.0	18–21	1.8	0.65	— ^[17]	G2–G4	500	40–45
— toilets	19–21	1.4	1.0	21–23	1.4	0.65	> 5 ACH	G4–G5	200	35–45
— waiting areas/rooms	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	— ^[16]	200	30–35
Hospitals and health care buildings:										
— bedheads/wards	22–24	0.9	1.4	23–25	0.9	1.2	10 ^[2]	F7–F9	— ^[18]	30
— circulation spaces (wards) ^[19]	19–24 ^[1]	1.8	0.75	21–25 ^[1]	1.8	0.65	10 ^[2]	F7–F9	— ^[18]	35
— consulting/treatment rooms	22–24	1.4	0.55	23–25	1.4	0.45	10 ^[2]	F7–F9	300/500 ^[18]	30
— nurses' station ^[19]	19–22	1.4	0.9	21–23	1.4	0.65	10 ^[2]	F7–F9	— ^[18]	35
— operating theatres	17–19	1.8	0.8	17–19	1.8	0.8	0.65–1.0 m ³ .s ⁻¹	F9	— ^[18]	30–35
Hotels:										
— bathrooms	20–22	1.2	0.25	23–25	1.2	0.25	12 ^[2]	F5–F7	150	40
— bedrooms	19–21	1.0	1.0	21–23	1.0	1.2	10 ^[2]	F5–F7	50/100	20–30
Ice rinks	12	—	—	—	—	—	3 ACH	G3	— ^[20]	40–50
Laundries:										
— commercial	16–19	1.8	0.85	— ^[12]	—	—	— ^[21]	G3–G4	300/500	45
— launderettes	16–18	1.6	1.15	20–22	1.6	0.65	— ^[21]	G2–G3	300	45–50
Law courts	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F5–F7	300	25–30
Libraries:										
— lending/reference areas ^[22]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F5–F7	200	30–35
— reading rooms	22–23	1.1	1.0	24–25	1.1	0.65	10 ^[2]	F5–F7	500 ^[23]	30–35
— store rooms	15	—	—	—	—	—	—	F6–F8	200	—
Museums and art galleries:										
— display ^[24]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F7–F8	200 ^[25]	30–35
— storage ^[24]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F7–F8	50 ^[25]	30–35
Offices:										
— executive	21–23	1.2	0.85	22–24	1.2	0.7	10 ^[2]	F7	300–500 ^[7]	30
— general	21–23	1.2	0.85	22–24	1.2	0.7	10 ^[2]	F6–F7	300–500 ^[7]	35
— open-plan	21–23	1.2	0.85	22–24	1.2	0.7	10 ^[2]	F6–F7	300–500 ^[7]	35
Places of public assembly:										
— auditoria ^[26]	22–23 ^[1]	1.0	1.0	24–25	1.1	0.65	10 ^[2]	F5–F7	100–150 ^[5]	20–30
— changing/dressing rooms	23–24	1.4	0.5	23–25	1.4	0.4	10 ^[2]	F5–F7	300	35
— circulation spaces	13–20 ^[1]	1.8	1.0	21–25 ^[1]	1.8	0.65	10 ^[2]	G4–G5	200	40
— foyers ^[27]	13–20 ^[1]	1.8	1.0	21–25 ^[1]	1.8	0.65	10 ^[2]	F5–F7	200	40
— multi-purpose halls ^[28]	—	—	—	—	—	—	10 ^[2]	G4–G5	300	—
Prison cells	19–21	1.0	1.7	21–23	1.0	1.2	10 ^[2]	F5	100 ^[4]	25–30
Railway/coach stations:										
— concourse (no seats)	12–19 ^[1]	1.8	1.15	21–25 ^[1]	1.8	0.65	10 ^[2]	G4–G5	200	45
— ticket office	18–20	1.4	1.15	21–23	1.4	0.65	10 ^[2]	G4–G5	300	40
— waiting room	21–22	1.1	1.15	24–25	1.1	0.65	10 ^[2]	G4–G5	200	40
Restaurants/dining rooms	21–23	1.1	1.0	24–25	1.1	0.65	10 ^[2]	F5–F7	50–200 ^[5]	35–40
Retailing:										
— shopping malls	12–19 ^[1]	1.8	1.15	21–25 ^[1]	1.8	0.65	10 ^[2]	G4–G5	50–300	40–50
— small shops, department stores ^[22]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F5–F7	500	35–40
— supermarkets ^[29]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F5–F7	500	35–45

Table 1.5 Recommended comfort criteria for specific applications — *continued*

Building/room type	Winter operative temp. range for stated activity and clothing levels*			Summer operative temp. range (air conditioned buildings†) for stated activity and clothing levels*			Suggested air supply rate / (L.s ⁻¹ per person) unless stated otherwise	Filtration grade‡	Maintained illuminance¶ / lux	Noise rating§ (NR)
	Temp. / °C	Activity / met	Clothing / clo	Temp. / °C	Activity / met	Clothing / clo				
Sports halls ^[30] :										
— changing rooms	22–24	1.4	0.55	24–25	1.4	0.35	6–10 ACH	G3	100 ^[20]	35–45
— hall	13–16	3.0	0.4	14–16	3.0	0.35	10 ^[2]	G3–F5	300 ^[20]	40–50
Squash courts ^[30]	10–12	4.0	0.25	—	—	—	4 ACH	G3	— ^[20]	50
Swimming pools:										
— changing rooms	23–24	1.4	0.5	24–25	1.4	0.35	10 ACH	G3	100 ^[20]	35–45
— pool halls	23–26 ^[31]	1.6	< 0.1	23–26 ^[31]	1.6	< 0.1	0–15 L.s ⁻¹ .m ⁻² (of wet area)	G3	— ^[20]	40–50
Television studios ^[26]	19–21	1.4	1.0	21–23	1.4	0.65	10 ^[2]	F5–F7	— ^[32]	25

Notes: Except where indicated^[1], temperature ranges based on stated values of met and clo and a PMV of ± 0.25 . Upper temperature of stated range may be increased and lower temperature decreased by approximately 1°C if PMV of ± 0.5 (i.e. 90 PPD) is acceptable (see section 1.3.2). Calculation assumes RH = 50% and $v_r = 0.15 \text{ m.s}^{-1}$. Insulation value of chair assumed to be 0.15 clo for all applications except dwellings, for which 0.3 has been assumed.

* See section 1.4.3. for additional data and variations due to different activities and levels of clothing.

† Higher temperatures may be acceptable if air conditioning is not present, see section 1.3.1.

‡ See also chapter 8, Table 8.2, which gives requirements for specific pollutants.

§ Illumination levels given thus: 200–500 indicate that the required level varies through the space depending on function and/or task. Illumination levels given thus: 300/500, indicate that one or the other level is appropriate depending on exact function. Illumination levels in this table give only a general indication of requirements. Reference must be made to the table of recommended illuminances in the SLL *Code for lighting*⁽³³⁾ and CIBSE/SLL Lighting Guides for design guidance on specific applications (see notes to individual entries).

¶ See also Table 1.11.

- | | |
|--|--|
| <p>[1] Based on PMV of ± 0.5</p> <p>[2] Assumes no smoking. For spaces where smoking is permitted, see section 1.7.2.</p> <p>[3] Based on comfort requirements for check-in staff</p> <p>[4] Local illumination may be required for specific tasks</p> <p>[5] Dimming normally required</p> <p>[6] Follow computer manufacturers' recommendations if necessary, otherwise design for occupant comfort</p> <p>[7] Refer to Lighting Guide LG7: <i>Office lighting</i>⁽³⁴⁾</p> <p>[8] Refer to The Building Regulations: Part F1: Means of ventilation⁽³⁵⁾</p> <p>[9] Podium may require special consideration to cater for higher activity level</p> <p>[10] Refer to Lighting Guide LG5: <i>The visual environment in lecture, conference and teaching spaces</i>⁽³⁶⁾</p> <p>[11] The Workplace (Health, Safety and Welfare) Regulations 1992⁽³⁷⁾ require 13 °C where there is severe physical effort</p> <p>[12] In the UK, air conditioning is not normally appropriate for this application. Cooling may be provided by local air jets. Some applications (e.g. steel mills, foundries) require special attention to reduce risk of heat stress</p> <p>[13] As required for industrial process, if any, otherwise based on occupants' requirements</p> <p>[14] Depends on difficulty of task</p> <p>[15] Refer to Lighting Guide LG1: <i>The industrial environment</i>⁽³⁸⁾</p> <p>[16] Filtration should be suitable for the areas to which these spaces are connected</p> | <p>[17] See CIBSE Guide B⁽³⁹⁾, section 2.3.6.</p> <p>[18] Refer to SLL <i>Code for lighting</i>⁽³³⁾</p> <p>[19] Design for clothing and activity levels appropriate to nurses</p> <p>[20] Refer to Lighting Guide LG4: <i>Sports</i>⁽⁴⁰⁾</p> <p>[21] As required for removal of heat and moisture</p> <p>[22] Based on comfort requirements of staff</p> <p>[23] Study tables and carrels require 500 lux</p> <p>[24] Conditions required for preservation/conservation of exhibits may override criteria for human comfort; abrupt changes in temperature and humidity should be avoided.</p> <p>[25] Critical conservation levels may apply, refer to Lighting Guide LG8: <i>Lighting in museums and art galleries</i>⁽⁴¹⁾</p> <p>[26] Performers may have wider range of met and clo values than audience, along with higher radiant component, necessitating special provision</p> <p>[27] Dependent on use</p> <p>[28] Design for most critical requirement for each parameter</p> <p>[29] Special provision required for check-out staff to provide conditions as for small shops</p> <p>[30] Audience may require special consideration depending on likely clothing levels</p> <p>[31] 2 °C above pool water temperature, to a maximum of 30 °C</p> <p>[32] Depends on production requirements</p> |
|--|--|

Table 1.6 Location of detailed guidance to environmental criteria

Parameter	Application and conditions	Section or table reference
Temperature	Known application, normal conditions	Table 1.5
	Other levels of clothing and/or activity	Section 1.3.1
Humidity	Relating to temperature	Section 1.3.1.3
	Relating to comfort	Section 1.3.1.3; ch. 8, section 8.3
	Relating to static electricity	Section 1.11.3; ch. 8, section 8.3
Outdoor air supply	Known application, odour sources unknown	Table 1.5 and section 1.7.2
	Specific pollutants, exposure limits	Chapter 8, section 8.4.2
	Specific pollutants, known emission rates, design exposure limits	Chapter 8, section 8.4.4
Filter selection	—	Table 1.5; ch. 8, section 8.4.3.2
Visual criteria	—	Table 1.5 and section 1.8
Noise	—	Table 1.5 and section 1.9
Vibration	—	Section 1.10
Electromagnetic fields	—	Section 1.11.1
Ionisation	—	Section 1.11.2
Static electricity	—	Section 1.11.3

1.4.2 Summer design temperatures and overheating criteria for free-running buildings in the UK

1.4.2.1 Introduction

Table 1.5 provides guidance for indoor temperatures for buildings with full year round temperature control. However the guidance is not always applicable to buildings without cooling or air conditioning systems under summertime operation. For free-running* modes, such as non-air conditioned buildings operating in summer, higher internal temperatures may be generally acceptable. Experience indicates, and research confirms, that people adapt over time and a temperature that may feel uncomfortably warm in a sudden short hot spell in April may be quite acceptable during warm weather in July.

The adaptive approach to comfort, see section 1.6, considers the way in which acceptable indoor conditions are related to those found outside. In the UK, in free-running (i.e. non-air conditioned) office buildings in the summer, research has shown that during warm summer weather 25 °C is an acceptable indoor temperature. At this temperature few people will be uncomfortable. As the indoor temperature rises from this design value an increasing number of people may become uncomfortable and there may be a decline in the productivity of office work and of learning in schools^(26,27). The peak temperature during the day should preferably not be more than 3 K above the design temperature, giving a benchmark maximum of 28 °C.

* Free-running can be defined as a mode of operation of a building rather than a specific building type. A building can be said to be free-running when it is not, at the time in question, consuming energy for the purpose either of heating or of cooling. Thus, typically, non-air conditioned UK buildings are in the free-running mode in summer, but not in winter. (Incidental gains from occupancy, equipment, insolation and use of energy by desk or ceiling fans are not considered in the classification.) The converse of the free-running mode is therefore the heated or cooled mode. This includes typical HVAC all the time and normal UK buildings during the heating season. The status of mixed mode buildings will vary.

1.4.2.2 Summer design conditions

For the free-running mode Table 1.7 indicates acceptable values for general summer indoor temperatures for a range of buildings.

However, in normal operation, it may not be possible to meet these summer internal design criteria under all conditions without the provision of mechanical cooling, and it is necessary to analyse the risk of overheating and aim to minimise the length and severity of any discomfort.

1.4.2.3 Overheating risk

In the past the summertime peak indoor temperature has been calculated for proposed building designs to give a measure of overheating or to decide whether cooling is required. However it is now recognised that more detailed analysis is needed, that considers both the frequency and the length of time that high temperatures may occur.

Summertime thermal performance of buildings is usually measured against a benchmark temperature that should not be exceeded for a designated numbers of hours or a percentage of the annual occupied period. The benchmark

Table 1.7 General summer indoor comfort temperatures for non-air conditioned buildings

Building type	Operative temp. for indoor comfort in summer / °C	Notes
Offices	25	Assuming warm summer conditions in UK
Schools	25	Assuming warm summer conditions in UK
Dwellings:		
— living areas	25	Assuming warm summer conditions in UK
— bedrooms	23	Sleep may be impaired above 24 °C
Retail	25	Assuming warm summer conditions in UK

temperature is usually related to the likelihood of discomfort, although it may be related to other factors, such as productivity or health. When the benchmark temperature is exceeded the building is said to have 'overheated' and if this occurs for more than the designated amount of time the building is said to suffer from 'overheating'. Accordingly, a design target for the assessment of overheating risk is set and this is called the overheating criterion.

1.4.2.4 Benchmark summer temperatures and overheating criteria

There has been little generally accepted UK guidance on benchmark summer peak temperatures or overheating criteria for use in the design of non-air conditioned buildings or spaces, with the exception of schools, where guidance is given in DfES Building Bulletin BB87⁽³⁰⁾, to which standard Building Regulations Approved Document L2⁽²⁸⁾ now refers.

CIBSE has undertaken considerable consultation and research on the impact of climate change on the indoor environment and on weather data. CIBSE TM36⁽²⁹⁾ provides an extensive discussion on overheating criteria, from which the guidelines given in Table 1.8 have been developed. This table gives guideline benchmark summer peak temperatures and overheating criteria for use in design for three non-air conditioned building types: offices, schools and dwellings. However, given the probable impact of climate change, this guidance will be kept under review.

It is recommended that the CIBSE Design Summer Years (DSYs) are used to assess the overheating risk (see section 5.10.4.1 for guidance on the assessment of overheating risk) as these provide a more stringent test of overheating risk than do the CIBSE Test Reference Years (TRYs) as the

Table 1.8 Benchmark summer peak temperatures and overheating criteria

Building	Benchmark summer peak temp. / °C	Overheating criterion
Offices	28	1% annual occupied hours over operative temp. of 28 °C
Schools	28	1% annual occupied hours over operative temp. of 28 °C
Dwellings:		
— living areas	28	1% annual occupied hours over operative temp. of 28 °C
— bedrooms	26	1% annual occupied hours over operative temp. of 26 °C

* DfES Building Bulletin BB87⁽³⁰⁾ recommends an allowable overheating criterion of 80 occupied hours in a year over an air temperature of 28 °C.

Notes:

- (1) It is reasonable to calculate the percentage of occupied hours over a year to reflect true hours of occupation, e.g. 08:00–18:00, and to allow for 5-, 6- or 7-day working as appropriate.
- (2) It is recommended that the overheating criteria be assessed against the CIBSE Design Summer Years (DSYs) using the calculation methods recommended in chapter 5, section 5.10.4.1. It is incumbent upon the designer to ensure that any software used for the purpose of predicting overheating risk is validated for that purpose and operated in accordance with quality assurance procedures described in chapter 5.

peak summer temperatures in the former are significantly warmer than those in the latter. CIBSE Design Summer Years are available for 14 UK locations, see chapter 2, section 2.1.2.

1.4.2.5 Peak indoor temperatures in operation

Although design can predict and can seek to limit the length and degree of overheating, in operation temperatures will exceed design values during hot spells. During hot summers, internal temperatures may rise above the design temperature and could also rise above the benchmark summer peak temperatures for periods of the day. It then becomes the responsibility of the building owner/operator to recognise this situation and to act to minimise the length and severity of any discomfort.

To date there has been little guidance on peak indoor temperatures in operation. CIBSE has reviewed this area and the following summarises CIBSE guidance on peak temperatures for some types of non-air conditioned UK building in summer.

Offices (non-air conditioned)

Table 1.7 recommends 25 °C as an acceptable summer indoor design operative temperature for non-air conditioned office buildings, and Table 1.8 recommends limiting the expected occurrence of operative temperatures above 28 °C to 1% of the annual occupied period (e.g. around 25–30 hours).

Between 25 °C and 28 °C increasing numbers of people may feel hot, uncomfortable and show lower productivity. Indoor operative temperatures that stay at or over 28 °C for long periods of the day will, except during prolonged hot spells, result in dissatisfaction for many occupants.

Good practice ways to reduce discomfort for occupants of office buildings in hot summer conditions when indoor operative temperatures rise above 25 °C include:

- relaxation of formal office dress to encourage individual adaptation to conditions
- individual control over the thermal environment, where practicable, such as by opening windows, the use of blinds, or moving out of sunny areas
- flexible working so people can work at more comfortable times
- availability of hot* or cold drinks
- increased air movement; e.g. the cooling effect of local fans can be equivalent to reducing the operative temperature by around 2 K.

Indoor operative temperatures of 30 °C or more are rarely acceptable to occupants of office buildings in the UK.

Schools

The guidance given above for offices is also applicable to non-air conditioned schools, with the current probable exception of flexible working.

* Hot drinks can be very beneficial in hot weather because they trigger the sweating response

Retail premises

Many retail premises are air conditioned, as the additional heat gains due to display glazing and lighting necessitate this. Non-air conditioned retail outlets are of two main kinds: small premises and large 'retail sheds'.

The good practice guidelines outlined for offices above are applicable and, in particular, the use of additional air movement is likely to be beneficial. Both increased natural ventilation and the use of local fans are recommended and should be considered as part of the design process. Further guidance on natural ventilation strategies is given in CIBSE AM10⁽³¹⁾.

Retail sheds can be hot in hot spells and could exceed 30 °C in the occupied zone for short periods of time. The majority of customers visit for short periods and will tend to have adapted to external conditions by dressing accordingly. For staff, some further relaxation in dress code may be acceptable to management, which could enable these temperatures to be tolerated for short periods. Conditions for staff in fixed locations such as the checkout and enquiry areas should be particularly considered, as these locations limit the opportunity for individual adaptation.

Industrial buildings

The guidance given above for offices and retail premises is generally applicable to non-air conditioned industrial buildings. However, depending on the processes carried out within the space, other criteria, such as heat stress, may need to be considered.

Dwellings

The individual has more freedom to adapt to conditions at home than at work. Bedroom temperatures are likely to be more critical than living area temperatures as most people find sleeping difficult in the heat. Research⁽³²⁾ has shown that high bedroom temperatures can result in poor sleep quality and poor performance on the following day at work. This is further discussed in section 1.6. The use of shading to reduce solar gain during the day and of night-time ventilation when feasible can reduce internal night-time temperatures. Additional air movement from quiet fans can also help improve comfort. CIBSE TM36⁽²⁹⁾ provides further discussion and relevant case studies.

1.5 Other factors potentially affecting comfort

1.5.1 Temperature variations

Relatively slow variations in temperature produce results which are directly predictable at any time from the steady state relationships between temperature and subjective sensations⁽⁴²⁾. As long as changes in operative temperature are within the ranges shown in Table 1.5, no significant discomfort should result. For guidance on day-to-day changes in response to outdoor temperature see section 1.6.

1.5.2 Age

Studies^(17,43–46) have found that at a given activity and clothing level the thermal environments preferred by older people did not differ significantly from those preferred by younger ones. The lower metabolism in older people is compensated by a lower evaporative loss⁽⁴⁷⁾.

1.5.3 Gender

Experiments^(8,17,44) have shown that at the same activity and clothing levels men and women preferred almost the same thermal environments. Women's skin temperature and evaporative loss are slightly lower than those for men, and this balances the slightly lower metabolic rate of women. The reason that women sometimes prefer higher ambient temperatures to those preferred by men may be explained by the lower thermal insulation provided by some clothing ensembles worn by women.

1.5.4 Colour of surfaces and lighting

Studies^(12,48) have found no significant relationship between the colour of interior surfaces or lighting and perceptions of thermal comfort.

1.5.5 Occupants' state of health

There is limited knowledge of the comfort requirements for people who are ill, disabled, undergoing treatments involving drugs etc. The comfort of immobilised people will depend on the insulation of their clothes or bed-clothes, along with clinical factors related to the nature of the illness or disability and the treatment regime. Recent studies have indicated that disabled people are more varied in their thermal responses than is the general population. It is therefore important that they should be given individual control over their thermal environment if it is practical to provide it^(49,50).

1.5.6 Vertical air temperature differences^(51–53)

A relationship between vertical air temperature differences and the percentage of occupants who are likely to be dissatisfied is given in Figure 1.4. Studies have focused on a rise in temperature with distance from the floor. In general, it is recommended that the gradient should be not more than 3 K between ankles and head⁽⁷⁾. If air velocities are higher at floor level than across the upper part of the body then a maximum gradient of 2 K·m⁻¹ is recommended.

1.5.7 Horizontal air temperature differences

The temperature at any given position within the occupied zone of a room should normally be within the ranges specified in Table 1.5. However, in rooms where people are free to choose their location, a variety of thermal environment may be advantageous, and increase the likelihood of comfort.

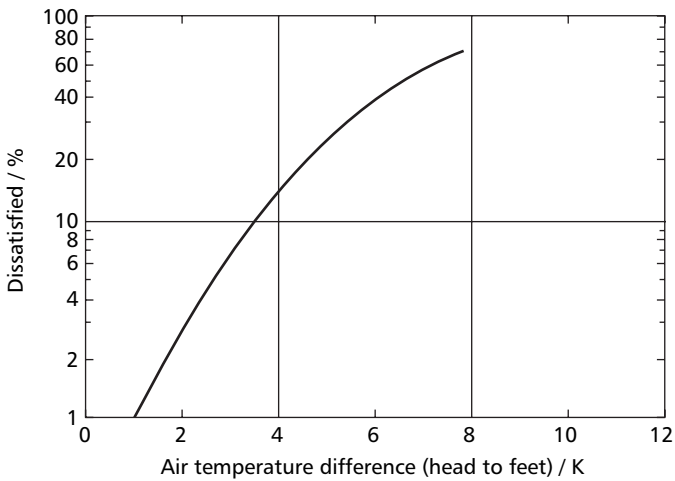


Figure 1.4 Percentage dissatisfied as a function only of vertical air temperature difference between head and ankles⁽⁵¹⁾

1.5.8 Warm or cold floors

Local discomfort of the feet can be caused by the floor temperature being too high or too low.

For rooms in which occupants spend much of their time with bare feet (e.g. swimming pools, bathrooms, dressing rooms etc.) or with their bodies in contact with the floor (e.g. gymnasia, kindergartens etc.), studies have found that the flooring material is important^(54,55). Comfort ranges for

Table 1.9 Comfortable temperature ranges for typical flooring materials

Material	Surface temperature range / °C
Textiles	21–28
Pine wood	21.5–28
Oak wood	24.5–28
Hard thermoplastic floor covering	24–28
Concrete	26–28

Note: data from laboratory experiments; 0.6 clo, 10 min standing exposures, subjects otherwise in thermal comfort (operative temperature ≈24 °C). The range is that in which fewer than 15% would be expected to report foot discomfort

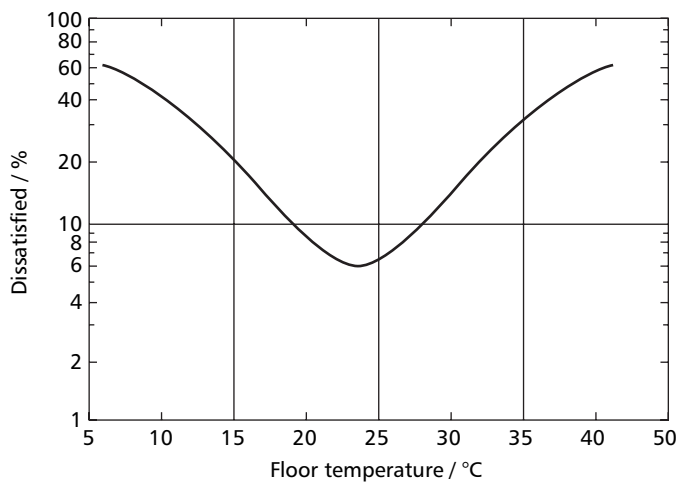


Figure 1.5 Percentage dissatisfied as a function of floor temperature only⁽⁵¹⁾; derived from climate laboratory experiments; sedentary and walking subjects combined, college age and elderly, light footwear, 3 h exposures

surface temperature of some typical flooring materials are given in Table 1.9.

For floors occupied by people wearing normal footwear, flooring material is unimportant. Studies have found an optimal surface temperature of 25 °C for sedentary and 23 °C for standing or walking persons^(56–58). The floor temperature is not critical. Figure 1.5 shows percentage dissatisfied as a function of floor temperature for seated and standing people combined. In general, it is recommended that floor temperature should be in the range 19–29 °C. (For the design of floor heating systems, BS EN 1264⁽⁵⁹⁾ suggests that a surface temperature of 29 °C is appropriate.)

1.5.9 Asymmetric thermal radiation

There are three cases of asymmetric radiation that may lead to discomfort:

- *local cooling*: radiation exchange with adjacent cool surfaces, such as cold windows
- *local heating*: radiation from adjacent hot surfaces, such as overhead lighting or overhead radiant heaters
- *intrusion of short-wavelength radiation*: such as solar radiation through glazing.

Radiant temperature asymmetry is defined as the difference between the plane radiant temperatures on opposite sides of the human body. The plane radiant temperature is the radiant temperature resulting from surfaces on one side of a notional plane passing through the point or body under consideration. The measurement and calculation of radiant temperature asymmetry are dealt with in BS EN ISO 7726⁽⁴⁾.

The radiant temperature asymmetry in the vertical direction is calculated from the difference in plane radiant temperature between the upper and lower parts of the space with respect to a small horizontal plane, taken as 0.6 m above the floor for a seated person and 1.1 m above the floor for a standing person.

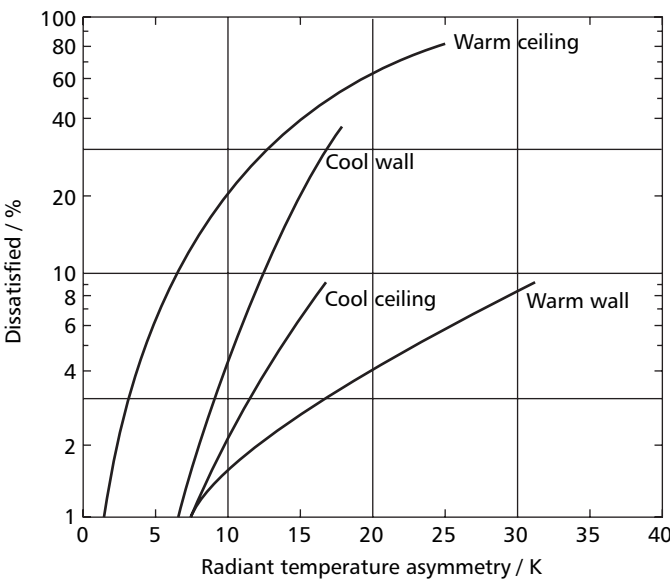


Figure 1.6 Percentage dissatisfied due to asymmetric radiation only^(60,61); data from climate chamber experiments, air temperature adjusted to compensate for cool or warm wall or ceiling; subjects seated, thermally neutral, 0.6 clo, resultant temperature 25 °C, 30 min exposures

In the horizontal direction it is the difference between plane radiant temperatures in opposite directions from a small vertical plane with its centre located 0.6 m (seated) or 1.1 m (standing) above the floor.

Figure 1.6^(60,61) can be used to predict dissatisfaction where surface temperatures are known and radiant temperature asymmetry can be calculated.

It is recommended that radiant temperature asymmetry should contribute no more than 5% dissatisfied. Hence, in the vertical direction radiant temperature asymmetry (warm ceiling) should be less than 5 K, and in the horizontal direction (cool wall) less than 10 K. Similarly, for a cool ceiling the maximum recommended radiant temperature asymmetry is 14 K and for a warm wall 23 K.

It appears that comfort conditions in rooms with chilled ceiling and displacement ventilation conform to this advice, and with that for temperature gradients⁽⁶²⁾.

1.5.10 Low temperature radiant heating systems

It may not be possible to provide an economic ceiling-mounted radiant heating system while keeping the radiant temperature asymmetry within 5 K. For such systems it is permissible to design for a maximum radiant temperature asymmetry of 10 K, although this could lead to 20% dissatisfaction. Based on this criterion, Figure 1.7 suggests design limits of downward emission from horizontal panels for various head to panel distances.

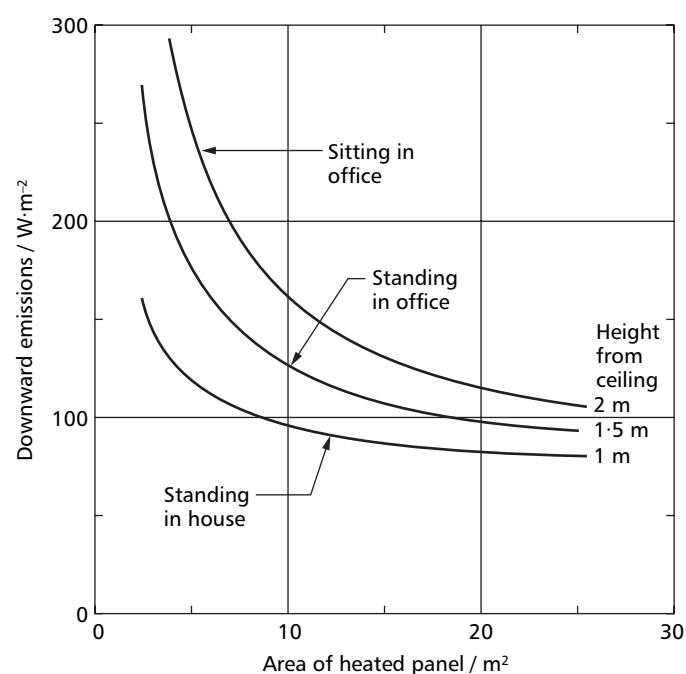


Figure 1.7 Downward heat emission from centre of a square low-temperature radiant panel

1.5.11 Lighting

Another possible source of radiant heat is lighting. Fluorescent lamps are relatively cool. For example, for an illuminance of 1000 lux, fluorescent lighting would increase the mean radiant temperature such that it would

be necessary to reduce the air temperature by 0.25–0.5 K, compared to the same room without lighting, in order to maintain the same operative temperature. For the same illuminance provided by tungsten filament lamps, a reduction in the air temperature of about 1.5 K would be required. Radiant temperature asymmetry could be a problem in the latter case.

1.5.12 Short-wave radiation

When solar radiation falls on a window the transmitted short-wave radiation is almost all absorbed by the internal surfaces. This raises the temperature of these surfaces which, as well as contributing to the convective gain, augments the mean radiant temperature. In comfort terms, the most significant component is the direct radiation falling on occupants near the window⁽⁶³⁾.

Figure 1.8 shows the elevation of mean radiant temperature and operative temperature due to incident short-wave radiation. Clothing absorptance of short-wave radiation will depend on the colour and the texture but can be taken as 0.7 for typical summer wear and 0.8 for the darker clothing typically worn in cold climates.

People exposed to direct solar gain may also experience discomfort due to glare and veiling reflections. Where extensive glazed areas face other than north, it will be necessary to consider the provision of solar control devices.

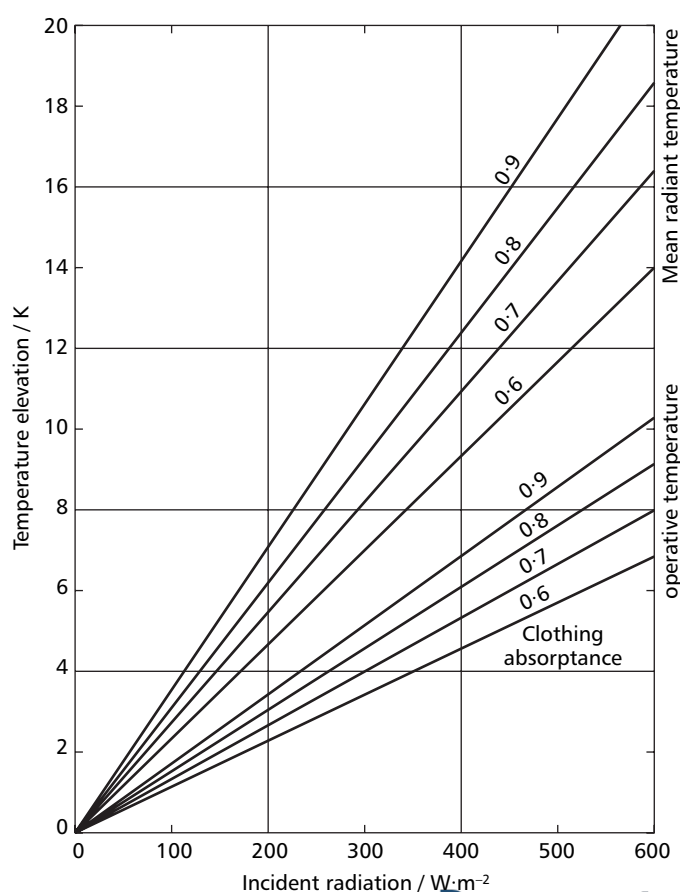


Figure 1.8 Effect of short-wave radiation on the mean radiant and operative temperatures

1.6 The adaptive approach and field-studies of thermal comfort

1.6.1 Introduction

The adaptive approach⁽⁶⁴⁾ to thermal comfort has been developed from field studies of people in daily life. While lacking the rigour of laboratory experiments, field studies have a more immediate relevance to ordinary living conditions; for examples see references 20, 65 and 66.

The adaptive method, unlike the heat-exchange method, does not require knowledge of the clothing insulation and the metabolic rate in order to establish the temperature required for thermal comfort. Rather it is a behavioural approach, and rests on the observation that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity. They do this by making adjustments (adaptations) to their clothing, activity and posture, as well as to their thermal environment.

1.6.2 Occupant control

Adaptation is assisted by the provision of control over the thermal environment. So where practicable, convenient and effective means of control should be provided, sufficient for the occupants to adjust the thermal environment to their own requirements. This 'adaptive opportunity'⁽⁶⁷⁾ may be provided, for instance, by ceiling fans and openable windows in summertime, or by local temperature controls in winter. A control band of ± 2 K (or an equivalent band of air speed)⁽⁶⁸⁾ should be sufficient to accommodate the great majority of people. Individual control is more effective in promoting comfort than is group-control.

1.6.3 Customary thermal environments and comfort

People tend to become well-adapted to thermal environments they are used to, and find them comfortable. The building services engineer should therefore aim to provide a thermal environment that is within the range customary for the particular type of accommodation, according to climate, season and cultural context. The values of the operative temperature given in Table 1.5 can be regarded as estimates of such customary temperatures, established from professional experience, and appropriate in buildings that are heated or air conditioned, and set in temperate climates.

1.6.3.1 Drift of comfort conditions

These customary temperatures, each intended to be a group-optimum for comfort, are not fixed, but are subject to gradual drift in response to changes in both outdoor and indoor temperature, and are modified by climate and social custom. A departure from the current group-optimum temperature (referred to hereafter as the 'comfort temperature'), if suddenly imposed upon the occupants, is likely to provoke discomfort and complaint, while a similar change, occurring gradually over several

days or longer, would be compensated by a corresponding change in clothing, and would not provoke complaint.

1.6.3.2 Dress codes

The extent of seasonal variation in indoor temperature that is consistent with comfort depends on the extent to which the occupants wear cool clothing in summertime and warm clothing in wintertime. Some dress codes restrict this freedom, and therefore have consequences for thermal design, for services provision, and consequently for energy consumption. Organisations that have dress codes should be made aware of this, and be encouraged to incorporate adequate seasonal flexibility.

1.6.3.3 Temperature drift during a day

Field research can indicate the extent and rapidity of clothing adaptation, and hence of the temperature drifts that are acceptable. During any working day, field-studies have found rather little systematic clothing-adjustment in response to variations in room temperature⁽⁶⁹⁾, so it is desirable that the temperature during occupied hours in any day should not vary much from the comfort temperature. Temperature drifts within ± 1 K of the comfort temperature would attract little notice, while ± 2 K would be likely to attract attention and could result in mild discomfort among a small proportion of the occupants.

1.6.3.4 Temperature drift over several days

Clothing and other adjustments in response to day-on-day changes in temperature, such as occur when a building is responding to weather and seasonal changes, occur quite gradually⁽⁶⁹⁻⁷¹⁾, and take a week or so to complete. So it is desirable that the day-to-day change in mean indoor operative temperature during occupied hours should not normally exceed about 1 K, nor should the cumulative change over a week exceed about 3 K. These figures apply to sedentary or lightly active people.

1.6.4 Probable comfort temperatures in relation to climate

During the summer months many buildings in temperate climates are free-running (i.e. not heated or cooled). The temperatures in such buildings will change according to the weather outdoors, as will the clothing of the occupants. Even in air conditioned buildings the clothing has been found to change according to the weather^(22,70). As a result the temperature that people find comfortable indoors also changes^(22,65,72). Guidance for limits on indoor temperature may therefore be related to the outdoor temperature^(1,73). The relationship between indoor comfort and outdoor temperature has usually been expressed in terms of the monthly mean of the outdoor temperature^(1,72). Important variations of outdoor temperature do however occur at much shorter than monthly intervals. Adaptive theory suggests that people respond on the basis of their thermal experience, with more recent experience being more important. A running mean of outdoor temperatures, weighted according to their distance in the past, is therefore more appropriate than a monthly mean.

1.6.4.1 Exponentially weighted running mean outdoor temperatures

An exponentially weighted running mean of the daily mean outdoor air temperature, θ_{rm} , is an appropriate expression of the outdoor temperature, and is calculated from the formula:

$$\theta_{rm} = (1 - \alpha_{rm})[\theta_{e(d-1)} + \alpha_{rm} \theta_{e(d-2)} + \alpha_{rm}^2 \theta_{e(d-3)} \dots] \quad (1.8)$$

where α_{rm} is a constant between 0 and 1 which defines the speed at which the running mean responds to outdoor temperature, $\theta_{e(d)}$ is the daily mean outdoor temperature (°C) for the previous day, $\theta_{e(d-1)}$ is the daily mean outdoor temperature (°C) for the day before that, and so on.

The use of an infinite series would be impracticable were not equation 1.8 reducible to the form:

$$\theta_{rm(n)} = (1 - \alpha_{rm}) \theta_{e(d-1)} + \alpha_{rm} \theta_{rm(n-1)} \quad (1.9)$$

where $\theta_{rm(n)}$ is the running mean temperature (°C) for day n , $\theta_{rm(n-1)}$ is the running mean temperature (°C) for day $(n-1)$, and so on.

So if the running mean has been calculated (or assumed) for one day, then it can be readily calculated for the next day, and so on.

1.6.4.2 Application to offices

Data applicable to Europe are available from extensive surveys of office workers^(68,74). A value in the region of 0.8 was found to be suitable for α_{rm} in the running mean temperature, a value previously found suitable for data from the UK⁽⁷¹⁾. This value suggests that the characteristic time subjects take to adjust fully to a change in the outdoor temperature is about a week.

Bands within which comfortable conditions have been found to lie are shown in relation to the running mean outdoor temperature in Figure 1.9⁽⁷⁴⁾, both for the free-running mode of operation and for the heated or cooled

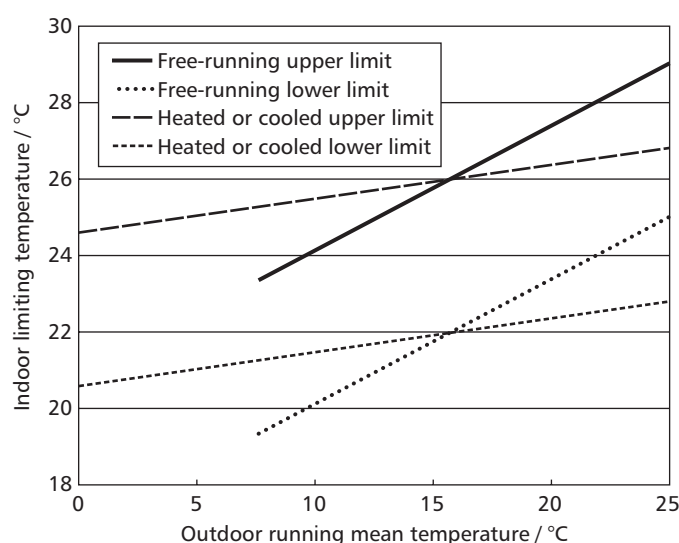


Figure 1.9 Bands of comfort temperatures in offices related to the running mean of the outdoor temperature; separate bands are shown for buildings in the free-running and the heated and cooled modes (from field surveys in Europe⁽⁵¹⁾)

mode. Comfortable conditions for mixed mode operation lie within and between these bands. The bands indicate the indoor temperatures within which people readily adapt, in relation to the outdoor temperature. A thermally successful building is one whose indoor temperatures change only gradually in response to changes in the outdoor temperature (see 1.6.2.3 and 1.6.2.4 above), and rarely stray beyond these bands. The limits of the bands are given by the following equations.

For free-running operation:

(a) upper margin:

$$\theta_{com} = 0.33 \theta_{rm} + 20.8 \quad (1.10)$$

(b) lower margin:

$$\theta_{com} = 0.33 \theta_{rm} + 16.8 \quad (1.11)$$

For heated or cooled operation:

(a) upper margin:

$$\theta_{com} = 0.09 \theta_{rm} + 24.6 \quad (1.12)$$

(b) lower margin:

$$\theta_{com} = 0.09 \theta_{rm} + 20.6 \quad (1.13)$$

where θ_{com} is the comfort temperature (°C)

Example 1.1: Naturally ventilated office in summer

For the assessment of the adequacy of the building in summer, the upper margin of the free-running zone is examined. This line may be used to indicate probable upper limit of the comfort temperature. In the UK the running mean outdoor temperature rarely exceeds 20 °C. At this temperature the upper limit of the band is 27.4 °C. So the temperature during occupied hours should preferably not exceed this value. Operative temperatures drifting a little above this value might attract little notice, but temperatures 2 K or more above it would be likely to attract increasing complaint. On a more normal summer day the running mean outdoor temperature would be about 15 °C. This would give a value of 25.8 °C, and the indoor temperature should preferably not be higher than this. Again, temperatures a little above this value would attract little notice, while temperatures more than about 2 K above the line would be likely to attract increasing complaint.

Expected percentages of occupants experiencing discomfort have sometimes been estimated, e.g. reference 1, but the percentage varies from building to building, depending on where its comfort temperature lies within the band, and on the adaptive opportunity it affords⁽⁷⁵⁾. Temperatures below these values would be found satisfactory provided the advice on within-day and day-on-day temperature changes (section 1.6.3 above) is observed.

1.6.4.3 Houses in summer

There are insufficient data to provide similar advice for houses. Oseland⁽⁷⁶⁾ among others has suggested that people are less sensitive to temperature changes in their own home than at work, and in general people have more adaptive opportunity at home. However, attention should

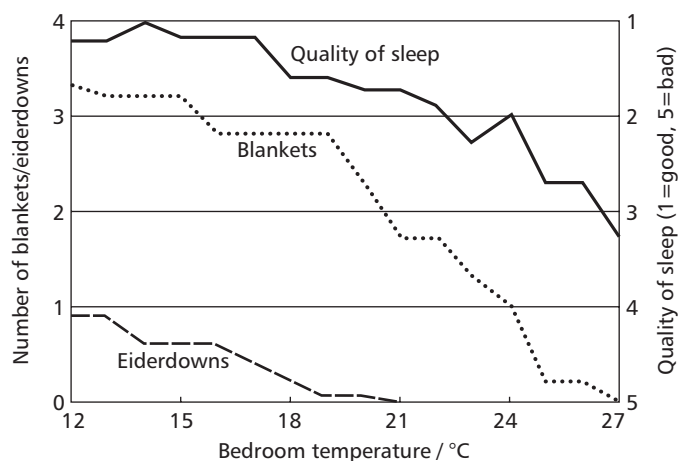


Figure 1.10 Bedclothing and sleep quality; data collected from UK subjects showing the drop in the number of bedclothes used as the bedroom temperature increases and the drop in quality of sleep above 24 °C when all bedclothes except the sheet are shed and little further adaptation is possible⁽⁴⁹⁾

be given to the bedroom temperature at night. Available field study data for the UK⁽⁶⁹⁾ show that thermal discomfort and quality of sleep begin to decrease if the bedroom temperature rises much above 24 °C, see Figure 1.10. At this temperature just a sheet is used for cover. It is desirable that bedroom temperatures at night should not exceed 26 °C unless ceiling fans are available.

1.7 Determination of required outdoor air supply rate

1.7.1 General

For consideration of indoor air quality, see chapter 8, section 8.4

Ventilation requirements for a wide range of building types are summarised in Table 1.5. Detailed information on specific applications is given in chapter 2 of CIBSE Guide B⁽³⁹⁾. For some industrial applications outdoor air may be required both to dilute specific pollutants and to make up the air exhausted through local extract ventilation systems, see CIBSE Guide B⁽³⁹⁾, chapter 3. Specialist advice should be sought in dealing with toxic and/or high emission pollutants.

In the following sections three methods are described for determining the outdoor air supply rate required for particular applications.

The first method (see section 1.7.2) is prescriptive, providing either an outdoor air supply rate per person or an air change rate, depending on the application. These values are based primarily on chamber studies, in which all sources of odour other than body odour and/or cigarette smoke were excluded. Therefore these prescribed rates may underestimate the outdoor air supply requirements if odour sources other than body odour or smoking dominate. Examples of such situations are spaces having large areas of new floor covering, upholstery, curtains etc. or spaces in which the standards of cleaning and maintenance are less than excellent.

Method 2 (see section 1.7.3) should be used in situations where there are known pollutants being released into the space at a known rate and local extract ventilation (LEV) is not practicable. To apply method 2, it is necessary to know the appropriate concentration limits for the pollutants. Local extract should be used wherever source location permits and for all applications where risks to the health of the occupants are not acceptable. The ventilation strategy should be based on a risk assessment under the Control of Substances Hazardous to Health Regulations 1994⁽⁷⁷⁾. Design guidance is given in CIBSE Guide B⁽³⁹⁾.

A further method has been suggested⁽⁷⁸⁾ which is intended for use where the pollution sources are known but (a) the emission rates of specific malodorous pollutants cannot be predicted, (b) their limiting concentrations are not known, or (c) odours are likely to result from complex mixtures of contaminants. Further research will be required to establish benchmark criteria. Ventilation rates calculated by this method will usually be higher than the prescribed rates determined using method 1. Details of this method are given in WHO publication CR 1752⁽⁷⁹⁾. At the time of writing (November 2005) this method has not gained international acceptance.

1.7.2 Method 1: Prescribed outdoor air supply rates

For applications in which the main odorous pollutants arise due to human activities, e.g. body odour, it is possible to supply a quantity of outdoor air based on the number of occupants in a given space. If smoking is prohibited, as is increasingly the case, then the recommended outdoor air supply rates given in Table 1.5 apply.

Spaces in which smoking is permitted should be regarded as 'smoking rooms' and an outdoor air supply rate of 45 L·s⁻¹ per person is suggested for such rooms. However, it should be noted that this recommendation aims only to reduce discomfort and does not ensure health protection.

1.7.3 Method 2: Specific pollutant control

1.7.3.1 Steady state conditions

For pollutants emitted at a constant rate, the ventilation rate required to prevent the mean equilibrium concentration rising above a prescribed level may be calculated from the following equation:

$$Q = \frac{P(10^6 - C_{pi})}{E_v(C_{pi} - C_{po})} \quad (1.14)$$

where Q is the outdoor air supply rate (L·s⁻¹), P is the pollutant emission rate (L·s⁻¹), C_{po} is the concentration of pollutant in the outdoor air (ppm), E_v is the ventilation effectiveness and C_{pi} is the limit of concentration of pollutant in the indoor air (ppm). Values for E_v are given in section 1.7.4, Table 1.10.

If the pollutant threshold is quoted in mg·m⁻³, the concentration in parts per million may be obtained from

$$C_p = (C_p' \times 24.05526) / M_p \quad (1.15)$$

where C_p is the concentration of pollutant (ppm), C_p' is the concentration of pollutant by volume ($\text{mg}\cdot\text{m}^{-3}$), M_p is the molar mass of the pollutant ($\text{kg}\cdot\text{mole}^{-1}$). The numerical factor is the molar volume of an ideal gas ($\text{m}^3\cdot\text{mole}^{-1}$) at 20 °C and pressure of 1 atmosphere. Molecular masses for pollutants are given in EH40: *Occupational exposure limits*⁽⁸⁰⁾ or from manufacturers' data.

If C_{pi} is small (i.e. $C_{pi} \ll 10^6$), equation 1.14 becomes:

$$Q = \frac{P \times 10^6}{E_v (C_{pi} - C_o)} \quad (1.16)$$

If the incoming air is not contaminated by the pollutant in question, this equation simplifies to:

$$Q = (P \times 10^6) / E_v C_{pi} \quad (1.17)$$

Where there is more than one known pollutant, the calculation should be performed for each pollutant separately. The outdoor air supply rate for ventilation is then the highest of these calculated rates.

If E_v is equal to one in equations 1.14, 1.16 and 1.17, this indicates that a substantially uniform concentration exists throughout the space. If the ventilation results in a non-uniform concentration so that higher than average concentrations occur in the inhaled air, the outdoor air supply rate would need to be increased above the value calculated by these equations.

Example 1.2

Toluene is being released at a rate of $20 \text{ mL}\cdot\text{h}^{-1}$; determine the rate of ventilation required to meet the WHO *Air Quality Guidelines for Europe*⁽⁸¹⁾, assuming a ventilation effectiveness (E_v) of 1.0.

The release rate of the pollutant, $P = 20 \text{ mL}\cdot\text{h}^{-1}$, which is equivalent to $5.56 \times 10^{-6} \text{ L}\cdot\text{s}^{-1}$.

From chapter 8, Table 8.2, the WHO AQG threshold for toluene is 68 ppb (i.e. 0.068 ppm).

Assuming there is no toluene in the outdoor air, $C_o = 0$.

Therefore, using equation 1.17:

$$Q = (5.56 \times 10^{-6} \times 10^6) / (1 \times 0.068) = 81.7 \text{ L}\cdot\text{s}^{-1}$$

1.7.3.2 Non-steady state conditions

The ventilation rate given by equation 1.17 is independent of the room or building volume. However the volume of the space affects the time taken for the equilibrium condition to be reached. This becomes important when the emission of a pollutant occurs for a limited duration only. In such cases the ventilation rate derived from equation 1.17 will exceed that required to maintain the concentration below the specified limit.

The ratio by which the steady state ventilation rate may be reduced in these circumstances is given by:

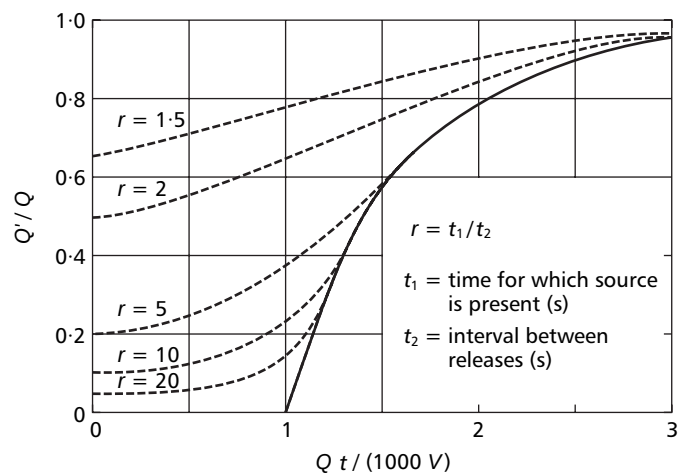


Figure 1.11 Reduction in fresh air rate for intermittent pollutant source

$$Q' / Q = f(Q t_p / 1000 V) \quad (1.18)$$

where Q' is the reduced ventilation rate ($\text{L}\cdot\text{s}^{-1}$), Q is the steady state ventilation rate ($\text{L}\cdot\text{s}^{-1}$), t_p is the duration of release of the pollutant (s) and V is the volume of the space (m^3).

The form of the function $f(Q t_p / 1000 V)$ is given by the solid curve in Figure 1.11. Although theoretically no ventilation is required when $(Q t_p / 1000 V) < 1.0$, some ventilation should be provided because subsequent releases of pollutant are likely to occur.

Recurrent emissions can be taken into account by considering a regular intermittent emission where the releases occur for periods of t_1 seconds at intervals of t_2 seconds. The ventilation rate ratio then becomes a function of $(Q t_1 / V)$ and the ratio of t_1 to t_2 . The broken lines in Figure 1.11 may be used to determine (Q' / Q) where these parameters are known.

Example 1.3

If the toluene in Example 1.2 were released into a ventilated space of 160 m^3 volume over a 40 minute period each day, determine the continuous outdoor air supply rate required to maintain the concentration of toluene at or below the WHO AQG value.

Initial data: $Q = 81.7 \text{ L}\cdot\text{s}^{-1}$, $t_p = 2400 \text{ s}$, $V = 160 \text{ m}^3$.

Therefore:

$$(Q t_p / 1000 V) = (81.7 \times 2400) / (1000 \times 160) = 1.23$$

From Figure 1.11:

$$(Q' / Q) = 0.35$$

Therefore:

$$Q' = 0.35 \times 81.7 = 28.6 \text{ L}\cdot\text{s}^{-1}$$

Example 1.4

If the toluene in Example 1.2 were periodically released for periods of 40 minutes with an interval of 20 minutes

between releases, determine the appropriate outdoor air supply rate.

Initial data: $Q = 81.7 \text{ L}\cdot\text{s}^{-1}$, $t_p = 2400 \text{ s}$, $V = 160 \text{ m}^3$.

As for Example 1.3:

$$(Q \theta_p / 1000 V) = 1.23$$

Ratio of source duration to return interval is given by:

$$r = t_1 / t_2 = 2400 / 1200 = 2$$

From Figure 1.11, for $r = 2$:

$$(Q' / Q) = 0.75$$

Therefore:

$$Q' = 0.75 \times 81.7 = 61.3 \text{ L}\cdot\text{s}^{-1}$$

1.7.3.3 Indoor air pollutants

See chapter 8, section 8.4.2.

1.7.4 Ventilation effectiveness

Guidance on the ventilation effectiveness for the ventilation arrangements shown in Figure 1.12 is given in Table 1.10. In each case, the space is considered as divided into two zones:

- the zone into which air is supplied/exhausted
- the remainder of the space, i.e. the ‘breathing zone’.

In mixing ventilation (cases (a) and (b) in Figure 1.12), the outside air supply rates given in Table 1.10 assume that the supply zone is usually above the breathing zone. The best conditions are achieved when mixing is sufficiently effective that the two zones merge to form a single zone. In displacement ventilation (Figure 1.12(c)), the supply zone is usually at low level and occupied with people, and the exhaust zone is at a higher level. The best conditions are achieved when there is minimal mixing between the two zones. The values given in Table 1.10 consider the effects of air distribution and supply temperature but not the location of the pollutants, which are assumed to be evenly distributed throughout the ventilated space. For other types of displacement system, the ventilation effectiveness (E_v) may be assumed to be 1.0.

Table 1.10 Ventilation effectiveness for ventilation arrangements shown in Figure 1.12

Ventilation arrangement	Temp. difference ($^{\circ}\text{K}$) between supply air and room air, ($\theta_s - \theta_{ai}$)	Ventilation effectiveness, E_v
Mixing; high-level supply and exhaust (Figure 1.12(a))	< 0	0.9–1.0
	0–2	0.9
	2–5	0.8
	> 5	0.4–0.7
Mixing; high-level supply, low-level exhaust (Figure 1.12(b))	< -5	0.9
	(–5)–0	0.9–1.0
	> 0	1.0
Displacement (Figure 1.12(c))	< 0	1.2–1.4
	0–2	0.7–0.9
	> 2	0.2–0.7

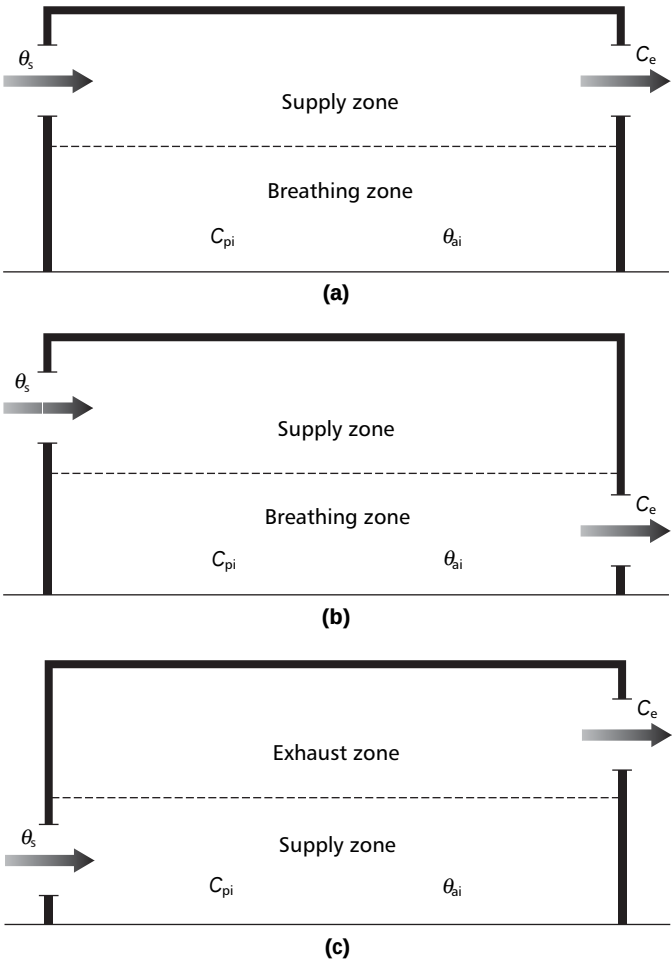


Figure 1.12 Supply/extract arrangements for ventilation; (a) mixing, supply and exhaust at high level, (b) mixing, supply at high level, exhaust at low level, (c) displacement

1.8 Visual environment

1.8.1 General

Lighting in a building has three purposes:

- to enable the occupant to work and move about in safety
- to enable tasks to be performed correctly and at an appropriate pace
- to create a pleasing appearance.

A satisfactory visual environment can be achieved by electric lighting alone, but most people have a strong preference for some daylight. This is supported by the Workplace (Health, Safety and Welfare) Regulations 1992⁽⁶²⁾, which require access to daylight for all workers where reasonably practicable. Where daylight is available a good design will make use of it to save energy and enhance internal appearance without glare, distracting reflections, overheating or excessive heat loss.

Good lighting can aid the avoidance of hazards during normal use of a building and in emergencies by revealing obstacles and clearly indicating exits. It makes tasks easier to perform and it can contribute to an interior that is considered satisfactory and, very inspiring by providing emphasis, colour and variety.

The balance between lighting for performance and for pleasantness is usually dependent upon the primary purpose for which the interior is intended. For example, in an engineering workshop the primary requirement of the lighting is to enable some product to be made quickly, easily and accurately. However, a cheerful but non-distracting atmosphere produced by careful lighting can be an aid to productivity. At the other extreme, the prime purpose of the lighting in restaurants is often to produce a particular atmosphere while ensuring that the food is not difficult to see. The lighting must be matched to the context and the operational requirements in order to be successful.

1.8.2 Lighting for safety

There are two aspects of lighting for safety. The first refers to the conditions prevailing in an interior when the normal lighting system is in operation, see chapter 8, section 8.5.

The second aspect becomes apparent when the normal lighting system fails, in which circumstances the alternative/standby lighting constitutes emergency lighting.

1.8.2.1 Emergency lighting

Emergency lighting can be divided into two classes:

- (a) standby lighting, which is intended to enable essential work to be carried out, e.g. hospital operating theatres
- (b) escape lighting which enables people to evacuate a building quickly and safely.

For general use an absolute minimum illuminance of 0.2 lux is required along the centre line of all escape routes and 1 lux average over open areas with no defined escape routes. However, such escape routes must be permanently clear of obstructions and this can rarely be guaranteed. The Workplace Regulations 1992⁽⁸²⁾ require that emergency lighting be 'suitable and sufficient'. Detailed guidance on the design of emergency lighting systems is given in BS 5266⁽⁸³⁾ and SLL Lighting Guide LG12: *Emergency lighting design guide*⁽⁸⁴⁾.

1.8.2.2 Layout of lighting

Escape routes

Emergency lighting must be located so as not to create glare and confusion. For example a 'headlight' style emergency light must not be positioned such that it throws light along an escape route towards the escapees. For emergency lighting, both BS 5266⁽⁸³⁾ and LG12⁽⁸⁴⁾ recommend that the ratio of maximum to minimum illuminance on escape routes should not exceed 40:1. It is particularly important that luminaires providing emergency lighting are arranged to draw attention to intersections and changes of direction or level. In addition to providing light for evacuation, an organised installation of luminaires serves to give a sense of orientation and direction. This is also true for normal lighting. Emergency lighting can be integrated into the normal lighting installation if required.

Staircases

The lighting of staircases must be given careful consideration, particularly if there are changes of direction at

short intervals. Lighting schemes designed for appearance only may combine visual confusion with poor visibility. For example, uplighters that throw light into the faces of people descending a staircase must be avoided. Staircases constitute zones of potential hazard and the guiding principle should be to reveal clearly the stair treads (by locating sources so that each riser is shadowed) and to make evident the location and direction of the stairway.

Workplaces

In workplaces, reflections from shiny surfaces can make objects, machinery, controls or indicators difficult to see. This may be avoided by the use of matt surfaces or arranging the lighting to avoid specular reflections towards the subject. Another hazard with rotating machinery is the stroboscopic effect produced by discharge lamps operating from an AC supply. This can be reduced by wiring adjacent luminaires to different phases of the supply or by the use of high frequency control gear. Such hazards are considered in CIBSE Lighting Guide LG1⁽³⁸⁾.

1.8.3 Lighting for performance

1.8.3.1 General

The exact relationship between visual performance and illuminance or luminance has been the subject of many investigations^(85–88). All of these studies indicate that this relationship depends upon many factors, which vary with task, individual and environment.

Where tasks involve the observation of fine detail (i.e. requiring high acuity), if the contrast (i.e. the difference in appearance of two parts of a visual field seen simultaneously or successively) is low then no amount of increase in illuminance will raise the visual performance to the level which can be attained by providing high contrast. However, performance can be improved by higher contrast, even with very low values of illuminance.

For larger task detail (i.e. requiring low acuity), the visual performance does not decline with low contrast or luminance to the same extent.

Task performance also depends on other factors such as the visual complexity of the task, task movement, the age and eyesight of the workers and the significance to the worker of the visual component of the work.

The SLL *Code for lighting*⁽³³⁾ contains illuminance recommendations for many different working situations. Table 1.11 summarises these in relation to different categories of visual task. It should be noted that these illuminances are intended to be measured on the appropriate working plane (i.e. horizontal, vertical or intermediate). Also, it is important to note that it is often more economic to improve performance by making the task easier through increase in apparent size of detail (e.g. by using optical aids) and improved contrast (e.g. by selecting a suitable task background) rather than by increasing illuminance.

Note that Table 1.11 is for information purposes only. Reference should be made to the comprehensive tables of specific task illuminance values in the *Code for lighting* and the *Code of practice for lighting*.

Table 1.11 Examples of activities/interiors appropriate for each maintained illuminance*

Standard maintained illuminance /lux	Characteristics of activity/interior	Representative activities/interiors
50	Interiors used rarely, with visual tasks confined to movement and casual seeing without perception of detail	Cable tunnels, indoor storage tanks, walkways
100	Interiors used occasionally, with visual tasks confined to movement, and casual seeing calling for only limited perception of detail	Corridors, changing rooms, bulk stores, auditoria
150	Interiors used occasionally, with visual tasks requiring some perception of detail or involving some risk to people, plant or product	Loading bays, medical stores, switchrooms, plant rooms
200	Continuously occupied interiors, visual tasks not requiring perception of detail	Foyers and entrances, monitoring automatic processes, casting concrete, turbine halls, dining rooms
300	Continuously occupied interiors, visual tasks moderately easy, i.e. large details > 10 min. arc and/or high contrast	Libraries, sports and assembly halls, teaching spaces, lecture theatres, packing
500	Visual tasks moderately difficult, i.e. details to be seen are of moderate size (5–10 min. arc) and may be of low contrast; also colour judgement may be required	General offices, engine assembly, painting and spraying, kitchens, laboratories, retail shops
750	Visual tasks difficult, i.e. details to be seen are small (3–5 min. arc) and of low contrast; also good colour judgements may be required	Drawing offices, ceramic decoration, meat inspection, chain stores
1000	Visual tasks very difficult, i.e. details to be seen are very small (2–3 min. arc) and can be of very low contrast; also accurate colour judgements may be required	General inspection, electronic assembly, gauge and tool rooms, retouching paintwork, cabinet making, supermarkets
1500	Visual tasks extremely difficult, i.e. details to be seen extremely small (1–2 min. arc) and of low contrast; visual aids and local lighting may be of advantage	Fine work and inspection, hand tailoring, precision assembly
2000	Visual tasks exceptionally difficult, i.e. details to be seen exceptionally small (< 1 min. arc) with very low contrasts; visual aids and local lighting will be of advantage	Assembly of minute mechanisms, finished fabric inspection

* Maintained illuminance is defined as the average illuminance over the reference surface at the time maintenance has to be carried out by replacing lamps and/or cleaning the equipment and room surfaces

take account of task contrast, age of operatives, consequences of error etc. as described in the *Code*.

These recommendations do not identify the source that is required to provide these illuminances and the recommended levels may be met using either daylight or electric light. However, when using daylight it is only possible to give the criteria in terms of daylight factor since the daylight illuminance varies continuously. Detailed guidance on daylighting is given in CIBSE Lighting Guide LG10: *Daylighting and window design*⁽⁸⁹⁾ and the SLL *Code for lighting*⁽³³⁾.

1.8.3.2 Distribution of light

When considering the distribution of light in an interior, alongside the visual performance of the occupants it is important to consider both the attractiveness of the space and the energy implications of the design.

For good visual performance, both sharp changes in surface luminance and the blandness caused by washing every surface with light should be avoided. The light needed for the visual task should be provided only over the immediate task area, with the task surround at a lower level and the circulation spaces at a lower level still. The maximum illuminance ratio between adjacent areas should be not more than 3:1.

Only in exceptional circumstances therefore should the whole area of a room be lit to the illuminance recommended for the tasks undertaken. This is wasteful of energy and can lead to bland, uninteresting spaces.

It is important if spaces are to appear pleasant that the walls are well lit, along with other parts of the visual scene in a 40 degree band above and below the horizontal at the observer's position.

If the lighting is controlled by presence/absence detectors, care is needed in open spaces that egress routes remain lit even when only a small proportion of the workers are present. This is both to provide a safe means of exit and to alleviate gloomy and oppressive conditions caused by odd pools of light in a dark area.

1.8.3.3 Directional effects

Some directional effects of light make it easier to recognise the details of a task, others make recognition more difficult.

The contrasts perceived in a task depend on the reflection characteristics of its surface and on how the task is lit. Contrast is reduced if the images of bright sources, such as luminaires or the sky, are seen in shiny surfaces. This veiling effect, see section 1.8.3.4 is often most apparent when a bright source is reflected from glossy paper.

and the best arrangement is usually achieved through adjustable luminaires or by experiment.

1.8.3.4 Disability glare

Veiling reflections directly affect the visibility of the task by reflection from the task area. However, disability glare can influence the task visibility without reflection from the task. This effect is due to light entering the eye and then being scattered in such a way that it forms a veil over the retinal image of the task.

The effect is most noticeable when the source is close to the line of sight between the observer and the task. Therefore, disability glare caused by the reflection of light sources in areas adjacent to the work is particularly troublesome.

The only way of eliminating disability glare is to separate all areas of high luminance from areas immediately surrounding the task. This is usually a matter of avoiding the use of glossy surfaces close to the task or moving the task to another location. In practice, disability glare direct from luminaires is rare in interior lighting.

1.8.3.5 Health effects

See chapter 8, section 8.5.

The average daylight factor may be used as an initial design parameter. It is calculated as follows:

where DF is the average daylight factor (%), T is the diffuse transmittance of the glazing material including effects of dirt (see Table 1.12^(89,90)), A_w is the net glazed area of the window (m^2), α is the vertical angle subtended by sky that is visible from the centre of the window (degree) (see Figure 1.14), M is the maintenance factor (see Table 1.13), A is the total area of the internal surfaces (ceiling, floor, windows and walls) (m^2) and R_a is the area-weighted average reflectance of the interior surfaces (ceiling, floor windows and walls) (Table 1.14⁽³³⁾).

Glazing type	Diffuse transmittance
Clear glazing:	
— single	0.8
— double	0.7
Double glazing, low emissivity	0.69
Double glazing with light shelf:	
— internal light shelf only	0.55
— internal and external light shelves	0.4
Double glazing with coated prismatic glazing	0.3
Double glazing with prismatic film	0.25
Double glazing with solar control mirrored louvers	0.3

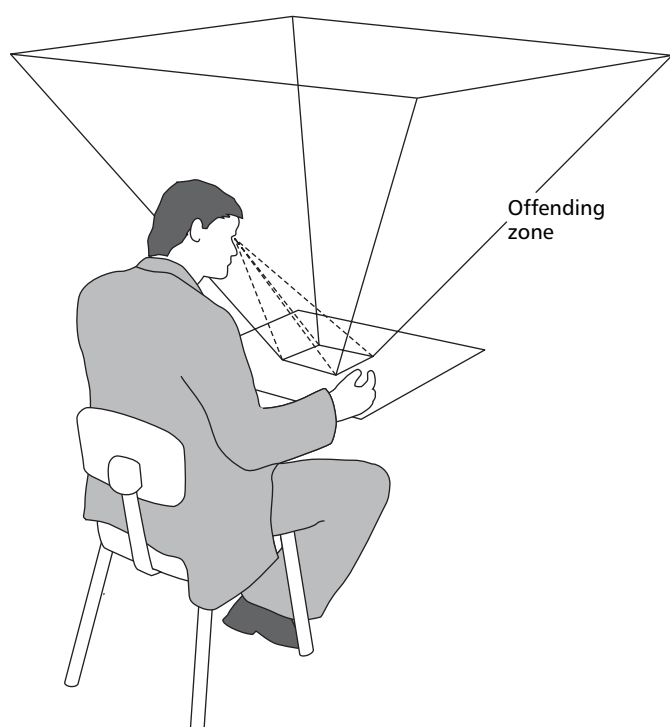


Figure 1.13 Avoidance of veiling reflections

Table 1.13 Calculation of maintenance factor for daylight factor

Room use	Percentage loss of daylight compared with clean glazing / %	
	Rural/suburban	Urban
Residential (private and communal); rooms with few occupants, good maintenance	4	8
Commercial, educational; rooms used by groups of people, office equipment	4	8–12
Polluted atmosphere; gymnasia, swimming pools, heavy smoking	12–24	12–24

Note: values in table must be adjusted for special conditions and exposure by applying multipliers as follows:

- (1) Multiplier for special conditions: vertical glazing sheltered from rain ($\times 3$); weathered or corroded glazing (no correction for rain) ($\times 3$); leaded glass ($\times 3$)
- (2) Multiplier for exposure:
 - (a) normal exposure for location: vertical glazing ($\times 1$); inclined glazing ($\times 2$); horizontal glazing ($\times 3$)
 - (b) exposed to heavy rain: vertical glazing ($\times 0.5$); inclined glazing ($\times 1.5$); horizontal glazing ($\times 3$)
 - (c) exposed to snow: vertical glazing ($\times 1$); inclined glazing ($\times 3$); horizontal glazing ($\times 4$)

Maintenance factor is then given by $(100 - \text{adjusted daylight loss}) / 100$

Table 1.14 Reflectances for early design calculations⁽⁸⁹⁾

Surface	Reflectance
Light walls and floor cavity	0.6
Medium walls and floor cavity	0.5
Dark walls and floor cavity	0.4

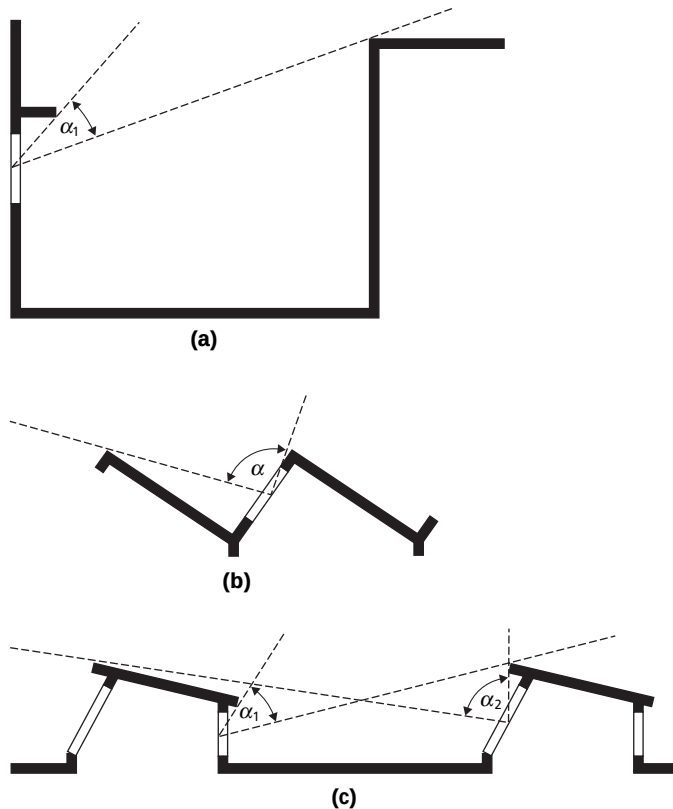


Figure 1.14 Angle of sky (α) seen from centre of window; (a) window obstructed by overhang and nearby wall, (b) rooflight obstructed by roof construction, (c) different windows facing different obstructions

If the average daylight factor exceeds 5% on the horizontal plane, an interior will look cheerfully daylight, even in the absence of sunlight. If the average daylight factor is less than 2% the interior will not be perceived as well daylight and electric lighting may need to be in constant use. BS 8206⁽⁹¹⁾ recommends average daylight factors of at least 1% in bedrooms, 1.5% in living rooms and 2% in kitchens, even if a predominantly daylight appearance is not required.

Where different windows face different obstructions, see Figure 1.14(c), the average daylight factor for each window should be calculated separately and the results added together.

Equation 1.19 can also be used to provide a preliminary estimate of window size for design purposes.

The determination of daylight factor at specific points in a room is more complex, see CIBSE LG10: *Daylighting and window design*⁽⁸⁹⁾.

1.8.5 Lighting for pleasantness

1.8.5.1 Quantity of light

It has been established that working environments lit uniformly to less than 200 lux tend to be rated as unsatisfactory for continuous occupation⁽⁹²⁾. Following the recommendations of BS EN 12464-1⁽⁹²⁾, the SLL *Code for lighting*⁽³³⁾ recommends this value as a minimum amenity level in continuously occupied spaces, even though it may not be justified on performance grounds for occupations where the visual tasks are not demanding. Studies⁽⁹³⁾ have also shown that the preference for high lighting levels declines above 2000 lux.

Considerations of energy efficiency also affect the specification of a general preferred illuminance and energy savings may be achieved by separating the task lighting from the general building lighting. Daylight is often inappropriate as task lighting but even modest daylight admission can provide satisfactory building lighting for much of the working day. Furthermore, the provision of daylight is in itself a desirable amenity.

If a combination of general and task lighting is to be employed, utilising daylight where available, it is important to note that human reaction to sunlight is less predictable than to electric lighting^(94,95) and effective sunlight control may be required for working environments.

For some interiors (e.g. circulation areas) there is no obvious visual task and reference to an illuminance on a working plane is not appropriate.

1.8.5.2 Distribution of light

Selective lighting may be used to make particular objects or spaces more conspicuous. In general, the brightest elements in the field of view should be those that it is wished to emphasise. If this is not so discomfort is experienced due to the visual conflict.

For working situations, the ratio of wall illuminance to working plane illuminance should be in the range 0.5–0.8

and ceiling/working plane illuminance ratio within the range 0.3–0.9⁽³³⁾. The upper limits are directed by the expectation that the working plane should appear to be more strongly illuminated than either the walls or the ceiling. The exception to this is uplighting, which creates a visual environment more akin to daylight outdoors. The provision of lighting that achieves these illuminance ratios will usually ensure an acceptable distribution of light onto the main room surfaces but will not necessarily ensure a satisfactory balance of lighting on objects within the room.

1.8.5.3 Directional effects

The directional characteristics of light may be defined by an 'illumination vector'⁽³³⁾. The magnitude of the illumination vector is the difference in illuminance on opposite sides of a flat surface that is so orientated to maximise this difference. Its direction is normal to this surface, the positive direction being from the higher illuminance to the lower.

Studies of the appearance of the human face show that a flow of light from above and to one side of the face gives the most natural appearance. This flow should not be too dominant or hard shadows below the brow and nose make faces appear harsh. A dominant flow of light across the space with general light to soften shadows is recommended, especially in areas where eye to eye contact is normal, e.g. reception areas and meeting rooms.

1.8.5.4 Discomfort glare

When the brightness of a surface or luminaire is higher than recommended then people may experience visual discomfort. Discomfort glare does not directly affect the visual difficulty of tasks.

For a detailed discussion of glare and its avoidance, reference should be made to the *SLL Code for lighting*⁽³³⁾.

1.8.5.5 Colour of light

All sources of light, both natural and electric, differ in their spectral composition. Surface colour is produced by a combination of the wavelengths of the incident light and the spectral reflectance of the surface. Therefore, different sources will produce changes of colour of the surface. For most purposes these changes are modified by chromatic adaption, whereby the observer adapts to the particular composition of the light. However, for some tasks, the perceived colour of the surface is important and a suitable light source must be chosen.

Natural light sources such as sunlight and daylight have visible spectra which approximate to that of a black-body radiator at the appropriate temperature. Non-incandescent electric lamps generally have discontinuous spectra, an extreme example being the low-pressure sodium lamp, which is a monochromatic source. Lamps of this type are widely used for street lighting. They have very poor colour properties, particularly colour rendering. Light sources having much better colour rendering properties are required for interior lighting.

The general colour rendering index (CRI) adopted by the Commission Internationale de l'Eclairage (CIE), R_a ,

specifies the accuracy with which lamps reproduce colours relative to a standard source. The CRI takes values up to a maximum of 100. The *SLL Code for lighting*⁽³³⁾ recommends ranges for the CIE colour rendering index for specific applications.

In general, the higher the CRI the more accurately colours are reproduced with respect to the standard, and the greater is the enhancement of differences between colours. The advice of the lamp manufacturer should be sought when selecting lamps for applications where colour judgement is particularly important.

The colour rendering index is not the only parameter that needs to be considered. The colour appearance of the source is also important. For almost all interiors, the recommended light sources are nominally white in appearance with varying degrees of warmth. This degree of warmth is quantified by the correlated colour temperature (CCT) of the lamp. This is the temperature of the black-body radiator which most closely approximates to the colour appearance of the lamp.

The commonly used light sources are classified as follows:

- warm (CCT < 3300 K)
- intermediate (3300 K < CCT < 5300 K)
- cold (CCT > 5300 K).

Having selected a source with the required CCT, a source having a high colour rendering index should be chosen to ensure that surface colours are rendered to an accuracy appropriate to the application. Detailed guidance is given in the *SLL Code for lighting*⁽³³⁾.

For daylight, this variation is catered for naturally when bright, blue-sky conditions give way to warm tints of sunset. Where electric lighting is being used in a daylight space, lamps with a cool colour appearance give a good blend with daylight.

Refer to the *Code*⁽³³⁾ for advice on the selection of warm or cool source colour appearance. Satisfaction with the appearance of surface colours is likely to be increased by selecting a source having a high colour rendering index. Reference should also be made to the *Code*⁽³³⁾ for guidance on allowances for maintenance.

1.9 Acoustic environment

Noise affects people in different ways depending on its level and may cause annoyance, interference to speech intelligibility or hearing damage. The acoustic environment must be designed, as far as possible, to avoid such detrimental effects.

1.9.1 Sound level in a room

The sound energy emitted by a source can be quantified by its sound power level. This is a property of the source and is not affected by the characteristics of the room in which it is located. The effects of a noise source are assessed in terms of sound pressure level. The sound power level of a source may be used to calculate the resulting sound pressure level.

in a room, which depends on the volume of the room and the amount of absorbing material it contains. These acoustic characteristics of a room contribute to its reverberation time, i.e. the time taken for a sound to decay by 60 dB.

For a constant sound power input, the sound pressure level within a room will vary from place to place. The highest level is experienced near the noise source(s), it then decreases roughly with the square of the distance from the source until it reaches an approximately constant level. This constant level depends on the reverberation time of the room.

The calculation of noise levels within a space due to individual noise sources has been investigated by Beranek⁽⁹⁷⁾. Noise from heating, ventilating and air conditioning plant is considered in CIBSE Guide B⁽³⁹⁾, chapter 5.

1.9.2 Human hearing response

The human hearing system responds to frequencies in the range 20 Hz to 20 000 Hz. The precise range differs from person to person and hearing acuity at high frequencies tends to diminish with age due to deterioration in the receptor cells in the ear.

The response of the hearing system is non-linear and it is less sensitive to low and high frequencies than to mid-range frequencies. The sensitivity of the ear is represented by the curves of equal loudness shown in Figure 1.15. These curves have been derived by subjective experiments and show that the sensitivity of the ear varies with both sound pressure level and frequency.

The unit of loudness level is the phon. For example, the curve representing a loudness of 60 phon illustrates that a 1000 Hz note at a sound pressure level of 60 dB is perceived as being of equal loudness to a 100 Hz note at 66 dB. However, this method of assessing loudness is too complicated for everyday use.

When sound levels are measured, the variation in the sensitivity of the ear can be taken into account by incorporating frequency-weighting networks in the measuring instrument. The most widely used of these is the A-weighting network. Other networks are known as B- and C-weightings. The B-weighting has fallen into disuse so the

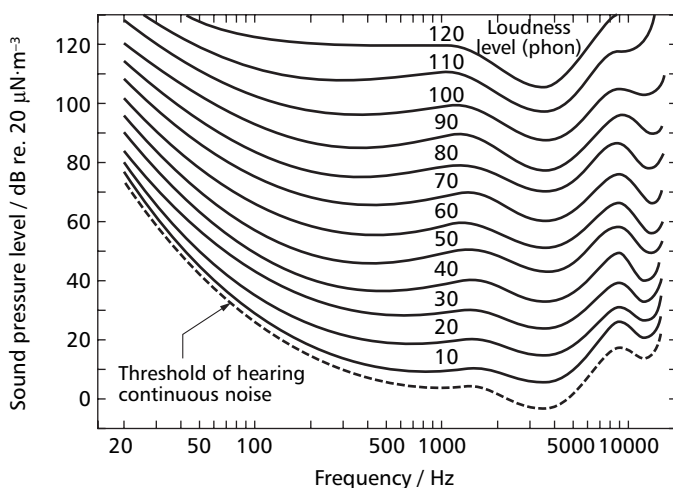


Figure 1.15 Equal loudness level contours

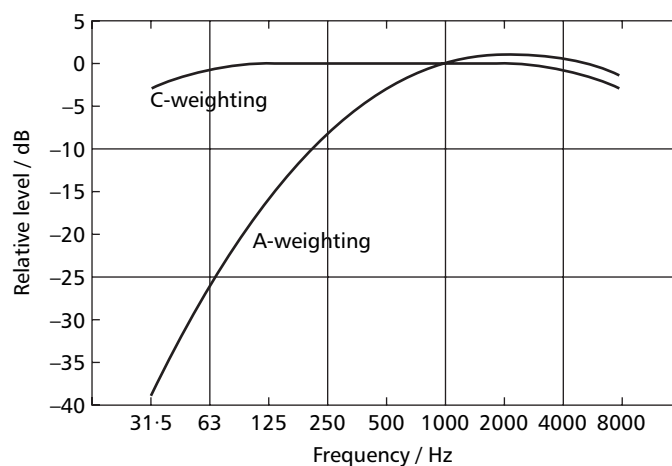


Figure 1.16 A- and C-weighting curves

main measurement curves are the A- and C-weighting curves, see Figure 1.16. The C-weighting gives more prominence to lower frequencies than does the A-weighting, having an approximately level response above 31.5 Hz. In contrast, the A-weighting rises gradually to 1000 Hz, thus discriminating against lower frequencies. The reason for these differences arises from the different equal loudness responses of the human ear over a range of sound pressure levels, see Figure 1.15.

A-weighting was proposed in the 1930s for low sound pressure levels and C-weighting for high sound pressure levels, see Figure 1.15. This distinction has since been lost with the result that the A-weighting is now employed at sound levels for which it was not originally intended. Problems may arise if there is an excess of low frequency noise, since this will not register its full subjective impact when measured using the A-weighting.

At the time that the weighting networks were devised, the complexities of the human hearing system were not fully understood. Methods of loudness evaluation were developed in the 1970s which take account of frequency and sound level in far more detail than do the simple A- and C-weighting networks.

1.9.3 Noise assessment

The dBA measure is often used as an indicator of human subjective reactions to noise across the full range of frequencies audible to humans. This index is simple to measure using a sound level meter incorporating an A-weighting network. In addition, the measured noise spectrum can be compared with reference curves such as the NR or NC curves which aid identification of any tonal frequency components. This is the usual method of assessment for mechanical services installations⁽⁹⁸⁾.

Noise rating (NR) curves, see Figure 1.17, are commonly used in Europe for specifying noise levels from mechanical services in order to control the character of the noise. However, it should be noted that NR is not recognised by the International Standards Organisation or similar standardisation bodies. Noise criteria (NC) curves, see Figure 1.18, are similar to NR but less stringent at high frequencies and more stringent at low frequencies. The curves are very close at middle frequencies and, as long as there are no spectrum irregularities at low and high frequencies, they may be regarded as reasonably interchangeable. Documents

opments in North America have lead to the introduction of room criterion (RC) curves⁽⁹⁹⁾, see see Figure 1.19.

The relationship between NR and dBA is not constant because it depends upon the spectral characteristics of the noise. However, for ordinary intrusive noise found in buildings, dBA is usually between 4 and 8 dB greater than the corresponding NR. If in doubt, both should be determined for the specific noise spectrum under consideration.

Noise from many sources, such as road traffic and aircraft, varies with time and the human response to the noise depends on its amplitude and temporal characteristics. Single number indices, such as $L_{A10,T}$, $L_{A90,T}$ and $L_{Aeq,T}$ may be used to describe these types of noise.

$L_{A10,T}$ is the A-weighted sound pressure level exceeded for 10% of the measurement period, T , which must be stated. Similarly, $L_{A90,T}$ denotes the level exceeded for 90% of the measurement period. It is often used to measure background noise levels. $L_{Aeq,T}$ is the A-weighted sound pressure level of a continuous steady sound having the same energy as the variable noise over the same time period. It is found to correlate well with subjective response to noises having different characteristics, and is used with BS 8233⁽¹⁰⁰⁾, which recommends appropriate design limits for common situations.

Noise from plant may be audible outside the building and control measures may be necessary to avoid complaints. Noise limits may also be set by the local authority. Noise emanating from industrial premises in mixed industrial and residential areas is usually assessed according to BS 4142⁽¹⁰¹⁾.

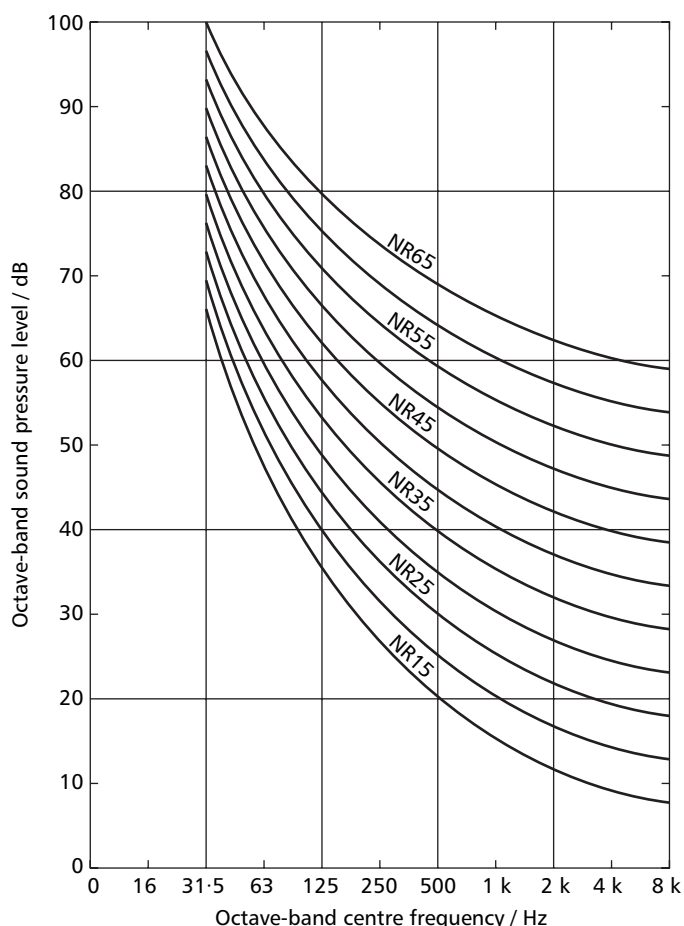


Figure 1.17 Noise rating (NR) curves

The past 15–20 years has seen significant developments in North American usage of noise criteria but these have not yet made an impact in Europe. NR was never adopted in the USA and ASHRAE no longer recommends NC as a design criterion. For some time the preferred assessment method has been room criterion (RC) curves, see Figure 1.19, as proposed by Blazier⁽¹⁰²⁾ in the early 1980s.

RC curves are based on actual measurements in air conditioned buildings in which the occupants are judged to have good acoustical environments. The result is a set of parallel lines falling from low to high frequencies at

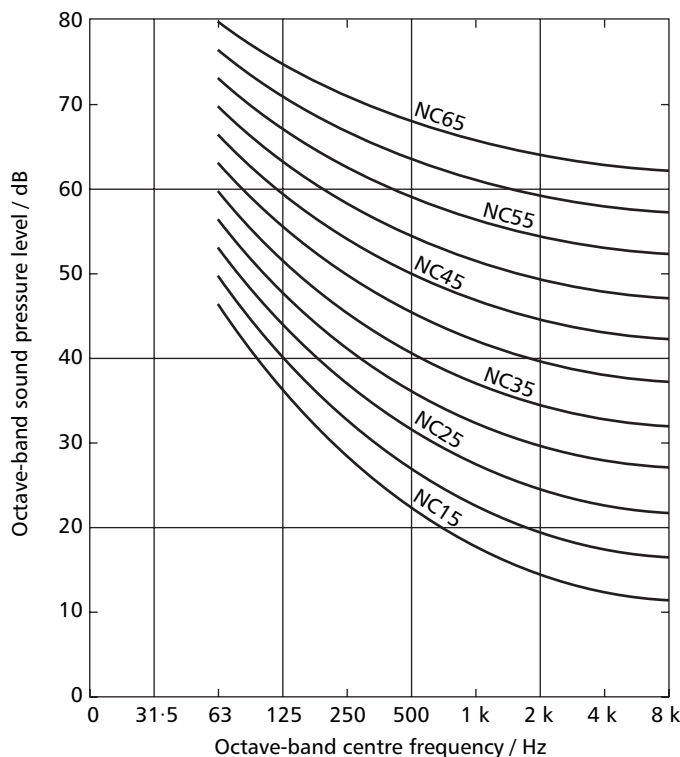


Figure 1.18 Noise criterion (NC) curves

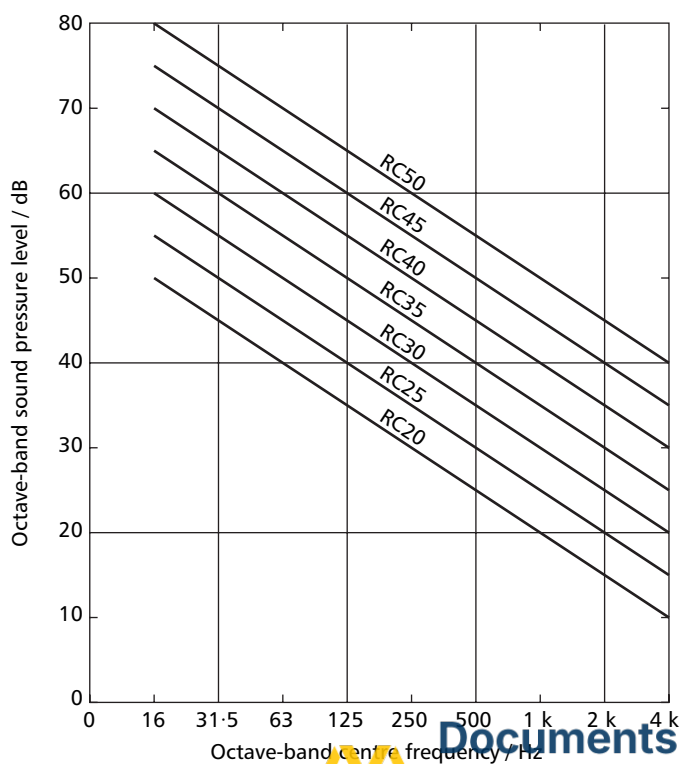


Figure 1.19 Room criterion (RC) curves

–5 dB/octave. Noise spectra following these slopes are acoustically ‘neutral’. The use of the curves is explained in ASHRAE Handbook: *Applications*⁽⁹⁹⁾, where it is shown how to determine whether a noise has ‘rumble’, ‘neutral’ or ‘hiss’ characteristics, and the frequency regions where improvement is required. More recent work by Blazier⁽¹⁰³⁾ has aimed at using the RC curves to determine the acoustical ‘quality’ of a noise by separating its low frequency (rumble), middle frequency (roar) and high frequency (hiss) characteristics and comparing these with subjective acceptability ratings.

RC curves provide a more detailed description of the noise than is available from NR. In addition, room criteria are more prescriptive at low frequencies than NR. At 31.5 Hz, permitted NR35 levels are 19 dB higher than RC35 levels. A noise which follows the NR curve will be unpleasantly ‘rumbly’ compared with the neutral sound of a noise that follows the RC curve. Therefore NR continues to be adequate only where low frequency noise levels are well below the NR limit. The potential drawback of NRs is that they permit unacceptable noises that would have been rejected if RC had been applied.

1.9.4 Noise due to building services and other sources

In specifying noise design goals for a building, a balance must be sought between noise from the building services and noise from the activities taking place within the building. The acceptability of noise from building services does not depend only upon its absolute level and frequency content, but also on its relationship with noise from other sources. It is important that the designer considers the likely activity-related and extraneous noise level and frequency content at an early stage of design. However, while noise from the building services is controlled by the building services engineer, activity noise is a function of the office or other equipment in the space and is therefore under the control of the office management. Noise from outside the building, e.g. traffic noise, is controlled mainly by the fabric of the building, which is the responsibility of the architect. The building services engineer must work to an agreed specification for the noise level from the building services and may be able to influence the level set down in the specification.

Reasonable design limits to minimise annoyance from broadband continuous noise from building services installations are given in Table 1.15. If the noise contains recognisable tones or is intermittent or impulsive it will be more annoying and the appropriate NR value from Table 1.15 should be corrected using the factors given in Table 1.16.

Noise levels for building services are often specified for the unoccupied space. Noise from the building services becomes more noticeable when other noise is at its minimum level, as is usually the case outside the occupied period. The building services designer cannot rely on external or activity noise in order to permit noise levels from services higher than those given in Table 1.15. Indeed, it may be necessary to control noise from these other sources to achieve an acceptable acoustical environment.

Table 1.15 Suggested maximum permissible background noise levels generated by building services installations⁽¹⁰⁰⁾

Situation	Noise rating (NR)
Studios and auditoria:	
— sound broadcasting (drama)	15
— sound broadcasting (general), television (general), sound recording	20
— television (audience studio)	25
— concert hall, theatre	20–25
— lecture theatre, cinema	25–30
Hospitals:	
— audiometric room	20–25
— operating theatre, single bed ward	30–35
— multi-bed ward, waiting room	35
— corridor, laboratory	35–40
— wash room, toilet, kitchen	35–40
— staff room, recreation room	30–40
Hotels:	
— individual room, suite	20–30
— ballroom, banquet room	30–35
— corridor, lobby	35–40
— kitchen, laundry	40–45
Restaurants, shops and stores:	
— restaurant, department store (upper floors)	35–40
— night club, public house, cafeteria, canteen, department store (main floors)	40–45
Offices:	
— boardroom, large conference room	25–30
— small conference room, executive office, reception room	30–35
— open plan office	35
— drawing office, computer suite	35–45
Public buildings:	
— law court	25–30
— assembly hall	25–35
— library, bank, museum	30–35
— washroom, toilet	35–45
— swimming pool, sports arena	40–50
— garage, car park	55
Ecclesiastical and academic buildings:	
— church	25–30
— classroom, lecture theatre	25–35
— laboratory, workshop	35–40
— corridor, gymnasium	35–45
Industrial:	
— warehouse, garage	45–50
— light engineering workshop	45–55
— heavy engineering workshop	50–65
Dwellings (urban):	
— bedroom	25
— living room	30

Note: dBA $\approx$ NR + 6

Table 1.16 Corrections to noise rating for certain types of noise

Type of noise	NR correction
Pure tone easily perceptible	+5
Impulsive and/or intermittent noise	+3

In the absence of noise from other sources, noise from building services may become noticeable. If so, the aim should be to reduce the services noise rather than to attempt to mask it by noise from other sources. However, provided that it is within the limits required by

specification, a steady level of services noise can sometimes help to improve acoustical privacy in open plan offices.

In modern offices, a prominent source of noise at workstations is the cooling fans in office equipment, such as personal computers. The characteristic of this noise is different from that of services noise, tending to have a tonal spectrum with peaks at about 250 Hz and associated harmonics, depending on the design of the fan. Clearly, this source of noise is not under the control of the building services engineer.

1.9.5 Speech intelligibility

Speech intelligibility is dependent upon the ambient noise and the distance between listener and speaker. Table 1.17 gives an indication of the distance at which normal speech will be intelligible for various ambient noise levels⁽¹⁰⁰⁾.

Ambient noise may also interfere with the intelligibility of telephone conversations. However, conversation can be carried out in reasonable comfort if the ambient level is below 60 dBA, which should be the case in well-designed offices where the maximum levels are not likely to exceed 45 dBA.

Table 1.17 Maximum steady noise levels for reliable speech communication⁽¹⁰⁰⁾(reproduced from BS 8233 by permission of the British Standards Institution)

Distance between talker and listener (m)	Noise level, L_{Aeq} (dB)	
	Normal voice	Raised voice
1	57	62
2	51	56
4	45	50
8	39	44

1.9.6 Hearing damage

Exposure to high noise levels, such as may occur in a plant room, can cause temporary or permanent hearing damage. Where workers are exposed to high levels of noise, the noise levels must be assessed by a qualified person. The Noise at Work Regulations 2005⁽¹⁰⁴⁾ identify two levels of 'daily personal noise exposure' (measured in a manner similar to $L_{Aeq,T}$) at which actions become necessary. These levels are 80 dBA for the lower level and 85 dBA for the higher level, corresponding to advisory and compulsory requirements. In addition, for impulse noise, there is a lower peak level limit of 112 Pa and a higher peak level limit of 140 Pa. These peak action levels control exposure to impulse noise. Suppliers of machinery must provide noise data for machines likely to cause exposure to noise above the action levels.

1.10 Vibration

1.10.1 General

In the context of building services installations, vibrations arise from reciprocating machines or from unbalanced forces in rotating machines. The vibration is often most noticeable during machine start-up (i.e. low-frequency

movement), during which some machines pass through a critical (resonant) speed before reaching their normal operating condition. Vibration associated with start-up may not be important if the machine operates for long periods, since that condition occurs only infrequently. However, machines which switch on and off under thermostatic control, for example, may require special precautions.

Vibrations transmitted from machines through their bases to the building structure may be felt and heard at considerable distances from the plant and, in extreme cases, even in neighbouring buildings. Therefore, adequate isolation is important in those cases where vibration is expected. Vibration isolators must be chosen to withstand the static load of the machine as well as isolate it from the structure. Efficient vibration isolation is the preferred way of controlling structure-borne noise, which occurs when vibration transmitted to building surfaces is re-radiated as noise. Structure-borne noise is enhanced when the excitation frequency corresponds with a structural resonance frequency, which may cause unexpected noise problems.

1.10.2 Response of the human body to vibration

Vibrating motion of the human body can produce both physical and biological effects. The physical effect is the excitation of parts of the body and under extreme conditions physical damage may result. Building vibration may affect the occupants by reducing both quality of life and working efficiency. Complaints about continuous vibration in residential situations are likely to arise from occupants when the vibration levels are only slightly greater than the threshold of perception.

The levels of complaint resulting from vibration and acceptable limits for building vibration depend upon the characteristics of the vibration and the building environment, as well as individual response. These factors are incorporated in guidance given in BS 6472⁽¹⁰⁵⁾ which gives magnitudes of vibrations below which the probability of complaints is low. This guidance takes the form of base curves of RMS acceleration against frequency over the range 1–80 Hz, for vibration along x-, y-, and z-axes. The axes of vibration with respect to the human body are shown in Figure 1.20. The values for the x- and y-axis curves are more severe than that for the z-axis curve, reflecting the greater sensitivity of the human body to x- and y-axis motion at low frequencies.

The base curves (not shown here) are modified by factors appropriate to the building environment, time of day and type of vibration (see Table 1.18) to produce curves of design maximum vibration magnitude, Figure 1.21. The curves are labelled to correspond to the multiplying factors appropriate to the situations listed in Table 1.18.

1.10.3 Effect on structure

Vibration can damage building structures. The degree of damage depends largely on the magnitude and frequency of vibration. In general, the level of vibration likely to cause cosmetic damage, such as plaster cracking, is significantly greater than that which would be easily perceptible to the occupants. Therefore, the occupants provide early warning of vibration levels likely to cause damage to the fabric.

Table 1.18 Multiplying factors used to specify satisfactory magnitudes of building vibration with respect to human response⁽¹⁰⁵⁾ (reproduced from BS 6472 by permission of the British Standards Institution)

Situation	Multiplying factor for stated vibration ^[1,5]	
	Exposure to continuous vibration (16 hour day, 8 hour night) ^[2]	Intermittent vibration with up to 3 occurrences
Critical working areas, e.g. hospital operating theatre, precision laboratory ^[3,9]		
— daytime	1	1
— night	1	1
Residential buildings:		
— daytime	2–4 ^[4]	60–90 ^[4,8]
— night	1.4	20
Offices:		
— daytime	4	128 ^[6]
— night	4	128
Workshops:		
— daytime	8 ^[7]	128 ^[6,7]
— night	8	128

Notes:

- [1] Magnitude of vibration below which the probability of adverse comments is low (any acoustical noise caused by structural vibration is not considered)

[2] Doubling of suggested vibration magnitudes may result in adverse comment and this may increase significantly if magnitudes are quadrupled (where available, dose/response curves may be consulted)

[3] Magnitudes of vibration in hospital operating theatres and critical working places pertain to periods of time when operations are in progress or critical work is being performed; at other times magnitudes as high as those for residences are satisfactory provided there is due agreement and warning

[4] In residential areas people exhibit wide variations of vibration tolerance; specific values dependent upon social and cultural factors, psychological attitudes and expected degree of intrusion

[5] Vibration to be measured at point of entry of the vibration to the subject; where this is not possible it is essential that transfer functions be evaluated
- [6] Magnitudes for vibration in offices and workshop areas should not be increased without considering the possibility of significant disruption of work activity

[7] Vibration acting on operators in certain processes such as drop forges or crushers, which cause the working place to vibrate, may be in a separate category from the workshop areas considered in the table. Vibration magnitudes specified in relevant standards apply to the operators of these processes

[8] When short term works such as piling, demolition and construction give rise to impulsive vibrations, undue restriction on vibration levels can significantly prolong these operations resulting in greater annoyance. In certain circumstances higher magnitudes can be used

[9] Where sensitive equipment or delicate tasks impose more stringent criteria than human comfort, the corresponding more stringent values should be applied

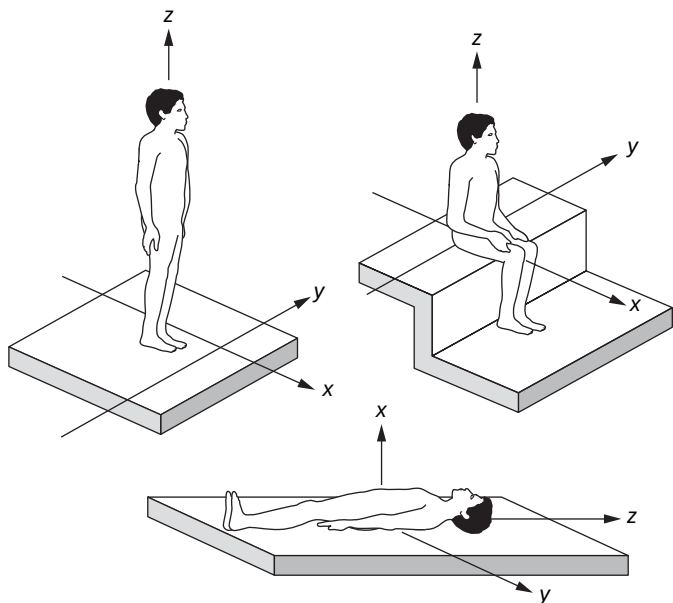


Figure 1.20 Definition of axes of vibration with respect to the human body⁽¹⁰⁵⁾; x-axis = back to chest, y-axis = right side to left side, z-axis = foot to head (reproduced from BS 6472 by permission of the British Standards Institution)

Although vibrations in buildings are often noticeable, there is little documented evidence to show that they produced even cosmetic damage^(105–107).

1.11 Electromagnetic and electrostatic environment

1.11.1 Electromagnetic fields

Since the 1960s concern has been expressed regarding the possible effects on health of extremely low frequency electromagnetic fields (i.e. below 300 Hz). Some reports have suggested that exposure to these fields, such as might be experienced by those living near high voltage overhead power lines, increases the risk of cancer, particularly leukaemia, especially amongst children. Other studies have raised the possibility that ‘electrical’ occupations, such as those that entail prolonged proximity to visual display terminals, result in an increased risk of illness.

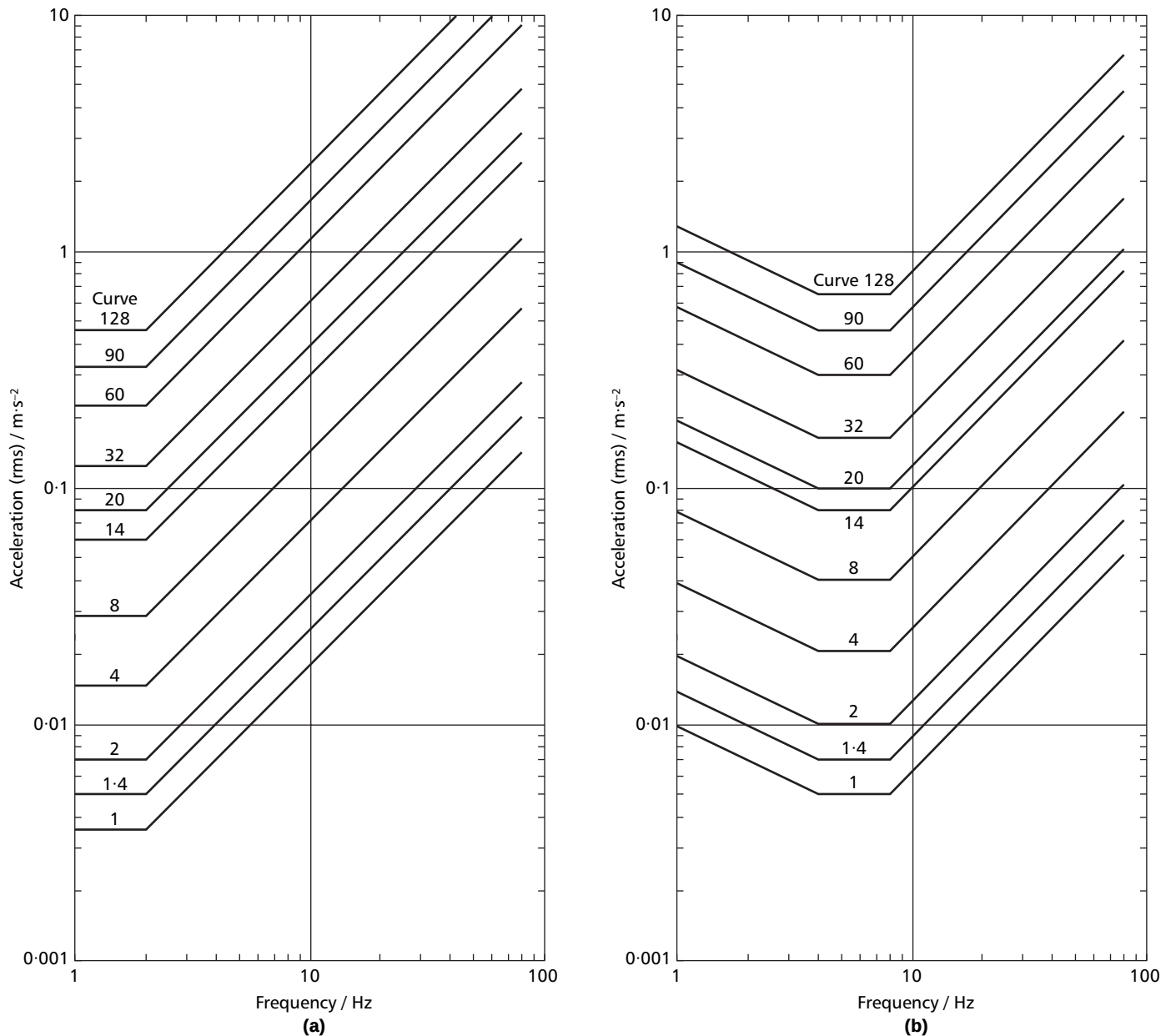


Figure 1.21 Design maximum vibration curves⁽¹⁰⁵⁾ corresponding to multiplying factors for the situations given in Table 1.17; (a) for x- and y-axes, (b) for z-axis (reproduced from BS 6472 by permission of the British Standards Institution)

A review of these studies⁽¹⁰⁸⁾ reveals that all suffer from methodological or other shortcomings but it is not clear whether these are sufficient to explain the results. Experiments with animals have produced conflicting and confusing results, and their relevance to the effect on humans is difficult to assess. No plausible mechanism for carcinogenesis due to exposure to electrical or magnetic fields has yet been deduced. It has been established that such fields affect the function of cardiac pacemakers but this is unlikely to be a hazard at the field strengths normally encountered and most modern pacemakers are designed to cope with high field strengths.

Therefore, current evidence does not permit firm conclusions to be drawn on the relationship between electromagnetic fields and physiological or psychological effects on humans. Until the situation is clarified by further research and provided that no significant cost penalties result, it is suggested that potential fields be minimised. Often this can be achieved by ensuring that line and return cables are in close proximity, as is usual practice for mains wiring.

1.11.2 Air ionisation

It has been suggested that the ion balance of the air is an important factor in human comfort in that negative ions tend to produce sensations of freshness and well-being and positive ions cause headache, nausea and general malaise. Present evidence on the effects of air ions and, in particular, the effectiveness of air ionisers is inconclusive and hence no design criteria can be established^(109,110).

1.11.3 Static electricity

Static electricity can lead to shocks when occupants are not adequately earthed via the floor covering. The incidence of electrostatic shocks depends on the electrical resistance of the floor covering. The resistance is a function of the material itself and its moisture content. The highest electrical resistance is produced by fibrous carpets with an insulating backing when low in moisture content.

At low room humidity, some types of carpet can become highly charged and electrostatic shocks may be experienced, see chapter 8, section 8.3.3.

References

- 1 ASHRAE Standard 55-04: *Thermal environmental conditions for human occupancy* (Atlanta, GA: American Society of Heating Refrigeration and Air-Conditioning Engineers) (2004)
- 2 Cain W S, See L C and Tosun T Irritation and odour from formaldehyde: chamber studies *Proc. ASHRAE Conf. IAQ '86: Managing the Indoor Air for Health and Energy Conservation, Atlanta GA, USA* (1986)
- 3 *Indoor air pollutants: exposure and health effects — Report of WHO meeting, Norlinger, 8–11 June 1982* (Copenhagen: World Health Organisation Regional Office for Europe) (1982)
- 4 BS EN ISO 7726: 2001: *Ergonomics of the thermal environment. Instruments for measuring physical quantities* (London: British Standards Institution) (2001)
- 5 BS EN ISO 9920: 2003: *Ergonomics of the thermal environment. Estimation of the thermal insulation and evaporative resistance of a clothing ensemble* (London: British Standards Institution) (2003)
- 6 BS EN 28996: 1994 (ISO 8996: 1990): *Ergonomics. Determination of metabolic heat production* (London: British Standards Institution) (1994)
- 7 BS EN ISO 7730: *Moderate thermal environments. Determination of the PMV and PPD indices and specification of the conditions for thermal comfort* (London: British Standards Institution) (1995)
- 8 Humphreys M A The optimum diameter for a globe thermometer for use indoors. *Ann. Occup. Hyg.* **20** 135–140 (1977)
- 9 Fanger P O, Melikov A, Hanzawa H and Ring J Air turbulence and sensation of draught *Energy and Buildings* **12** 21–39 (1988)
- 10 Fanger P O and Pedersen C J Discomfort due to air velocities in spaces *Proc. IIR Commissions B1/B2/E1, Belgrade, 1977* (1977)
- 11 Fountain M E Laboratory studies of the effect of air movement on thermal comfort: a comparison *ASHRAE Trans.* **97** (1), 1991]
- 12 Fountain M E *An empirical model for predicting air movement preferred in warm environments* in Nicol F, Humphreys M and Sykes O (eds.) *Standards for thermal comfort* (London: Spon) (1995)
- 13 Griefahn B, Kunemund C and Gehring U *Annoyance caused by draught, the extension of the draught-rating model (ISO 7730) in McCartney K (ed.) Moving thermal comfort standards into the 21st century* (Oxford: Oxford Brookes University) (2001)
- 14 McIntyre D A Response to atmospheric humidity: a comparison of three experiments *Ann. Occupational Hygiene* **21** 177–190 (1978)
- 15 Nevins R G, Rohles F H, Springer W E and Feyerherm A M Temperature–humidity chart for thermal comfort of seated persons *ASHRAE Trans.* **72** (1) 283 (1966)
- 16 Morey P R, Hodgson M J, Sorenson W G, Kullman G J, Rhodes W W and Visvesvara G S Environmental studies in mouldy office buildings: biological agents, sources and preventive measures *Ann. American Conference Governmental Industrial Hygienists — Evaluating Office Environmental Problems* **10** (1984)
- 17 de Dear R, Brager G and Cooper D *Developing an adaptive model of thermal comfort and preference* ASHRAE Final Report RP-884 (Sydney: Macquarie University) (1997)
- 18 Fanger P O *Thermal comfort* (Malabar, FL, USA: Krieger) (1982)
- 19 Hensel H *Thermoreception and temperature regulation* Physiological Society Monograph No. 38 (London: Academic Press) (1981)
- 20 Humphreys M A Field studies of thermal comfort compared and applied *J. Inst. Heating and Ventilating Engineers* **44** 5–27 (1975)
- 21 Humphreys M A *Thermal Comfort requirements, climate and energy* in Sayigh A A M (ed.) *Renewable Energy, Technology and the Environment* (Oxford: Pergamon) (1992)
- 22 de Dear R and Brager G Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55 *Energy and Buildings* **34** (6) (2002)
- 23 Humphreys M A and Nicol J F The validity of ISO-PMV for predicting comfort votes in every-day thermal environments *Energy and Buildings* **34** (6) 667–684 (2002)
- 24 Control of Fuel and Electricity. The Fuel and Electricity (Heating) (Control) Order 1974 Statutory Instrument 1974 No. 2160 (London: The Stationery Office) (1974)
- 25 Control of Fuel and Electricity. The Fuel and Electricity (Heating) (Control) (Amendment) Order 1980 Statutory Instrument 1980 No. 1013 (London: The Stationery Office) (1980)
- 26 Witterseh T, Wyton D P and Clausen G The effects of moderate heat stress and open plan office noise distraction on SBS symptoms and on the performance of office work *Indoor Air* **14** (supplement 8) 30–40 (2004)
- 27 Wyon D P Studies of children under imposed noise and heat stress *Ergonomics* **13** (5) 598–609 (1970)
- 28 *Conservation of fuel and power* The Building Regulations 2000 Approved Document L1/L2 (London: The Stationery Office) (2002)
- 29 *Climate change and the internal environment* CIBSE TM36 (London: Chartered Institution of Building Services Engineers) (2005)
- 30 *Guidelines for environmental design in schools* Building Bulletin BB87 (London: Department for Education and Skills) (2003)
- 31 *Natural ventilation in non-domestic buildings* CIBSE AM10 (London: Chartered Institution of Building Services Engineers) (2005)
- 32 Thomas M et al. Brain and behaviour changes during sleep deprivation *Proc. Human Factors and Ergonomics Society* **2** (1998)
- 33 *Code for lighting* (London: Society of Light and Lighting) (2004)
- 34 *Office lighting SLL Lighting Guide LG7* (London: Society of Light and Lighting) (2005)
- 35 *Ventilation* The Building Regulations 1991 Approved Document F (London: Her Majesty's Stationery Office) (1991)
- 36 *The visual environment in lecture, teaching and conference rooms* CIBSE Lighting Guide LG5 (London: Chartered Institution of Building Services Engineers) (1991)
- 37 The Workplace (Health, Safety and Welfare) Regulations 1992 (London: The Stationery Office) (1992)
- 38 *The industrial environment* CIBSE Lighting Guide LG1 (London: Chartered Institution of Building Services Engineers) (1989)
- 39 *Heating, ventilating, air conditioning and refrigeration* CIBSE Guide B (London: Chartered Institution of Building Services Engineers) (2001–2)
- 40 *Sports* CIBSE Lighting Guide LG4 (London: Chartered Institution of Building Services Engineers) (1990 plus addendum 1999)

- 41 *Lighting for museums and art galleries* CIBSE Lighting Guide LG8 (London: Chartered Institution of Building Services Engineers) (1994)
- 42 Griffiths I D and McIntyre D A Sensitivity to temporal changes in thermal conditions *Ergonomics* **17** 499–507 (1974)
- 43 Griffiths I D and McIntyre D A The balance of radiant and air temperature for warmth in older women *Environmental Res.* **6** (4) 382–388 (1973)
- 44 Fanger P O and Langkilde G Inter-individual differences in ambient temperature preferred by seated persons *ASHRAE Trans.* **81** (2) 140–147 (1975)
- 45 Langkilde G Thermal comfort for people of high age Comfort thermique: *Aspects Physiologiques et Psychologiques (INSERM)* **75** 187–193 (1979)
- 46 Rohles F H and Johnson M A Thermal comfort in the elderly *ASHRAE Trans.* **78** (1) 131 (1972)
- 47 Collins K J and Hoinville E Temperature requirements in old age *Building Serv. Eng. Res. Technol.* **1** (4) 165–172 (1980)
- 48 Berry P C The effect of coloured illumination on perceived temperature *J. Applied Psychol.* **45** 248–250 (1961)
- 49 Parsons K C The effects of gender, acclimation state, and the opportunity to adjust clothing and physical disability on requirements for thermal comfort *Energy and Buildings* **34** (6) 593–599 (2002)
- 50 Haghighat F, Megri A C, Donnini G and Giorgi G Responses of disabled, temporarily ill, and elderly persons to thermal environments *ASHRAE Trans.* **5** (2) (2000)
- 51 Olesen B W, Schfler M and Fanger P O *Vertical air temperature differences and comfort* in Fanger and Valbjørn (eds.) *Indoor Climate* (Copenhagen: Danish Building Research Institute) (1979)
- 52 McNair H P *A preliminary study of the subjective effects of vertical air temperature gradients* British Gas Corporation Reports WH/T/R and D/73/94 (London: British Gas Corporation) (1973)
- 53 McNair H P and Fishman D S *A further study of the subjective effects of vertical air temperature gradients* British Gas Corporation Reports WH/T/R and D/74/2 (London: British Gas Corporation) (1974)
- 54 Olesen B W Thermal comfort requirements for floors *Proc. IIR Commissions B1/B2/E1 Belgrade* 337–343 (1977)
- 55 Olesen B W Thermal comfort requirements for floors occupied by people with bare feet *ASHRAE Trans.* **83** (2) (1977)
- 56 Nevins R G, Michaels K B, Feyerherm A M The effect of floor surface temperatures on comfort, Part I: College-age males *ASHRAE Trans.* **70** (1964)
- 57 Nevins R G, Michaels K B, Feyerherm A M The effect of floor surface temperatures on comfort, Part II: College-age females *ASHRAE Trans.* **70** 1964
- 58 Springer W E, Nevins R G, Feyerherm A M and Michaels K B The effect of floor surface temperatures on comfort, Part III: the elderly *ASHRAE Trans.* **72** (1) (1966)
- 59 BS EN 1264: *Floor heating. Systems and components* (London: British Standards Institution) (1998)
- 60 Fanger P O, Banhidi L, Olesen B W and Langkilde G Comfort limits for heated ceilings *ASHRAE Trans.* **86** (1980)
- 61 Fanger P O, Ipsen G, Langkilde G, Olesen B W, Christiansen N K and Tanabe S Comfort limits for asymmetric thermal radiation *Energy and Buildings* **8** 225–236 (1985)
- 62 Loveday D L, Parsons K C, Taki A H and Hodder S G Displacement ventilation environments with chilled ceilings, thermal comfort design within the context of the BS EN ISO 7730 *Energy and Buildings* **34** (6) 573–579 (2002)
- 63 Owens P G T Air conditioned comfort and sunshine *J. Inst. Heating Ventilating Engineers* **37** 92–96 (July 1969)
- 64 Humphreys M A and Nicol J F Understanding the adaptive approach to thermal comfort *ASHRAE Trans.* **104** (1) 991–1004 (1998)
- 65 Auliciems A Towards a psycho-physiological model of thermal perception *Int. J. Biometeorology* **25** 109–122 (1981)
- 66 de Dear R A Global database of thermal comfort field experiments *ASHRAE Trans.* **104** (1) 1141–1152 (1998)
- 67 Baker N V and Standeven M A Thermal comfort in free-running buildings *Energy and Buildings* **23** (1996)
- 68 Nicol J F and Humphreys M A Maximum temperatures in European offices to avoid heat discomfort *Solar Energy J.* (to be published)
- 69 Humphreys M A *The influence of season and ambient temperature on human clothing behaviour* in Fanger P O and Valbjørn O (eds.) *Indoor Climate* (Copenhagen: Danish Building Research) (1979)
- 70 Morgan C A, de Dear R and Brager G Climate clothing and adaptation in the built environment *Proc. Conf. Indoor Air 2002: 9th Int. Conf. on Indoor Air Quality and Climate, Santa Cruz CA, USA* **5** 98–103 (2002)
- 71 Nicol F and Raja I *Thermal comfort, time and posture: exploratory studies in the nature of adaptive thermal comfort* (Oxford: School of Architecture, Oxford Brookes University) (1996)
- 72 Humphreys M A *The dependence of comfortable temperature upon indoor and outdoor climate* in Cena K and Clark J A (eds.) *Biengineering, Thermal Physiology and Comfort* (Oxford: Elsevier) (1981)
- 73 Boerstra A et al. A New Dutch adaptive thermal comfort guideline *Proc. Conf. Indoor Air 2002: 9th Int. Conf. on Indoor Air Quality and Climate, Santa Cruz CA, USA* **2** (2002)
- 74 McCartney K J and Nicol J F Developing an adaptive control algorithm for Europe: results of the SCATs project *Energy and Buildings* **34** (6) 623–635 (2002)
- 75 Baker N V and Standeven M A A behavioural approach to thermal comfort assessment in naturally ventilated buildings. *Proc. CIBSE Nat. Conf., Eastbourne, 1995* 76–84 (1995)
- 76 Oseland N A Predicted and reported thermal sensation in climate chambers, offices and homes *Energy and Buildings* **23** (2) 105–116 (1995)
- 77 The Control of Substances Hazardous to Health Regulations 1988 (London: The Stationery Office) (1988)
- 78 Fanger P O The new comfort equation for indoor air quality *Proc. ASHRAE Conf. IAQ '89: The Human Equation — Health and Comfort, San Diego CA, USA* (April 1989)
- 79 PD CR 1752: 1999: *Ventilation for buildings. Design criteria for the indoor environment* (London: British Standards Institution) (1999)
- 80 *Occupational Exposure Limits* HSE EH40 (London: The Stationery Office) (published annually)
- 81 *Air quality guidelines for Europe* (Copenhagen: World Health Organisation) (1987)
- 82 The Workplace (Health, Safety and Welfare) Regulations 1992 (London: The Stationery Office) (1992)
- 83 BS 5266-1: 1999: *Emergency lighting. Code of practice for the emergency lighting of premises other than cinemas and certain other specified premises used for entertainment* (London: British Standards Institution) (1999)
- 84 *Emergency lighting design guide* SLL Lighting Guide LG12 (London: Society of Light and Lighting) (2004)
- 85 Weston H C *The relation between environmental conditions and performance* Industrial Health Research Board Report 87 (London: The Stationery Office) (1945)

- 86 Stenzel A G and Sommer J The effect of illumination on tasks which are independent of vision *Lichttechnik* **21** 143–146 (1969)
- 87 Boyce P R Age, illuminance, visual performance and preference *Lighting Res. Technol.* **5** (3) 125–144 (1973)
- 88 Rea M S and Ouellette M J Visual performance using reaction times *Lighting Res. Technol.* **20** (4) 139–153 (1988)
- 89 *Daylighting and window design* CIBSE Lighting Guide LG10 (London: Chartered Institution of Building Services Engineers) (1999)
- 90 Littlefair P J *Designing with innovative daylighting* BRE Report BR305 (London: Construction Research Communications) (1996)
- 91 BS 8206-2: 1992: *Lighting for buildings. Code of practice for daylighting* (London: British Standards Institution) (1999)
- 92 BS EN 12464-1: 2002: *Light and lighting. Lighting of work places. Indoor work places* (London: British Standards Institution) (2002)
- 93 Saunders J E The role of the level and diversity of horizontal illumination in an appraisal of a simple office task *Lighting Res. Technol.* **1** (1) 37–46 (1969)
- 94 Fischer D The European approach to the integration of lighting and air-conditioning *Lighting Res. Technol.* **2** (3) 174–185 (1970)
- 95 Bitter C and Van Ireland J F A A Appreciation of sunlight in the home *Proc. CIE Int. Conf. Newcastle-on-Tyne* (April 1965)
- 96 Ne'eman E Visual aspects of sunlight in buildings *Lighting Res. Technol.* **6** (3) 159–164 (1974)
- 97 Beranek L L Noise and vibration control (Washington DC: Institute of Noise Control Engineering) (1988)
- 98 *Noise Control in Building Services* (London: Pergamon Press) (1988)
- 99 *Sound and vibration control in ASHRAE Handbook: HVAC Applications* (Atlanta GA: American Society of Heating, Ventilating and Air-conditioning Engineers) (1995)
- 100 BS 8233: 1999: *Sound insulation and noise reduction for buildings. Code of practice* (London: British Standards Institution) (1999)
- 101 BS 4142: 1997: *Method for rating industrial noise affecting mixed residential and industrial areas* (London: British Standards Institution) (1997)
- 102 Blazier W E Revised noise quality criteria for application in the acoustic design and control of HVAC systems *Noise Control Eng.* **16** (2) 64–73 (1981)
- 103 Blazier W E Sound quality criteria in rating noise from heating, ventilating and air-conditioning (HVAC) systems in buildings *Noise Control Eng.* **43** (3) 53–63 (1995)
- 104 The Noise at Work Regulations 2005 Statutory Instrument 2005 No. 1643 (London: The Stationery Office) (2005)
- 105 BS 6472: 1992: *Guide to evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)* (London: British Standards Institution) (1992)
- 106 *Damage to structures from ground-borne vibration* BRE Digest 353 (Garston: Building Research Establishment) (1990)
- 107 BS 7385: *Evaluation and measurements for vibration in buildings: Part 1: 1990: Guide for measurement of vibration and evaluation of their effects on buildings* (London: British Standards Institution) (1990)
- 108 Naismith O F *Electromagnetic fields: A Review of the evidence for effects on health* BR 206 (Garston: Building Research Establishment) (1991)
- 109 Hamilton G and Kew J *Negative air ionisation in buildings* Technical Note TN 4/85 (Bracknell: Building Services Research and Information Association) (1985)
- 110 Raw G *Sick Building Syndrome: a review of the evidence* HSE CRR 42/1992 (London: Health and Safety Executive) (1992)

Appendix 1.A1: Determination of predicted mean vote (PMV)

1.A1.1 Equation for determination of PMV

The predicted mean vote (PMV) is given by the equation:

$$\begin{aligned} \text{PMV} = & (0.303 e^{-0.036M} + 0.028) \{(M - W) \\ & - 0.00305 [5733 - 6.99 (M - W) - p_s] \\ & - 0.42 [M - W - 58.15] \\ & - (1.7 \times 10^{-5}) M (5867 - p_s) \\ & - 0.0014 M (34 - \theta_{ai}) \\ & - (3.96 \times 10^{-8}) f_{cl} [(\theta_{cl} + 273)^4 \\ & - (\theta_c + 273)^4] - [f_{cl} h_c (\theta_{cl} - \theta_{ai})]\} \end{aligned} \quad (1.20)$$

where PMV is the predicted mean vote, M is metabolic rate ($\text{W} \cdot \text{m}^{-2}$ of body surface), W is external work ($\text{W} \cdot \text{m}^{-2}$ of body surface) (0 for most activities), f_{cl} is the ratio of the area of the clothed human body to that of the unclothed human body, θ_{ai} is the average air temperature surrounding the body ($^{\circ}\text{C}$), θ_c is the operative temperature ($^{\circ}\text{C}$), p_s is the partial water vapour pressure in the air surrounding the body (Pa), h_c is the convective heat transfer coefficient at the body surface ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) and θ_{cl} is the surface temperature of clothing ($^{\circ}\text{C}$).

The surface temperature of clothing (θ_{cl}) is given by:

$$\begin{aligned} \theta_{cl} = & 35.7 - 0.028 (M - W) - I_{cl} \{(3.96 \times 10^{-8}) \\ & \times f_{cl} [(\theta_{cl} + 273)^4 - (\theta_c + 273)^4] \\ & + f_{cl} h_c (\theta_{cl} - \theta_{ai})\} \end{aligned} \quad (1.21)$$

where I_{cl} is the thermal resistance of clothing ($\text{m}^2 \cdot \text{K} \cdot \text{W}^{-1}$).

For $\{2.38 (\theta_{cl} - \theta_{ai})^{0.25}\} > 12.1 \sqrt{v_r}$:

$$h_c = 2.38 (\theta_{cl} - \theta_{ai})^{0.25} \quad (1.22)$$

For $\{2.38 (\theta_{cl} - \theta_{ai})^{0.25}\} < 12.1 \sqrt{v_r}$:

$$h_c = 12.1 \sqrt{v_r} \quad (1.23)$$

For $I_{cl} \leq 0.078 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$:

$$f_{cl} = 1 + 1.29 I_{cl} \quad (1.24)$$

For $I_{cl} > 0.078 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$:

$$f_{cl} = 1.05 + 0.645 I_{cl} \quad (1.25)$$

1.A1.2 Computer program for determination of PMV

The following BASIC program computes the PMV for a given set of input variables, as follows:

```

CLO  Clothing (clo)
MET  Metabolic rate (met)
WME  External work (met)
TAI  Air temperature ( $^{\circ}\text{C}$ )
TR   Mean radiant temperature ( $^{\circ}\text{C}$ )
VEL  Relative air velocity (m/s)
SAT  Percentage saturation (%)
PS   Partial vapour pressure (Pa)

10  'Computer program (BASIC) for calculation of
20  'Predicted Mean Vote (PMV) in accordance with
30  'CIBSE Guide A1: Environmental criteria for design (2006)
40  CLS:PRINT"DATA ENTRY":data entry
50  INPUT "Clothing" (clo)"; CLO
60  INPUT "Metabolic rate" (met)"; MET
70  INPUT "External work, normally around 0" (met)"; WME
80  INPUT "Air temperature" (C)"; TA
90  INPUT "Mean radiant temperature" (C)"; TR
100 INPUT "Relative air velocity" (m/s)"; VEL
110 PRINT "ENTER EITHER %SAT OR VAPOUR PRESSURE BUT NOT BOTH"
120 INPUT "Percentage saturation" (%)" ; SAT
130 INPUT "Vapour pressure" (Pa)"; PS
140 DEF FNPS(T)=EXP(16.6536-4030.183/(T+235)):saturated vapour pressure,KPa
150 IF PS=0 THEN PS=SAT*10*FNPS(TAI) :vapour pressure,Pa

```

```

160  ICL = .155 * CLO      : 'thermal insulation of the clothing in m2K/W
170  M = MET * 58.15      : 'metabolic rate in W/m2
180  W = WME * 58.15      : 'external work in W/m2
190  MW = M - W          : 'internal heat production in W/m2
200  IF ICL < .078 THEN FCL = 1 + 1.29 * ICL ELSE FCL = 1.05 + .645*ICL : 'clothing area factor
210  HCF=12.1*SQR(VEL)
220  TAA = TA + 273       : 'air temperature in kelvins
230  TRA = TR + 273       : 'mean radiant temperature in kelvins
240  '—————CALCULATE SURFACE TEMPERATURE OF CLOTHING BY ITERATION—————
250  TCLA = TAA + (35.5-TA) / (3.5*(6.45*ICL + .1)) : 'first guess for surface temp of clothing
260  P1 = ICL * FCL       : 'calculation term
270  P2 = P1 * 3.96       : 'calculation term
280  P3 = P1 + 100        : 'calculation term
290  P4 = P1 * TAA        : 'calculation term
300  P5 = 308.7 - .028 * MW + P2 * (TRA/100) ^ 4 : 'calculation term
310  XN = TCLA / 100
320  XF = XN
330  N = 0                : 'N: number of iterations
340  EPS = .00015         : 'stop criterion in iteration
350  XF = (XF + XN)/2
360  HCN=2.38*ABS(100*XF-TAA) ^ .25 : 'heat trans coeff by nat convection
370  IF HCF > HCN THEN HC = HCF ELSE HC = HCN
380  XN=(P5+P4*HC-P2*XF ^ 4) / (100+P3*HC)
390  N = N + 1
400  IF N > 150 THEN GOTO 550
410  IF ABS(XN-XF) > EPS GOTO 350
420  TCL = 100*XN-273     : 'surface temperature of the clothing
430  '—————HEAT LOSS COMPONENTS—————
440  HL1 = 3.05*.001*(5733-6.99*MW-PS) : 'heat loss diff. through skin
450  IF MW > 58.15 THEN HL2 = .42*(MW-58.15) ELSE HL2 = 0! : 'heat loss by sweating (comfort)
460  HL3 = 1.7*.00001*M*(5867-PA)      : 'latent respiration heat loss
470  HL4 = .0014*M*(34-TA)             : 'dry respiration heat loss
480  HL5 = 3.96*FCL*(XN ^ 4-(TRA/100) ^ 4) : 'heat loss by radiation
490  HL6 = FCL*HC*(TCL-TA)             : 'heat loss by convection
500  '—————CALCULATE PMV—————
510  TS = .303*EXP(-.036*M) + .028     : 'thermal sensation trans coeff
520  PMV = TS*(MW-HL1-HL2-HL3-HL4-HL5-HL6) : 'predicted mean vote
530  GOTO 550
540  PMV = 999999!
550  PRINT:PRINT"OUTPUT"                : 'output
560  PRINT " Predicted mean vote (PMV): ";PRINT USING "###.##"; PMV
570  PRINT: INPUT "NEXT RUN (Y/N)"; R$
580  IF (R$ = "Y" OR R$ = "y") THEN RUN
590  END

```

1.A1.3 Example

DATA ENTRY:

Clothing (clo)? 1.0
 Metabolic rate (met)? 1.2
 External work, normally around 0 (met)? 0
 Air temperature (C)? 19.0
 Mean radiant temperature (C)? 18.0
 Relative air velocity (m/s)? 0.1

ENTER EITHER %SAT OR WATER VAPOUR PRESSURE BUT NOT BOTH

Percentage saturation (%)? 40
 Water vapour pressure (Pa)?

OUTPUT:

Predicted mean vote (PMV): -0.7



Appendix 1.A2: Measuring operative temperature

An ordinary liquid-in-glass or digital thermometer is not suitable for measuring operative temperature if the radiant temperature differs greatly from the air temperature.

The globe thermometer is an instrument that combines the effects of air and radiant temperature in a way related to the response of a human subject. It is essentially an integrating sphere (made of metal or plastic) whose temperature will closely approximate the operative temperature (see page 1-2).

Spheres of various diameters have been used for globe thermometers, but it has been estimated^(A2.1) that the optimum diameter for a globe thermometer to sense operative temperature to be about 40 mm (similar to that of a table tennis ball). The surface of the sphere should be painted grey or black to approximate the reflectivity of the clothed human body to any diffuse solar radiation reflected from the room surfaces.

A globe thermometer can be made by inserting a temperature sensor (electronic or liquid-in-glass) into a suitable 40 mm sphere, with a grey or black surface. The sensor should be at the centre of the globe. The thermometer should fit closely through the globe, to prevent the exchange of air between its interior and the room. The temperature measured at the centre will approximate the mean temperature of the enclosing sphere. Depending on the thermal capacity of the sphere and of the sensor itself, the instrument will take some time to settle. This means that from 5 to 20 minutes may need to elapse before taking the final reading.

To assess the operative temperature of a space several readings of the globe thermometer should be taken, in

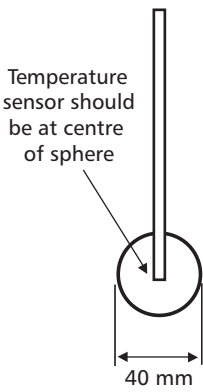


Figure 1.22 Schematic of a globe thermometer

places representative of the occupied area, such as on the working plane, but out of direct sunlight. The thermometer should be suspended or clamped, and not held in the hand. Each time the thermometer is moved it needs time to stabilise, so it may be useful to have two or more identical globe thermometers, allowing multiple readings to be taken in different locations in the space over a period of 30 minutes or so. This will be particularly important if the temperature is changing. The operative temperature for the space is taken to be the average of the readings.

Reference

A2.1 Humphreys M A The optimum diameter for a globe thermometer for use indoors *Ann. Occupational Hygiene* **20**(2) 135–140 (1977)

2 External design data

2.1 Introduction

2.1.1 General

The intention of this chapter is to provide the basic weather and solar data required for manual calculation of heating and cooling loads in the UK and Europe. More extensive data are contained in CIBSE Guide J: *Weather, solar and illuminance data*⁽¹⁾, which deals in detail with meteorological and solar data and provides the basis for the data presented in this chapter.

The main changes from the 1999 edition of CIBSE Guide A involve moving the 20-year basis for the averages from 1976–1995 to 1983–2002 in order to bring the tables and figures up-to-date. Some changes to the contents of the chapter were also felt necessary to reflect the need for useful and meaningful data.

2.1.2 Scope of data

Cold and warm weather data for eight locations in the UK are given in sections 2.3 and 2.4. Since the 1999 edition of this Guide some Met. Office stations have closed. In addition, the formats for data storage have changed with the result that, for some sites, almost a whole year's worth of data are missing. Therefore, their 20-year windows span 1982–2002 with the missing data year omitted. Furthermore, data for some sites had to be compiled from two neighbouring stations. In doing so, efforts were made to ensure that the data are geographically consistent. Table 2.1 shows the 20-year windows for all eight UK sites.

Heating and cooling design temperatures for a range of world-wide locations are given in section 2.6. These data have been selected from the extensive tables of design temperatures for world-wide locations contained in ASHRAE Handbook: *Fundamentals*⁽²⁾ and are reproduced here by kind permission of ASHRAE.

Measured solar radiation data and sol-air temperatures derived from surface observations are given in this Guide for three UK locations (but not for the same periods), as follows:

- London area (Bracknell)
- Manchester (Aughton) (on CD-ROM)
- Edinburgh (Mylnefield/Strathallan) (on CD-ROM)

Tables of data for Bracknell are included within this section. Tables for all three sites are included on the CD-ROM that accompanies this Guide. The CD-ROM also contains tables of theoretical solar irradiances, based on computer algorithms, for all latitudes. The theoretical basis for these tables is fully explained in CIBSE Guide J: *Weather, solar and illuminance data*⁽¹⁾.

Incomplete radiation data sets are available for a number of UK locations⁽³⁾.

In addition to the tabulated data, for building simulation purposes, hourly data for CIBSE-defined Test Reference Years (TRYs) and Design Summer Years (DSYS) have been derived for 14 locations in the UK, see Table 2.2. These are available separately from CIBSE. The basis for selection of the DSYS is given in CIBSE Guide J⁽¹⁾.

Table 2.1 Locations and averaging periods for tabulated data

Location	Station	WMO station number	Lat.	Long.	Altitude / m	Start year	End year	Missing year
Belfast	Aldergrove	39170	54.66 °N	6.22 °W	63	1983	2002	—
Birmingham*	Elmdon	35340	52.45 °N	1.74 °W	96	1982	1996	1997
	Coleshill	35350	52.48 °N	1.69 °W	96	1998	2002	—
Cardiff*	Rhoose	37150	51.40 °N	3.34 °W	65	1982	1996	1997
	St. Athan	37160	51.40 °N	3.44 °W	49	1998	2002	—
Edinburgh	Turnhouse	31600	55.95 °N	3.35 °W	35	1983	2002	—
Glasgow	Abbotsinch	31400	55.87 °N	4.43 °W	5	1983	2002	—
London	Heathrow	37720	51.48 °N	0.45 °W	25	1982	2002	1997
Manchester	Ringway	33340	53.36 °N	2.28 °W	69	1983	2002	—
Plymouth	Mount Batten	38270	50.35 °N	4.12 °W	50	1982	2002	1999

* Data for this site compiled from neighbouring stations



Table 2.2 Locations for which hourly data for CIBSE Design Summer Year and Test Reference Year are available

Location	Station	WMO station number	Lat.	Long.	Alt. / m
Belfast	Aldergrove	39170	54.66 °N	6.22 °W	63
Birmingham*	Elmdon	35340	52.45 °N	1.74 °W	96
	Coleshill	35350	52.48 °N	1.69 °W	96
Cardiff*	Rhoose	37150	51.40 °N	3.34 °W	65
	St. Athan	37160	51.40 °N	3.44 °W	49
Edinburgh	Turnhouse	31600	55.95 °N	3.35 °W	35
Glasgow	Abbotsinch	31400	55.87 °N	4.43 °W	5
Leeds	Leeds W.C.	33470	53.80 °N	1.56 °W	64
London	Heathrow	37720	51.48 °N	0.45 °W	25
Manchester	Ringway	33340	53.36 °N	2.28 °W	69
Newcastle	Newcastle W.C.	32450	54.98 °N	1.59 °W	52
Norwich	Coltishall	34950	52.76 °N	1.36 °E	17
Nottingham	Nottingham W.C.	33540	53.01 °N	1.25 °W	117
Plymouth	Mount Batten	38270	50.35 °N	4.12 °W	50
Southampton	S'hampton W.C.	38650	50.90 °N	1.41 °W	3
Swindon	Boscombe Down	37460	51.16 °N	1.75 °W	126

* Data for this site compiled from neighbouring stations

2.1.3 Time differences

With the exception of solar radiation data, climatological data for the UK are referred to mean time, i.e. Greenwich Mean Time (GMT). Solar radiation data are referred to sun time, i.e. local apparent time (LAT), on which scale the sun crosses the north–south meridian at noon. The difference between the two scales leads to GMT being slow relative to sun time by a maximum of 16 minutes in early November and fast by a maximum of 14 minutes in mid-February. There is a further difference at longitudes other than 0° (the reference longitude for GMT), GMT being slow/fast on sun time by 4 minutes for every degree east/west of 0° longitude, respectively.

In other countries, local mean time (LAT) is that given by the corresponding time zone, which usually differs by an integer number of hours from GMT. LAT in these other countries differs from LAT in the same manner that LAT differs from GMT in the UK. Care must be taken in design to account for daylight saving time where applicable.

2.2 Notation

A	Weibull coefficient
C	Proportion of the year (%)
$C_R(z)$	Roughness coefficient at height z (for wind speed calculations)
C_T	Topography coefficient (for wind speed calculations)
DF	Daylight factor (%)
E_v	Diffuse illuminance received on the horizontal plane (klux)
$E_{vd}(c)$	Diffuse horizontal irradiance available for proportion c (%) of the year (klux)

f_o	Orientation factor
$\bar{F}(v)$	Probability that wind speed v will be exceeded
$f(v)$	Frequency of occurrence of wind speed v
H	Effective height of topographical feature (for wind speed calculations) (m)
k	Weibull coefficient
K_R	Terrain factor (for wind speed calculations)
L_d	Length of the downwind slope in the wind direction (m)
L_e	Effective length of upwind slope (for wind speed calculations) (m)
L_u	Length of the upwind slope in the wind direction (m)
s	Slope factor (for wind speed calculations)
v	Wind speed to nearest metre per second ($m \cdot s^{-1}$)
v_{ref}	Reference regional wind speed ($m \cdot s^{-1}$)
v_z	Wind speed at height z ($m \cdot s^{-1}$)
x	Horizontal distance of site from the top of crest (for wind speed calculations) (m)
z	Vertical distance from ground level of site (for wind speed calculations) (m)
z_{min}	Minimum height (for wind speed calculations) (m)
z_0	Roughness length (for wind speed calculations) (m)
Φ	Upwind slope (H / L_u) in wind direction

2.3 UK cold weather data

2.3.1 Winter design temperatures

2.3.1.1 General

Outside design temperatures are near-extreme values of dry bulb temperature used to determine the sizes of central plant, distribution systems and room terminals for heating in winter. Design temperature has a large influence on the capital cost of building services systems, and some influence on running costs. No single design temperature is given for a particular location; rather, a range from which the designer can select an appropriate design temperature in consultation with the client (bearing in mind the previous sentence).

The selection method described in this Guide is founded in that first presented by Jamieson⁽⁴⁾. This method reflects the thermal response of the building by defining two different averaging times. For most buildings, a 24-hour mean temperature is appropriate. However, a 48-hour mean temperature is more suitable for buildings with high thermal inertia (i.e. high thermal mass, low heat losses), with a response factor $f_r \geq 6$. Response factor is defined in chapter 5.

It is important to choose the correct temperature for the type of building and the level of performance needed. This Guide recommends selection based on variable risk, so that different design temperatures may be chosen for different risks of exceedence. This choice needs to be agreed between designer and client, taking account of the consequences for the building, its users and contents, and of the severity and duration of periods when external design temperatures are exceeded. For buildings with low thermal inertia, earlier editions of Guide A recommended design temperatures such that, on average, only one day in each heating season had a lower mean temperature. Similarly, for buildings with

high inertia, a design temperature was recommended such that only one two-day period in each heating season had a lower mean temperature.

Initial selection of an external winter design temperature should be based upon meteorological data from the nearest recording station to the site of the subject building. Then corrections for specific sites should be applied to account for altitude and heat island effects. Suitable corrections are suggested in sections 2.3.1.3 and 2.10, respectively. Correction of tabulated wind data to the actual site conditions is complicated and methods are given in section 2.8

2.3.1.2 Average frequency of occurrence of low temperatures

Data for eight sites are presented to provide an indicative guide to the selection of an external winter design temperature, based on 24-hour and 48-hour means, suitable for determining building fabric heat loss, see Table 2.3. The data are presented in graphical form in Figures 2.1 to 2.8.

The graphs show the average number of times per year that 24-hour and 48-hour mean temperatures fall below a given value. Overlapping 48-hour periods have been eliminated to avoid giving undue weight to several consecutive days of cold weather. Thus, if it were found that, for example, the average daily temperature for January 1 and January 2 of a year fell between -1°C and 2°C , the next 48-hour average would be taken between January 3 and January 4, and not between January 2 and January 3. However, if it were found that the average did not fall below -1°C , then the next 48-hour average would be taken between January 2 and January 3 in order to check if the temperature fell below -1°C .

Note that two different vertical scales are used for frequency: 0 to 12 for the colder sites (Glasgow, Birmingham and Edinburgh), and 0 to 6 for the remainder. The numerical data on which these graphs are based are given in Table 2.3.

In Table 2.3 the data are cumulative, i.e. the -1 limit represents all values that were less than -1 , the -2 value represents all values less than -2 , and so on.

Table 2.3 Binned frequencies of occurrence of low 24-hour and 48-hour average temperatures

Upper bin temp.*/ $^{\circ}\text{C}$	Binned frequency of occurrence of low 24-hour and 48-hour average temperatures / $^{\circ}\text{C}$							
	Belfast (Aldergrove) (altitude: 68 m)		Birmingham (Edmdon) (altitude: 96 m)		Cardiff (Rhoose) (altitude: 67 m)		Edinburgh (Turnhouse) (altitude: 35 m)	
	24-hour	48-hour	24-hour	48-hour	24-hour	48-hour	24-hour	48-hour
-13	0	0	0	0	0	0	0	0
-12	0	0	0	0	0	0	0	0
-11	0	0	0	0	0	0	0.05	0
-10	0	0	0	0.05	0	0	0.05	0
-9	0	0	0.05	0.05	0	0	0.1	0.05
-8	0	0	0.1	0.05	0	0	0.15	0.05
-7	0	0	0.2	0.2	0.05	0	0.15	0.05
-6	0	0	0.45	0.25	0.1	0.05	0.2	0.05
-5	0.15	0	0.9	0.35	0.3	0.1	0.7	0.1
-4	0.3	0.05	1.55	0.5	0.5	0.2	1	0.2
-3	0.6	0.2	2.5	1.15	0.85	0.3	2.25	0.75
-2	0.85	0.4	5.05	2.5	1.8	0.6	3.95	1.5
-1	1.8	0.8	8.05	4.15	3.45	1.75	6.3	3.2

* Temperature equal to or less than stated upper bin temperature; 1 degree bins

Note: single zero indicates no occurrence

Table 2.3 Binned frequencies of occurrence of low 24-hour and 48-hour average temperatures — continued

Upper bin temp.*/ $^{\circ}\text{C}$	Binned frequency of occurrence of low 24-hour and 48-hour average temperatures / $^{\circ}\text{C}$							
	Glasgow (Abbotsinch) (altitude: 68 m)		London (Heathrow) (altitude: 96 m)		Manchester (Ringway) (altitude: 67 m)		Plymouth (Mount Batten) (altitude: 35 m)	
	24-hour	48-hour	24-hour	48-hour	24-hour	48-hour	24-hour	48-hour
-13	0	0.05	0	0	0	0	0	0
-12	0	0.05	0	0	0	0	0	0
-11	0.05	0.05	0	0	0	0	0	0
-10	0.05	0.05	0	0	0	0	0	0
-9	0.05	0.05	0	0	0	0	0	0
-8	0.1	0.1	0	0	0	0	0	0
-7	0.15	0.15	0.05	0	0.1	0	0	0
-6	0.25	0.2	0.1	0.05	0.1	0.1	0	0
-5	0.6	0.25	0.15	0.05	0.25	0.1	0.1	0
-4	1.25	0.4	0.55	0.1	0.55	0.1	0.15	0.05
-3	2.55	0.95	0.8	0.25	0.95	0.1	0.25	0.1
-2	4.1	1.55	1.95	0.75	1.85	0.7	0.6	0.25
-1	6.9	3.2	3.55	1.85	4	2.25	1.15	0.55

* Temperature equal to or less than stated upper bin temperature; 1 degree bins

Note: single zero indicates no occurrence



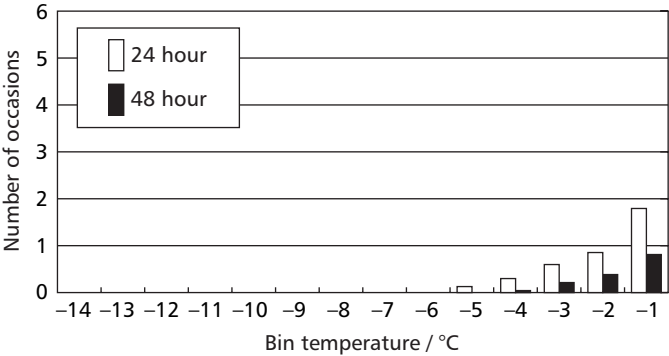


Figure 2.1 Winter temperature distribution: Belfast (Aldergrove) (1983–2002)

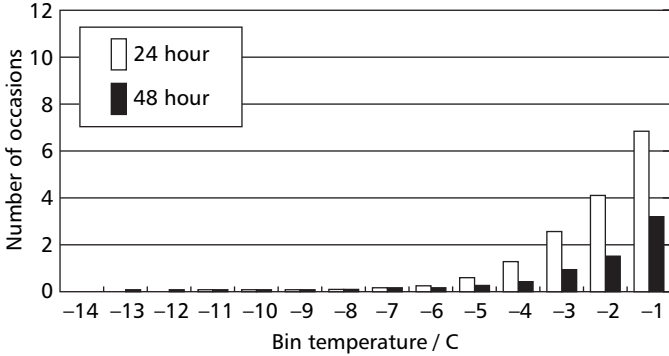


Figure 2.5 Winter temperature distribution: Glasgow (Abbotsinch) (1983–2002)

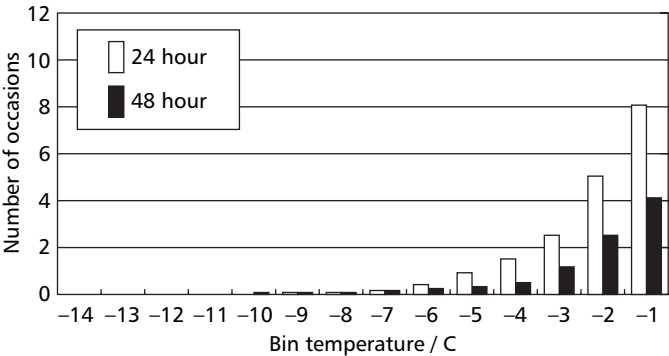


Figure 2.2 Winter temperature distribution: Birmingham (Elmdon) (1982–1996), (Coleshill) (1998–2002)

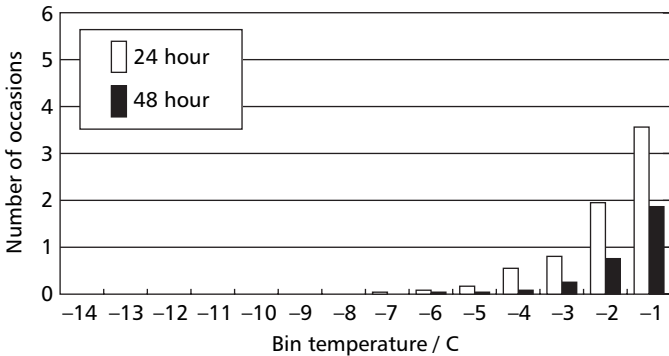


Figure 2.6 Winter temperature distribution: London (Heathrow) (1982–2002)

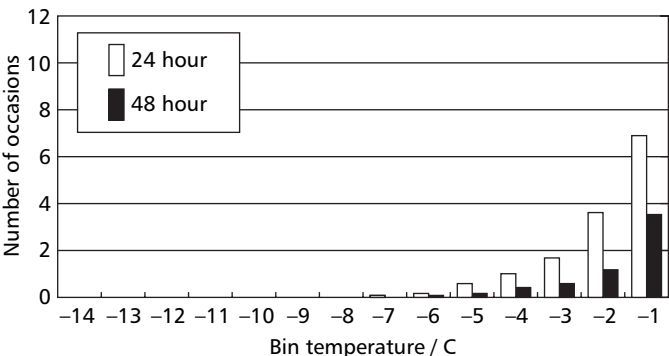


Figure 2.3 Winter temperature distribution: Cardiff (Rhoose) (1982–1996), (St. Athan) (1998–2002)

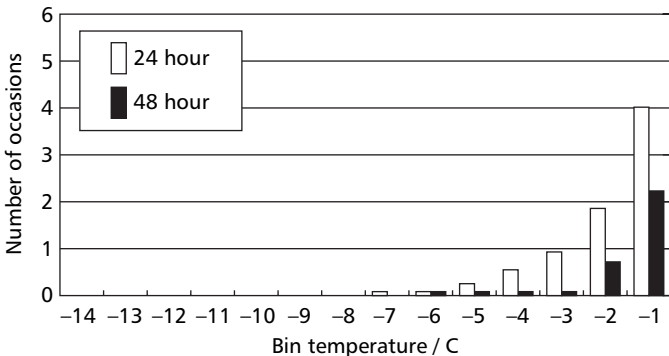


Figure 2.7 Winter temperature distribution: Manchester (Ringway) (1982–2002)

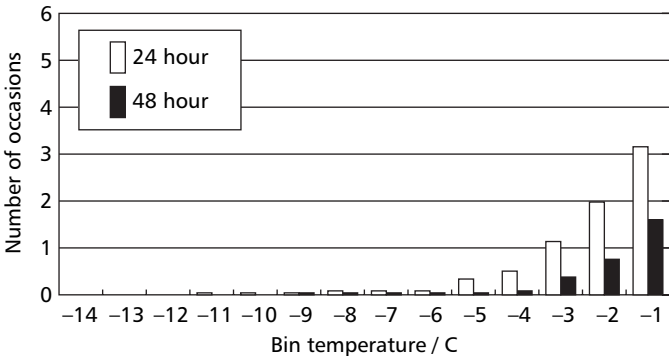


Figure 2.4 Winter temperature distribution: Edinburgh (Turnhouse) (1983–2002)

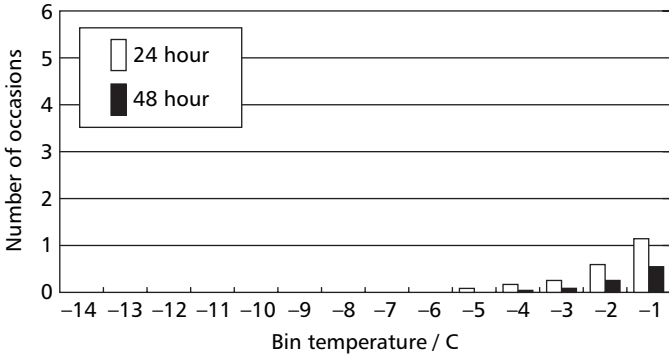


Figure 2.8 Winter temperature distribution: Plymouth (Mount Batten) (1983–2002)

Table 2.4 Wintertime dry bulb temperatures and coincident wet bulb temperatures equal to or exceeded for given percentages of hours in the year (approx. 1982–2002; see Table 2.1)

Location	Hourly temperature (/ °C) equal to or exceeded for stated percentage of hours in the year							
	99.6%		99%		98%		95%	
	Dry-bulb	Wet-bulb	Dry-bulb	Wet-bulb	Dry-bulb	Wet-bulb	Dry-bulb	Wet-bulb
Belfast	–2.6	–3.1	–1.2	–1.8	–0.2	–0.8	1.3	0.5
Birmingham	–5.4	–5.6	–3.4	–3.8	–2.0	–2.4	0.3	–0.4
Cardiff	–3.2	–4.0	–1.6	–2.4	–0.4	–1.2	1.5	0.6
Edinburgh	–5.4	–5.6	–3.4	–3.7	–1.9	–2.3	0.3	–0.5
Glasgow	–5.9	–6.0	–3.9	–4.1	–2.1	–2.6	0.2	–0.5
London	–3.3	–4.0	–1.8	–2.5	–0.6	–1.3	1.4	0.5
Manchester	–3.6	–4.0	–2.2	–2.7	–0.9	–1.7	0.9	0.0
Plymouth	–1.6	–2.6	–0.2	–1.2	0.9	–0.1	2.9	1.9

2.3.1.3 Design temperatures corresponding to given frequencies of occurrence

An alternative approach, useful for an air heating system, is to determine the temperature that is not exceeded for a given frequency of occurrence. Table 2.4 provides for eight sites, the winter dry bulb temperatures equal to or exceeded by specified percentage of hours in the year with coincident wet bulb temperatures.

These design temperatures should be reduced by 0.6 °C for every complete 100 m by which the altitude of the design site exceeds that of the recording station indicated.

2.3.2 Warm front condensation

In addition to the condensation that may occur due to moisture generated within buildings, see chapter 7, condensation may also occur when the weather changes at the end of a cold spell, if a cold air-mass is replaced within a few hours by a warm, moist air-mass. For heavyweight structures, the atmospheric dew-point may rise more quickly than the surface temperature, producing temporary condensation on such surfaces exposed to outside air. This is most likely to happen internally on surfaces in poorly heated or unheated buildings such as warehouses and storage buildings. Condensation may also occur on the contents of the building. In such conditions, unheated

buildings should, as far as possible, be closed to exclude humid external air.

Table 2.5 shows the frequency of such conditions for eight UK locations. These values are based on positive differences between the dew-point temperature in the middle of the day (mean of values at 09, 12 and 15 GMT) and the mean dry bulb temperature of the previous day (mean of hourly values from 01 to 24 GMT). Almost all days with a risk of condensation from external air occur during the cold half of the year. The values given in Table 2.5 indicate the likely frequency of condensation following a rapid rise in atmospheric dew-point assuming that the surface temperature of an unheated, heavyweight building at the end of a cold spell is equal to the mean outside dry bulb temperature. Note that Table 2.5 is not a cumulative distribution. Therefore, the 0.0 to 0.9 bin represents only those values that lay between 0.0 and 0.9.

For a typical heavyweight structure that has approached thermal equilibrium during a cold spell and is ventilated at 1 air change per hour, the surface temperature of the inside walls will increase by only one-quarter of the rise in outside air temperature during the first 12 hours. Condensation will occur on the walls but at only about 20% of the possible rate because the low ventilation rate limits the amount of water vapour available. Increasing the rate of ventilation causes a corresponding increase in condensation.

Table 2.5 Average number of occasions per year when the mean of the dew-point temperature at 09:00, 12:00 and 15:00 exceeds the preceding day's dry bulb temperature by the amount indicated (approx. 1982–2002; see Table 2.1)

Amount by which dry bulb temperature is exceeded / K	Average number of occasions per year for stated location*							
	Belfast	Birmingham	Cardiff	Edinburgh	Glasgow	London	Manchester	Plymouth
0.0–0.9	21.7	18.8	21.9	17.4	18.8	14.7	16.1	21.5
1.0–1.9	10.7	10.3	10.9	11.2	11.3	8.1	8.9	10.6
2.0–2.9	6	5.9	6	5.4	5.6	4.4	4.2	5.4
3.0–3.9	3.4	2.4	2.7	3.1	3.2	3	2.7	2.3
4.0–4.9	2.1	1.9	1.5	1.5	2.3	1.2	1.2	0.9
5.0–5.9	0.4	0.9	0.4	0.75	1.3	0.9	0.4	0.7
6.0–6.9	0.3	0.3	0.3	0.2	0.4	0.3	0.2	0.2
7.0–7.9	0.05	0.3	0.05	0.2	0.3	0.1	0.05	0.05
8.0–8.9	0	0.1	0.05	0.1	0.3	0.2	0.05	0
9.0–9.9	0	0.05	0	0.05	0.05	0	0	0
10.0–10.9	0	0.05	0	0	0	0	0	0
11.0–11.9	0	0	0	0	0.05	0	0	0
> 12	0	0	0	0	0	0	0	0

Notes: single zero indicates no occurrences; calculated using 24-hour average daily dry and wet bulb temperatures and standard pressure