ENGINEERING TRIPOS PART IIB

Wednesday 11 May 2011 9 to 10.30

Module 4D11

BUILDING PHYSICS

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

Attachments: Building Physics Environmental Data Sheets (11 pages)

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

1 (a) A cavity wall has three layers. The outer layer is brickwork, 100 mm thick. The central layer is an 80 mm cavity filled with mineral wool, and the inner layer is 120 mm of concrete blockwork. The thermal conductivities of brick, wool, and concrete block are 0.84 W/mK, 0.04 W/mK, and 0.20W/mK respectively. Assume that the external and internal surface resistances are 0.1 m^2K/W and 0.12 m^2K/W respectively.

(i) Determine the U-value of the wall. [20%]

(ii) Under steady state conditions of internal and external air temperatures of 20 °C and –3 °C respectively, determine the steady-state heat flux through the wall and the temperature at the interface between the outer and the central layer. [30%]

(b) Explain briefly the concept of the environmental node in the CIBSE simple model. [30%]

(c) Explain briefly what a psychrometric chart is, and how it may be of use to a building physicist. [20%]

2 (a) Describe with the aid of sketches the main components and operating principles of:

(i) a low temperature solar collector; [10%]

(ii) a high temperature solar collector; [10%]

(iii) an off-grid photovoltaic (PV) system. [10%]

(b) A building has a load demand of 750 Wh/day in direct current (12 V) and 8000 Wh/day in alternating current (240 V). The owner wishes to install a PV array consisting of 200 W panels to meet this demand, but is constrained to either install the panels vertically on a south-facing wall, or horizontally on the roof.

(i) Use the solar irradiation chart provided in the Data Sheets to determine the number of PV panels required for a grid-connected system and for an off-grid system. [30%]

(ii) Use the discounted cash flow method to calculate the cost of electricity generated per kWh for an off-grid system with a 20-year service life. In your calculation assume that the discount rate is 5%, the capital cost of a 200 W photovoltaic panel is £800 and the cost of ancillary equipment and maintenance is negligible. [20%]

(iii) The constraint on the inclination of the PV panels has now been removed. How would this affect your answers to b(i) and b(ii)? [20%]

3 The open plan office shown in Fig. 1 has a lighting requirement of 300 lux.

(a) Artificial lighting is provided by 1.5 m long fluorescent tubes rated at 40 W with an efficiency of 85 lm/W. The tubes are mounted in luminaries giving a utilisation factor of 78%. Determine the number of luminaries required and suggest a suitable layout. [15%]

(b) The office window has a transparency of 75% and the internal reflectance of the office is 50%. Determine the daylight factor at point A and point B. [50%]

(c) Use the daylight availability curves provided in the Data Sheets to calculate the fraction of standard annual office hours for which artificial lighting is required in order to meet the lighting requirement at point A. [20%]

(d) One option for reducing unwanted solar heat gain is to replace the standard glazing in the window with solar control glass. This change would also reduce the transparency of the glazing to 60%. Without carrying out detailed calculations comment on the effect this option would have on the lighting energy demand, and suggest alternative measures for reducing solar heat gain. [15%]

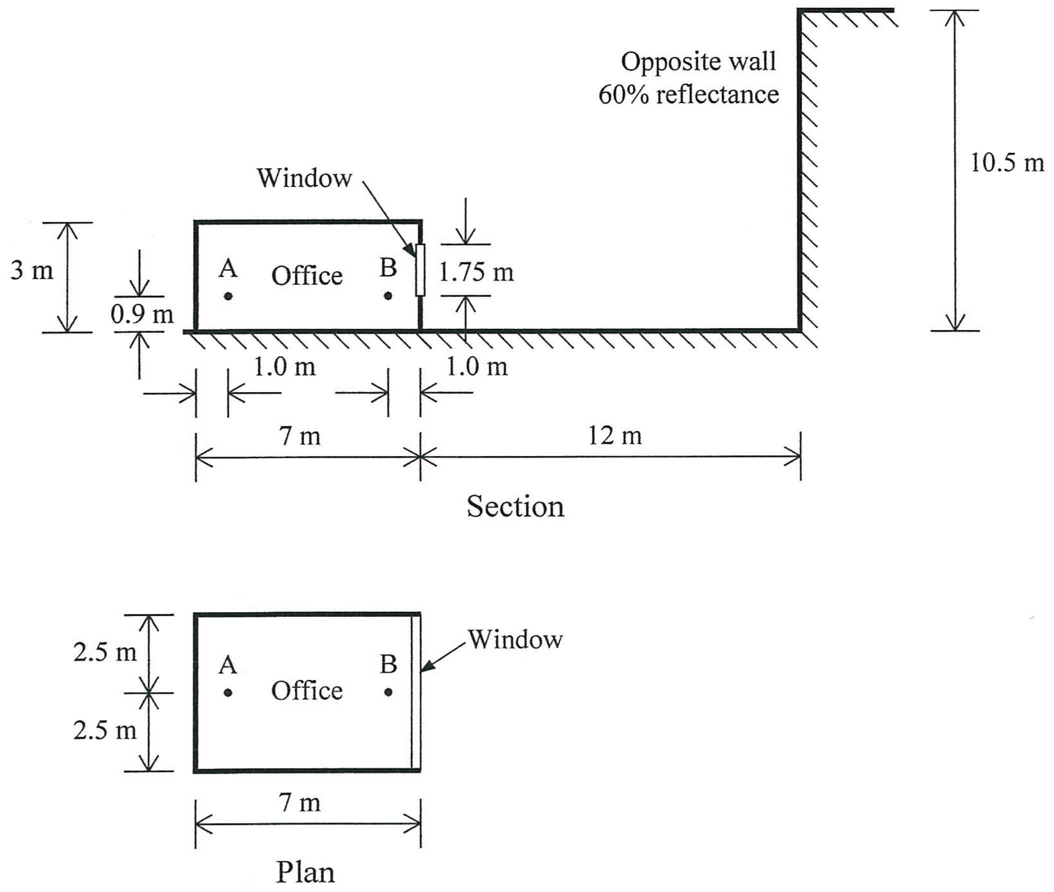


Fig. 1

(TURN OVER

4 A basement hall 12 m wide, 17 m long and 3.3 m high, with a flat ceiling, has been found to have a reverberation time at mid frequencies of 4.25 s. The absorption coefficients of the existing walls, floor and ceiling are negligible.

(a) What area of 50 mm thick mineral wool with an absorption coefficient of 0.9, should be introduced into the hall to reduce the reverberation time to 1 s? [25%]

(b) What simple recommendation can be made about the placement of this absorption? [15%]

(c) The hall is used for meetings, dining and sport. By reducing the hall's reverberation time, what benefits can be expected for each of these activities? [25%]

(d) The reverberation time in the 63 Hz octave band is also very long. Why is this a significant additional problem and what can be done about it? [20%]

(e) The current background noise level due to the ventilation system has been found to be NR45. Comment on whether this is acceptable, and if not what a more appropriate level would be. [15%]

END OF PAPER

1. Lighting & PV Systems

(a) Definitions		units
Luminous flux – rate of flow of light energy	–	lumens (1m)
Illuminance – density of light flux reaching a surface	–	lumens/m^2 or lux (1x)
Luminous intensity – light flux per unit solid angle from a point source, i.e. power to emit in a particular direction	–	candela (cd) (1 cd $\equiv 4\pi$ 1m)

(b) Artificial light

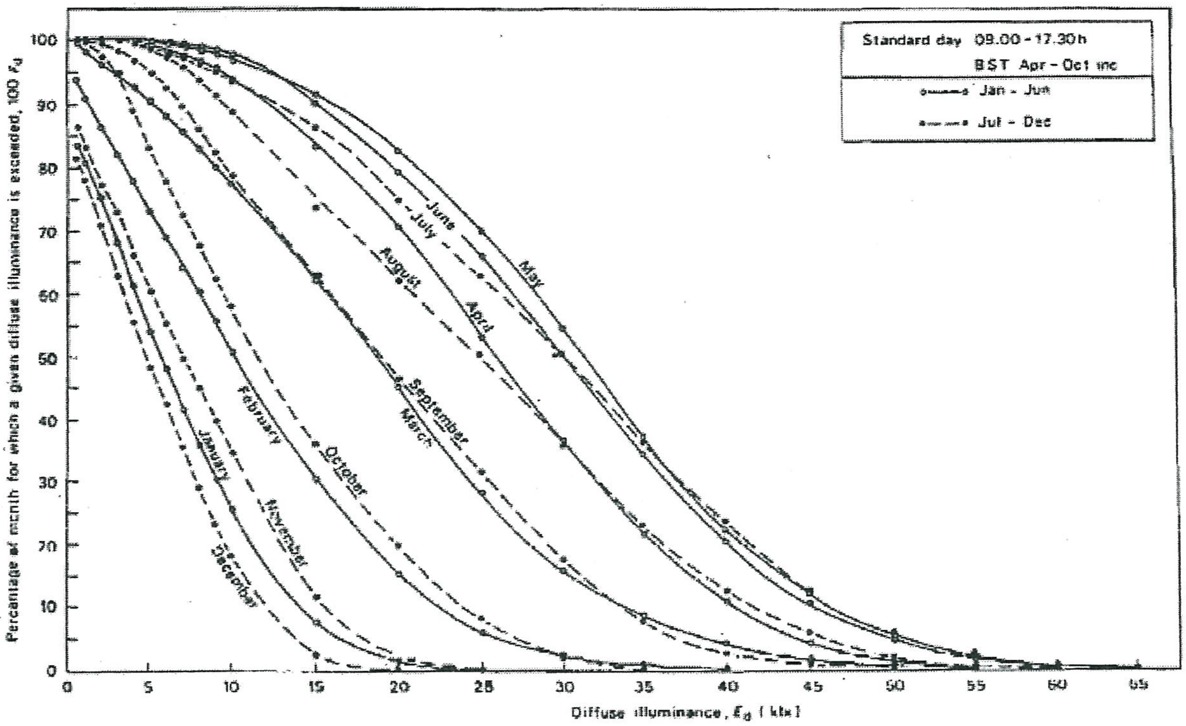
Recommended illuminances, on horizontal working plane, vary from 150 lux for storage areas, through 500 lux for general offices, to 1500 lux for precision bench work.
"Utilisation factor" is the proportion of light emitted by the luminaires which actually reaches the working plane.
Typical luminous efficacies (lumens/Watt): tungsten filament (GLS) 12, tubular florescent 60, low pressure sodium 180, daylight 115.

(c) Daylight

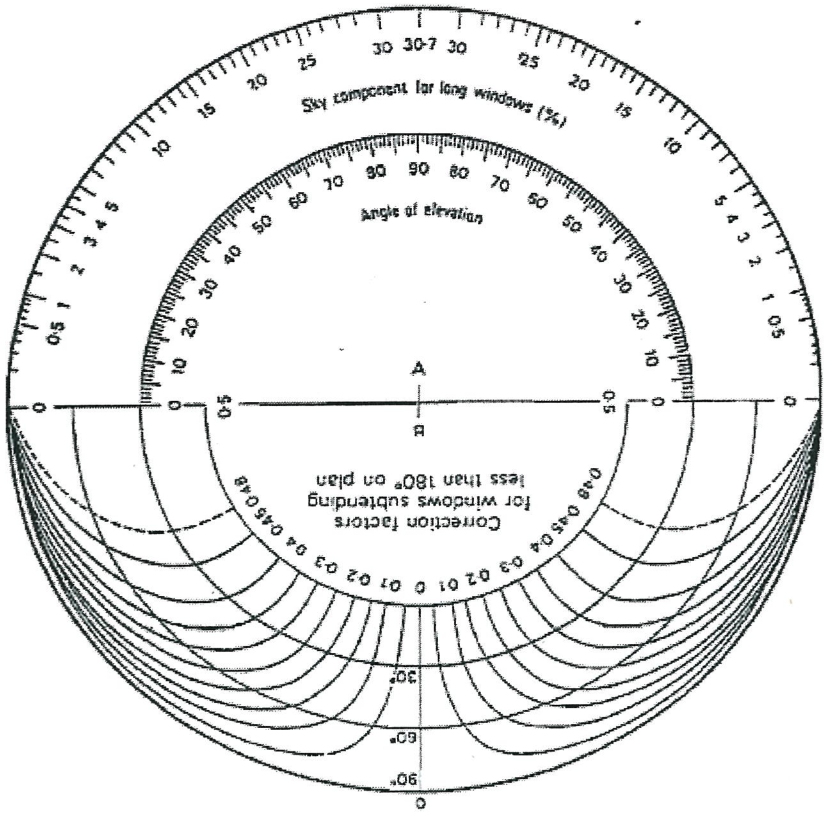
Sky as a diffuse source: sky luminance B_θ from elevation θ above horizon, where B_Z is luminance at the zenith: $B_\theta \approx B_Z(1+2\sin\theta)/3$ "CIE sky"

Example of monthly daylight availability curves for Bracknell; Percentage of working time exceeded vs diffuse illuminance level in *klx*.

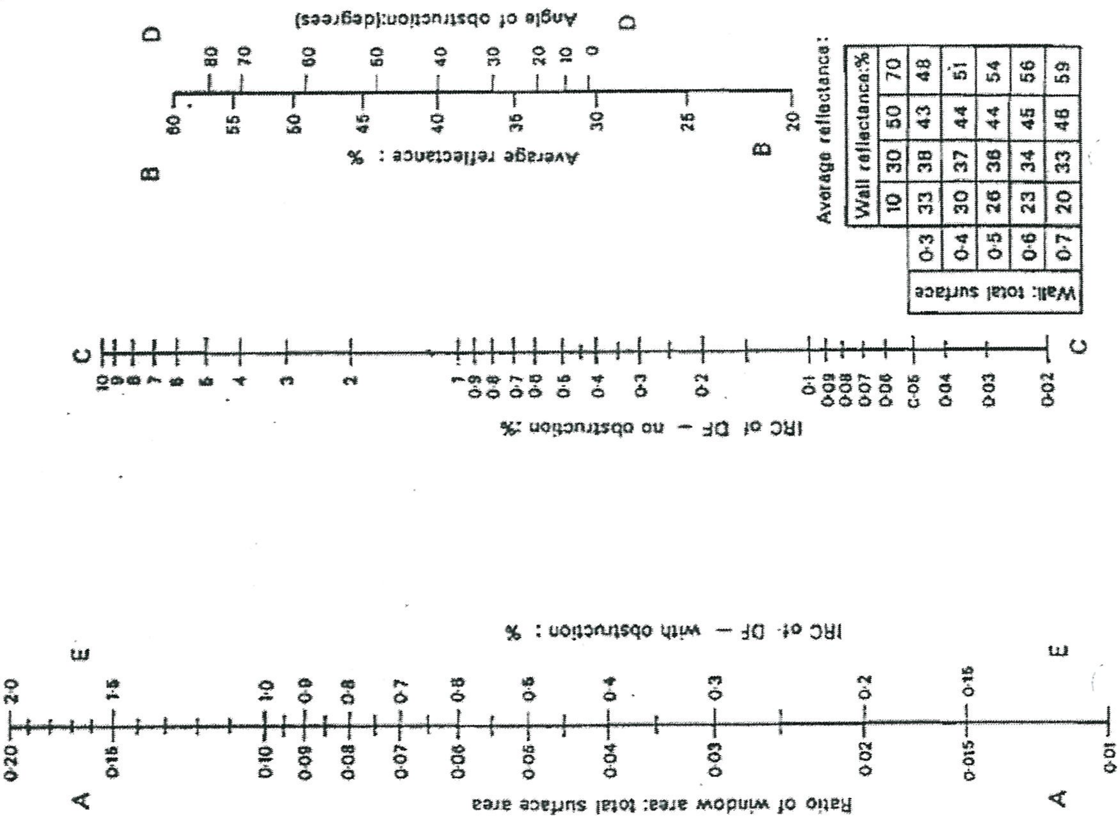
Average daylight factor (%) in a room is approx. TWMd/A(1 – ρ^2) where T is glazing transmittance; W is net window area; M is 'maintenance factor' (i.e. cleaning); d (degrees) is the angle at the window centre in the vertical plane between the vertical and the highest external building obstruction; A is the total area of all internal surfaces; and ρ is the weighted mean reflectance of the internal surfaces.



BRE Sky Component protractor: single clear vertical glazing, CIE overcast sky, illuminance on a horizontal surface indoors. Externally reflected component is SC with a further correction factor of 0.2.

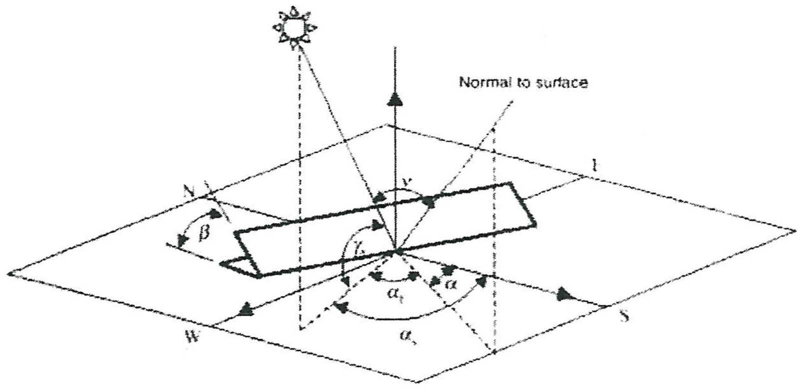


Typical nomogram for internally-reflected component:
(ground reflectance 0.1 in this case)



Wall: total surface	10	30	50	70
0·3	33	38	43	48
0·4	30	37	44	51
0·5	26	36	44	54
0·6	23	34	45	56
0·7	20	33	46	59

(d) Solar irradiation



Typical mean daily irradiation on South facing panel in Southern Europe (kWh/m^2)

Angle	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
0	2.25	2.92	3.88	4.98	5.66	6.38	6.67	5.75	4.20	3.18	2.23	1.70	4.15
5	2.56	3.19	4.08	5.09	5.69	6.36	6.68	5.84	4.46	3.42	2.49	1.93	4.32
10	2.86	3.44	4.26	5.18	5.70	6.32	6.66	5.90	4.61	3.64	2.74	2.16	4.46
15	3.14	3.67	4.42	5.25	5.67	6.25	6.61	5.94	4.73	3.84	2.98	2.37	4.57
20	3.40	3.87	4.55	5.28	5.62	6.15	6.52	5.94	4.82	4.03	3.19	2.57	4.66
25	3.65	4.05	4.66	5.29	5.54	6.03	6.41	5.91	4.89	4.18	3.39	2.75	4.73
30	3.86	4.21	4.73	5.26	5.44	5.88	6.26	5.85	4.93	4.31	3.57	2.92	4.77
35	4.05	4.34	4.78	5.21	5.31	5.70	6.08	5.75	4.94	4.42	3.72	3.07	4.78
40	4.22	4.45	4.81	5.13	5.15	5.49	5.88	5.63	4.93	4.50	3.85	3.19	4.77
45	4.36	4.53	4.80	5.03	4.97	5.26	5.65	5.48	4.88	4.55	3.96	3.30	4.73
50	4.47	4.58	4.77	4.89	4.77	5.01	5.39	5.29	4.81	4.57	4.04	3.39	4.66
55	4.55	4.60	4.71	4.73	4.55	4.74	5.11	5.09	4.71	4.57	4.09	3.45	4.57
60	4.60	4.59	4.62	4.55	4.30	4.45	4.80	4.85	4.58	4.53	4.12	3.49	4.46
65	4.62	4.55	4.50	4.34	4.04	4.14	4.48	4.59	4.42	4.47	4.12	3.51	4.32
70	4.61	4.49	4.36	4.11	3.77	3.83	4.15	4.31	4.25	4.38	4.10	3.51	4.15
75	4.57	4.39	4.19	3.86	3.48	3.50	3.80	4.02	4.05	4.27	4.04	3.48	3.97
80	4.50	4.27	4.00	3.59	3.18	3.17	3.44	3.70	3.82	4.13	3.97	3.43	3.77
85	4.40	4.13	3.79	3.31	2.88	2.84	3.08	3.37	3.58	3.96	3.87	3.36	3.55
90	4.27	3.95	3.55	3.02	2.57	2.51	2.86	3.04	3.32	3.78	3.74	3.27	3.24

(d) Photovoltaic Systems

Nominal power of PV panels (W): $P_0 = \dfrac{L}{PSH}$

Where L = load (Wh); PSH = peak solar hours (h)

Battery Capacity (Ah): $Q = \dfrac{L\ C_s}{V\ DOD_{\max}}$

Where L = load (Wh); C_s = days of autonomy; V = voltage;
DOD_{max} = maximum draw down (%).

2. Thermal matters

(a) Temperatures

Air temperature in shade T_a – the 'dry bulb' temperature, usually in degrees C db.

'Wet bulb' temperature, C wb, in a small damp sponge in air current (taken with T_a indicates humidity).

'Mean radiant temperature' T_r – the uniform surface temperature of a surrounding black enclosure delivering the same radiant heat to the point in question as arrives in the actual non-uniform space (in practical rooms, approx. the mean surface temperature T_m of all the enclosing surfaces).

Radiant heat flow is roughly $Q_r = A\, \varepsilon\, \sigma\, (T_b^4 - T_r^4)$ where A and T_b (K) are the surface area and temperature of the radiating body, ε is emissivity (usually 0.95, but 1.0 for a 'black' body), and σ is 5.67×10^{-8} W/m^2K^4.

'Globe temperature' (measured inside a small black sphere) is roughly the 'operational temperature', the mean of T_a and T_r.

'Environmental temperature' T_e in a room is $(T_a + 2T_m)/3$.

'Corrected effective temperature' CET depends on globe and wet-bulb temperatures, and air velocity – the wind-chill effect – and is obtained from charts.

'Neutral temperature' (CET in C at which most people feel comfortable) is
$T_n = 11.9 + 0.564\ T_o$ +/- 2.5 (Humphreys) for a sedentary occupation, where T_o is the mean outdoor temperature for the month in question.

(b) Thermal Comfort

Comfort will depend on many factors, not just the temperature but also such things as the humidity, the freshness of the air, and the amount of clothing being worn (0.1 clo for shorts only, 1.0 clo for a business suit, 2.5 clo for a heavy overcoat).

Also important will be the metabolic rate M (ranging from 70 W when sleeping, through 150 W when typing, 300 W for fast walking, to 650 W for hard sustained work); the rate W watts at which work is being done; and the rate H watts of loss of heat, which will depend on radiation, convection, and evaporation from the skin, as well as heat and water-vapour losses in breathing.

Fanger introduced the Predicted Mean Vote (PMV) for people's sensation of comfort on a scale of – 3 to + 3 (very cold to very hot). His equation has over 15 terms, based on metabolic rate, work being done, temperature etc, with empirical constants and factors based on surveys of large numbers of people – and with some subsequent dispute whether the equation is correct in all circumstances.

Fanger also investigated the 'Predicted Percentage Dissatisfied' at a given PMV, suggesting the relation $PPD = 100 - 95 \exp\{-(0.04\, PMV^4 + 0.22\, PMV^2)\}$.

(c) <u>Heat loss and gain calculations for buildings</u>

Total 'specific heat loss' $Q = Q_c + Q_v$ in watts per degree difference between environmental temperature inside and air temperature outside.

By conduction $Q_c = \Sigma U A$ W/K , where A is area of wall, roof, windows etc, each with their individual 'U-value'. For layered construction, the U-value in W/m^{2}K is given by

$$1/U = R_i + \Sigma\, r\, t + R_c + R_e$$

where R_i and R_e are thermal resistances at internal and external surfaces (depending on radiative and convective heat transfer), R_c is for any cavity, and r and t are respectively reciprocal of conductivity, and thickness, of the various layer materials (typical conductivities being given in tables of data).

By ventilation Q_v depends on room volume, number of air changes per unit time, and the appropriate coefficient for air (ρc_p, approx 1200 J/m^{3}K at 20 C).

'Degree days', presented in statistics for each month for a locality, are the integral over time of the shortfall of the outside air temperature below a chosen internal design temperature, often 18 C.

'Mean internal environmental temperature' , over a long period say 24 hours, can be calculated, as an increment above the mean outside air temperature, from the mean internal casual heat gains (people, lights, computers etc) plus the mean solar gains (window area, gain in W/m^2 depending on aspect and time of year, and a Solar Gain Factor) – giving total mean heat gains (in W) – and the specific heat loss Q in W/K .

Typical solar gains in June for a South-facing window are 700 W/m^2 .

Swings in internal environmental temperature (mean to peak) can be estimated, for the time of day when the peak is likely to occur, from;

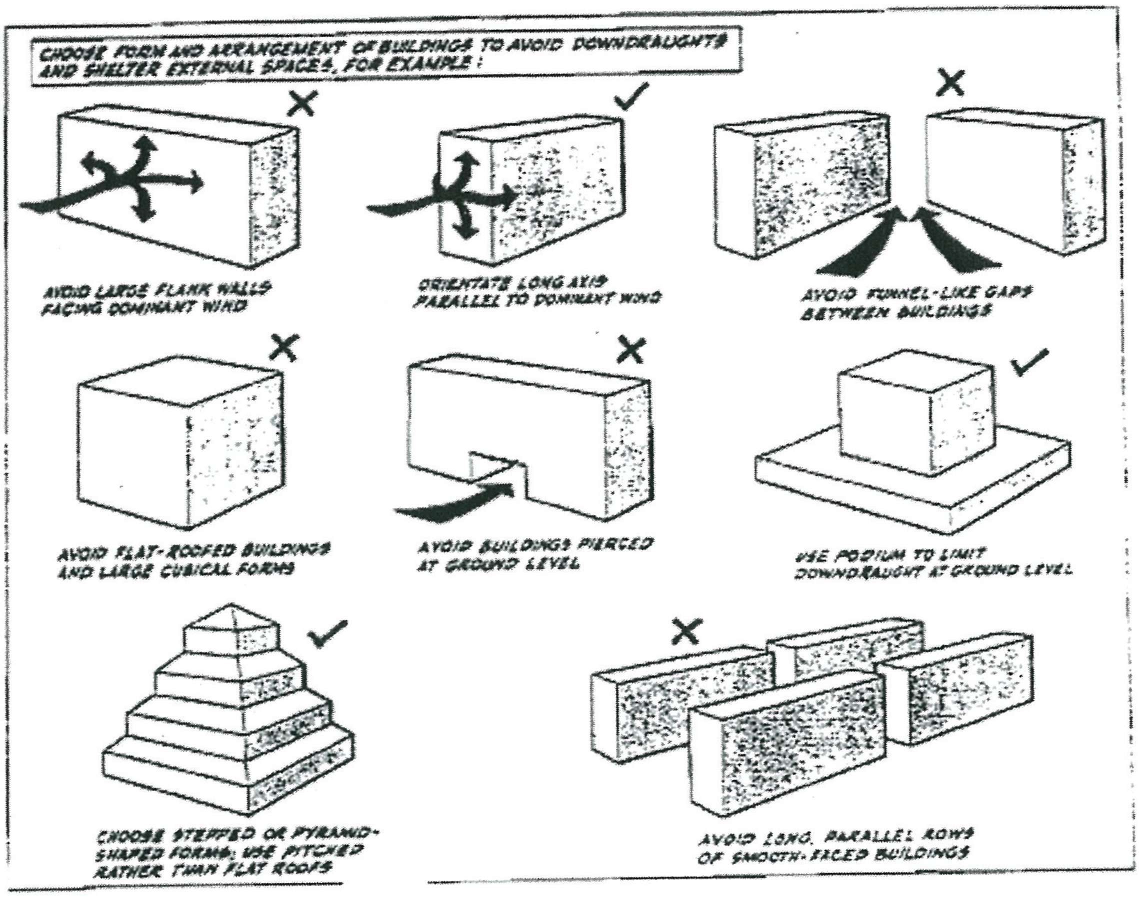
(i) the swing in solar gain (W) using the window area, the difference between peak and mean gains (W/m^2) and an Alternating Solar Gain Factor;
(ii) any simultaneous swing in casual gain (W) from its mean; and
(iii) any departure of the outdoor air temperature at the peak time from its mean, multiplied by a new 'specific heat loss factor' Q (now from window area and U-value for glazing, plus ventilation)

to give a total apparent swing of heat gain in W.

This total is divided by another specific heat loss factor – now ventilation Q_v plus the sum of wall areas times Y-values ('admittances' in W/m^{2}K) – to give the swing in environmental temperature from the mean. Y-values for the various materials are available from tables of data.

3. Ventilation

(a) Reducing the wind sensitivity of buildings (from Building Research Establishment, Digest 350)



Wind pressure coefficients (tabulated) ; $C_p = \dfrac{p - p_{ref}}{\frac{1}{2}\rho U_{ref}^2}$;

where $U_{ref} = U_{ambient}$ is typically taken as wind velocity 10 m above ground level.

(b) Orifice flow

$$\Delta p = K \frac{1}{2} \rho U^2 \text{ , with } K \approx 1$$

whence $$U = \sqrt{\frac{2\Delta p}{\rho}}$$

Q (volume flow rate) = $C_D \times U \times Area$
C_D = discharge coefficient due to streamline contraction.

(c) Momentum jets

$$R \quad \alpha \quad x$$

$$U \,\alpha \left(\frac{M_o}{\rho}\right)^{\frac{1}{2}} x^{-1} \; ; M_o = source\ momentum\ flux = \rho\, Q_o U_o$$

(d) Buoyancy effects

Stack effect; $U \approx \sqrt{g\frac{\Delta\rho}{\rho}H}$ for two equal area vents, depending on discharge C_D etc.

Empirical equations used in practice:

nominal pressure difference $\Delta p = 0.043\ h\ (T_i - T_o)$ Pa , where h (m) is the height between inlet and outlet of the stack and T_i and T_o are average internal and air outside temperatures.

then volume flow is $Q = 0.827\ A\ (\Delta p)^{1/2}\ m^3/s$, where A (m^2) is given for inlet area A_1 and outlet area A_2 by $A = A_1 A_2/(A_1^2 + A_2^2)^{1/2}$.

Exchange flows Q (one fluid) $= \begin{pmatrix} 0.25\ horizontal \\ 0.05\ vertical \end{pmatrix} \sqrt{g\frac{\Delta\rho}{\rho}d}$ (Area)

Gravity currents $U = (\sim 1.0)\sqrt{g\frac{\Delta\rho}{\rho}h}$

Buoyant plumes

$$R = 0.12\ z$$

$$U = 2.55\ F_o^{\frac{1}{3}}\ z^{-\frac{1}{3}}$$

$$g\left(\frac{\Delta\rho}{\rho}\right) = 8.66\ F_o^{\frac{2}{3}}\ z^{-\frac{5}{3}}$$

$$F_o = Q_o g\frac{\Delta\rho_o}{\rho} = \frac{\dot{Q}_g}{\rho T C_p}$$

Consistent with assumptions in derivation we have $\rho \approx \rho_a$ and use ρ_a and T_a as reference conditions whenever necessary.

4. Acoustics

(a) Fundamentals and definitions

Velocity of sound in air at 20 °C : $c \approx 344 m/s$ when air density $\rho \approx 1.2 kg/m^3$

Consider root mean square pressure fluctuation $\bar{p}$ Pa and standard reference level $p_o = 2.0 \times 10^{-5}$ Pa at 1000Hz. Sound pressure level (SPL) defined as $20 \log_{10} (\bar{p}/p_o)$ decibels.
Sound intensity (rate of energy transmission across given surface):

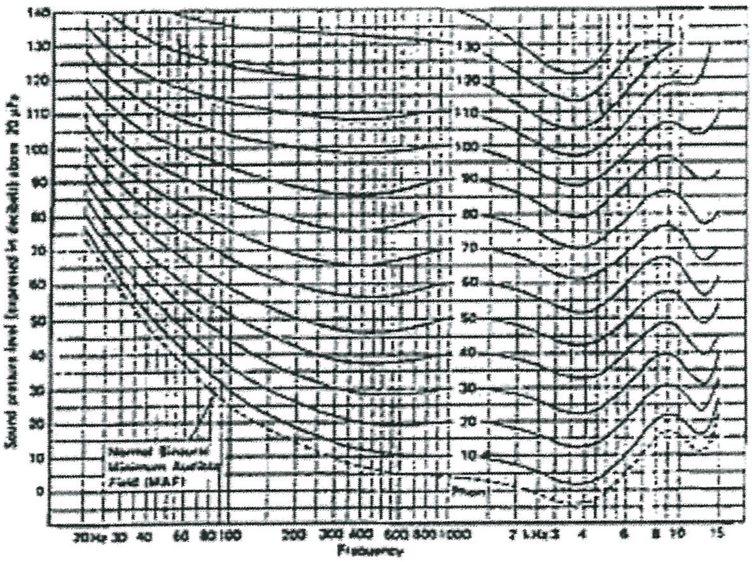
$$I = \frac{\bar{p}^2}{\rho c} : \quad IL = SPL = 10 \log (I/I_o) : \quad I_o = \frac{p_o^2}{\rho c} \approx 10^{-12}$$

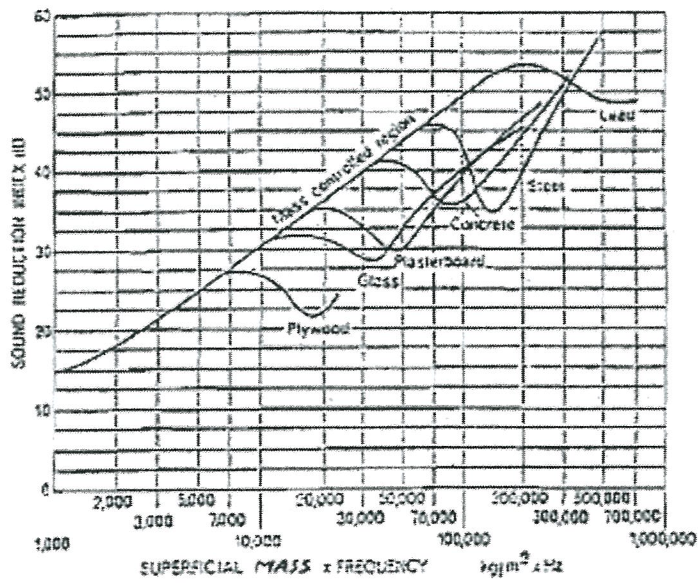
Sound energy density (energy per unit volume):

$$D = \frac{\bar{p}^2}{\rho c^2} : \quad SPL = 10 \log (D/D_o) : \quad D_o = \frac{p_o^2}{\rho c^2}$$

Source power W watts : SWL = 10 log (W/10^{-12})

Human ear: curves of equal perceived loudness (men) on left below: sound pressure level in dB versus frequency in Hz.





So adjusted curves (e.g. dBA from 40 phon line) to allow for ear characteristics varying with frequency.

Addition and comparison of incoherent sound: add mean square pressures to find overall mean square and hence SPL (or L_{eq} using average over time for varying sound levels).

(b) Acoustics of room-like enclosures (volume V, total surface S)

From uniform omnidirectional source W, at radius r (m) :
direct SPL = SWL – 10 log 4π - 20 log r

(from practical sources, intensity varies with direction). Reverberant sound due to reflections from walls: energy density D tends to 4W/Ac where A is the total absorption of the enclosure surface i.e. total of areas times absorption coefficients α, or $A = S\overline{\alpha}$ where $\overline{\alpha}$ is the mean absorption coefficient. Intensity in enclosure is Dc/4.

So reverberant SPL = SWL + 10 log 4 – 10 log A.

"Room radius" is the distance from the source at which direct and reverberant sound levels are equal.

On switching off source, energy density D decays exponentially, with time constant 4V/Ac related to the "reverberation time" T (Sabine's Law). Eyring's modification: use A = - S ln (1- $\overline{\alpha}$). Preferred values for T: speech 1.0 secs, orchestral music 1.8 to 2.2 secs.

(c) Noise control

Barriers and screens: if uninterrupted wave travels distance d and diffracted wave $a+b$, wavelength λ, "insertion loss" on introducing an infinitely long barrier across the path is 10 log (3 + 20N) dB where $N = 2(a+b-d)/\lambda$.

Partitions: 'transmission coefficient' τ = transmitted/ incident intensity, and 'sound reduction index' $R = 10 \log (1/\tau)$. For source and receiver rooms separated by area S of partition,

difference in SPL's = R – 10 log (S / A) dB

where A is absorption in receiving room. For compound partitions, use transmission coefficient τ weighted by areas.

Mass law: plane wave incident at θ to normal of single leaf wall

$$R = 10 \log \left[1 + \left(\frac{\pi M f \cos\theta}{\rho c} \right)^2 \right]$$

where f is sound frequency and M is wall mass per unit area. For high frequencies and diffuse sound field $R = 20 \log (Mf) - 47$ dB.

Problems with mass Law: resonance effect at frequencies proportional to $\sqrt{B/M}$ and dependent on panel span, where B is bending stiffness per unit width; "coincidence effect", when speed of bending waves in panel equals speed of sound in air, at frequency proportional to $\sqrt{M/B}$ and independent of panel span. See curves of R for different materials, on right above, storing R in dB versus superficial mass x frequency in kgHz/m^2.

Double wall mass-air-mass resonance: frequency f_d

$$f_d = \frac{1}{2\pi} \sqrt{\frac{\gamma P_o}{d} \cdot \frac{(M_1 + M_2)}{M_1 M_2}}$$

where γ is 1.4 for air, P_o is atmospheric pressure, d is cavity width, and M is wall mass per unit area.

5. Whole-life costing

(a) Discounted cash flow table

Capital repayment period/years[1]	Real discount rate /%						
	0	2	5	8	10	12	15
5	200	212	231	250	264	277	298
10	100	111	130	149	163	177	199
15	67	78	96	117	131	147	171
20	50	61	80	102	117	134	160
25	40	51	71	94	110	127	155
30	33	45	65	89	106	124	152
40	25	37	58	84	102	121	151
50	20	32	55	82	101	120	150
60	17	29	53	81	100	120	150

1 This is not necessarily equal to the total physical lifetime of the project.