ENGINEERING TRIPOS PART IIB
ENGINEERING TRIPOS PART IIA

Thursday 5 May 2005 9 to 10.30

Module 4D11

BUILDING PHYSICS

*Answer **three** questions, one from each of Sections A, B and C.*

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"
CIBSE Psychrometric Chart

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.

(TURN OVER

SECTION A

1 Fig. 1 shows a vertical section through a building with a central atrium.

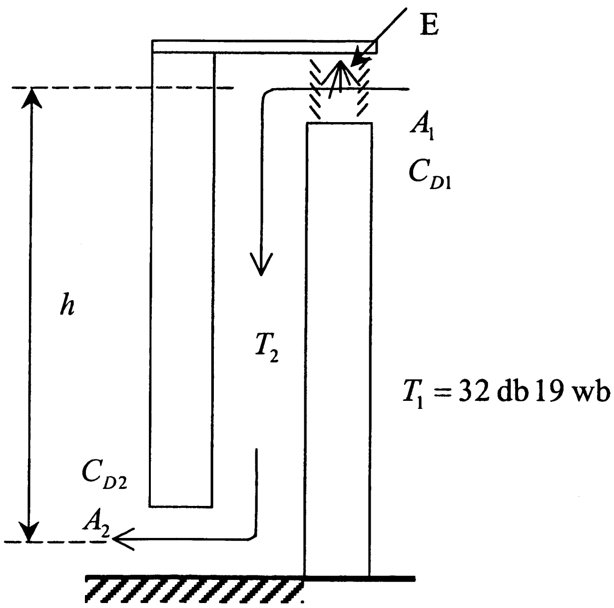


Fig. 1

(a) If A_1 and A_2 are openings of equal area A and the coefficients of discharge are equal, show that the rate Q of air flow through the atrium is given by:

$$Q = C_D A \left(gh \frac{\Delta T}{\overline{T}} \right)^{1/2}$$

where the terms have their usual meaning, and $\Delta T = T_1 - T_2$ [40%]

(b) The atrium is cooled by an evaporative cooler at E which sprays water into the airstream thereby increasing to 60% the saturation of the air going into the building. Use the Psychrometric Chart to calculate the dry bulb temperature T_2 which results from this process.

If A_1 and A_2 are 10 m^2, the coefficients of discharge are both unity, and h is 30 m, at what rate, in kg/s, must water be sprayed into the airstream to maintain T_2 at the calculated temperature? [60%]

2

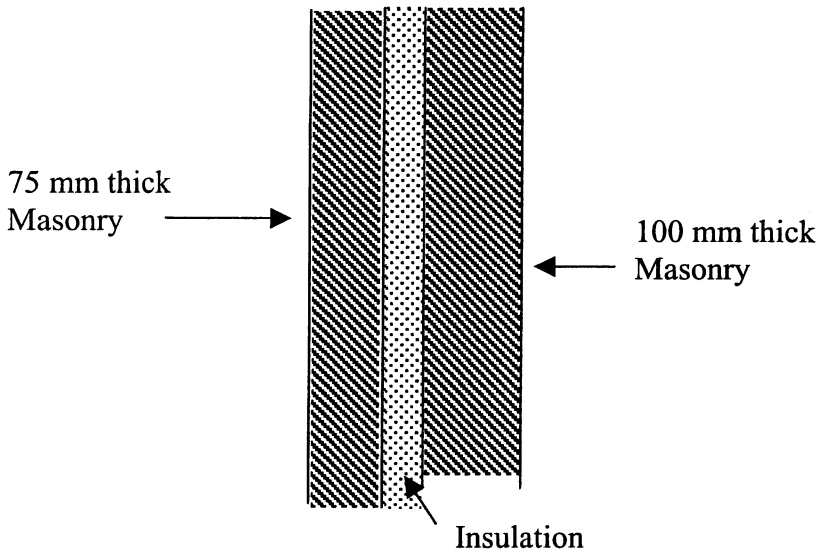


Fig. 2

(a) Fig. 2 shows a section through an element of wall construction. Using information from the list below, calculate the U value of the wall element. [30%]

(b) The wall system is used to construct a building in the form of a 4 m cube. The building is electrically heated. What is the maximum percentage of wall that can be replaced by glazing if the annual energy budget of £300 for heating is not to be exceeded? The total heat loss through the roof and floor totals 20 W/K. Casual gains and ventilation losses may be ignored. [50%]

(c) Outline briefly the principles and methods you would use to assess whether condensation is likely to occur within such a wall at certain times of the year. [20%]

Conductivity of masonry	0.8 W/mK
Resistance of insulation layer	1.4 m^2K/W
Internal surface resistance	0.04 m^2K/W
External surface resistance	0.1 m^2K/W
U value of glazing	2.2 W/m^2K
'Degree-days' per year	1940
Price of electricity	0.08 £/kWh

(TURN OVER

SECTION B

3 (a) Discuss the advantages of natural light in offices. Discuss the implications of obstructions to the natural light through a window, and simple methods of evaluating their impact. [25%]

(b) Fig. 3 (on the next page) shows a plan of a room with a single window, and a vertical section of the room and an adjacent building. The reflectance of the building opposite is 20%, and the average reflectance of the internal surfaces of the room is 50%. Calculate the daylight factor on the working plane at the two points A and B indicated on the figure. [50%]

(c) In order to increase the daylight in the back of the room, it is suggested that a 'light shelf' be provided on the external façade. Explain why this might improve the situation, and discuss how to evaluate the efficacy of such a shelf. [25%]

(cont.

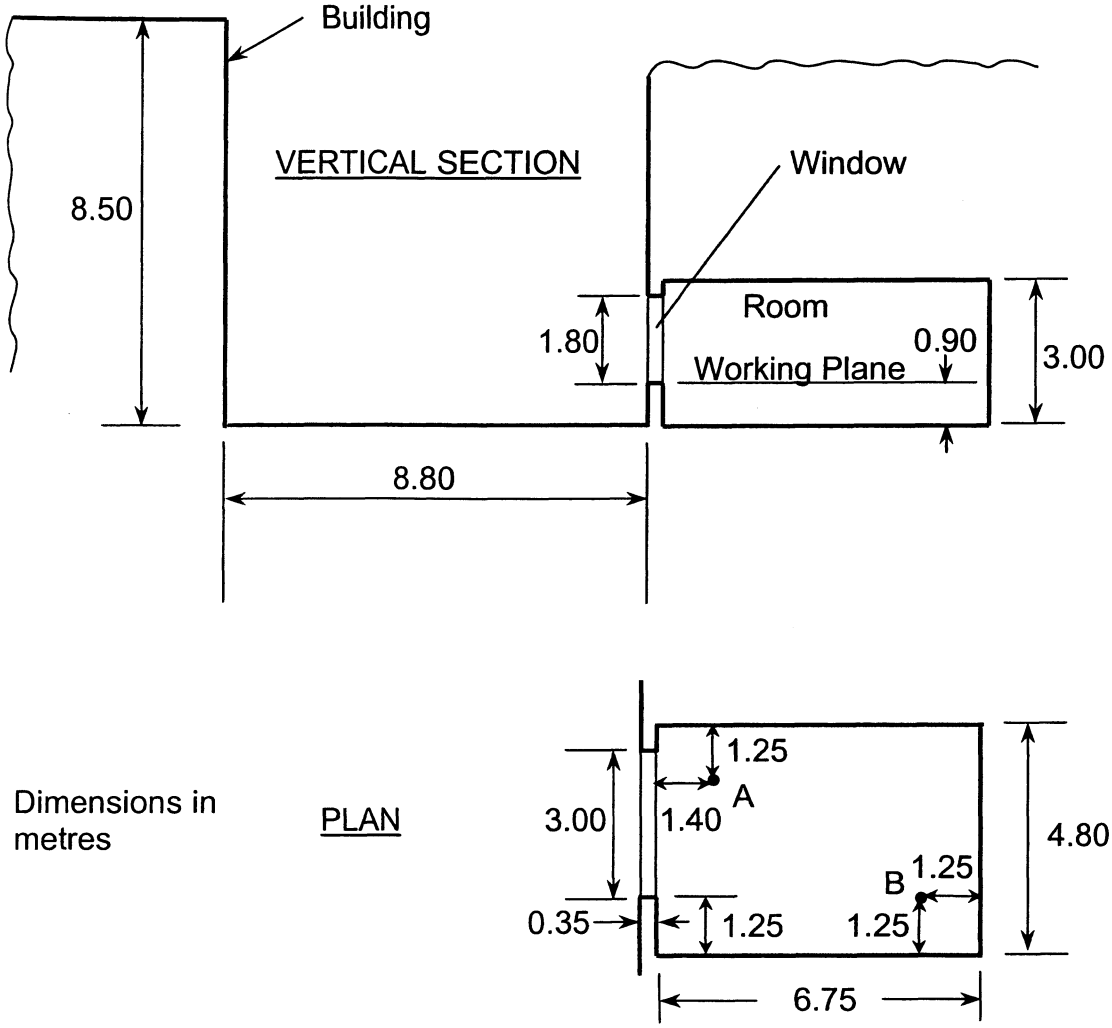


Fig. 3

(TURN OVER

4 An open-plan office space 10 m by 12 m in plan has a floor to ceiling height of 2.95 m and a typical desk height of 0.85 m. The room is to be lit artificially using ceiling-mounted twin-tubular fluorescent luminaires, each giving 4400 lm output. The utilisation factor U for these luminaires depends on the 'room index' $K = LW/H(L+W)$, where L and W are the room length and width and H is the height of the luminaires above the working plane, according to the following Table:

K	0.75	1.0	1.25	1.5	2.0	2.5	3.0	4.0	5.0
U	0.43	0.49	0.55	0.6	0.66	0.71	0.75	0.8	0.83

(a) Applying a further factor of 0.80 to the light output to allow for poor maintenance, determine how many luminaires are needed to achieve the illuminance level recommended for general office use. Propose a suitable layout for the luminaires, which are 1500 mm long. [30%]

(b) During the day, the same office is daylit evenly from windows on two opposite long sides only, giving an average daylight factor of 4%. For what fraction of standard office hours during March will there be sufficient diffuse natural light? Discuss briefly what switching options for the luminaires should be considered, to exploit daylight and minimise electrical energy consumption for lighting. What is the maximum amount of energy that could be saved during March? [40%]

(c) Discuss briefly how the design of museums and art galleries has been affected by changing perceptions of the desirable levels of illumination for exhibits. [30%]

SECTION C

5 (a) Explain why speech intelligibility may be poor in lecture theatres with a long reverberation time. Discuss briefly how to measure reverberation time in a room, the ideal reverberation time in a lecture theatre, and any other acoustic characteristics you would measure or consider if asked to improve speech intelligibility in a lecture theatre. [30%]

(b) A rectangular lecture theatre has a volume of $700\ m^3$ and plan dimensions $14\ m$ by $8\ m$, with the speaker and displays near one short side. The reverberation time at 63 Hz is 2.2 s and at 500 Hz is 2.1 s. The only absorption present in the room is on the ceiling. Speech intelligibility is poor.

Additional absorption is available in the form of panel absorbers with absorption coefficients 0.5 at 63 Hz and 0.25 at 500 Hz and/or porous absorbers with absorption coefficients 0.1 at 63 Hz and 1.0 at 500 Hz.

Propose a solution to the problem of poor speech intelligibility, calculating the area(s) of the absorbers required. Would the calculation be significantly affected if Eyring's modification were introduced? Where in the room would you install the absorbers? [70%]

(TURN OVER

6 (a) Discuss briefly the ways in which total sound pressure level varies with distance from a single source or multiple sources of incoherent sound (i) in the open air and (ii) inside a large room. [30%]

(b) An industrial facility has a compact continuously-operating condensing unit mounted on soft ground well away from reflecting surfaces. Measurements of the noise level generated by the condensing unit show that its attenuation with distance follows the inverse square law and that the noise level 10 m from the unit is 75 dBA. A second identical condensing unit is to be installed immediately next to the first and will also operate continuously.

A new bungalow is to be built near the industrial facility. Planning authorities require that the background noise level outside the bedroom window, which is to be 80 m from the condensing units, be no greater than 45 dBA between 23.00 and 07.00, when the only significant noise sources will be the condensing units.

Assuming that the centre of the window and the effective noise sources are both 1.2 m above ground level and using information from the table below, calculate the height, width and distance from the condensing units of a barrier which will achieve the required noise condition. What form of barrier would you propose?

Path difference (m)	*Attenuation due to barrier (dBA)*
0	5
0.2	10
0.4	12
0.6	14
0.8	15
1.0	16 (max achievable)

[70%]

END OF PAPER

1. Lighting

(a) Definitions

		units
luminous flux - rate of flow of light energy	-	lumens (lm)
illuminance - density of light flux reaching a surface	-	lumens/m^2 or lux (1
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 = 4 π lm)

(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.

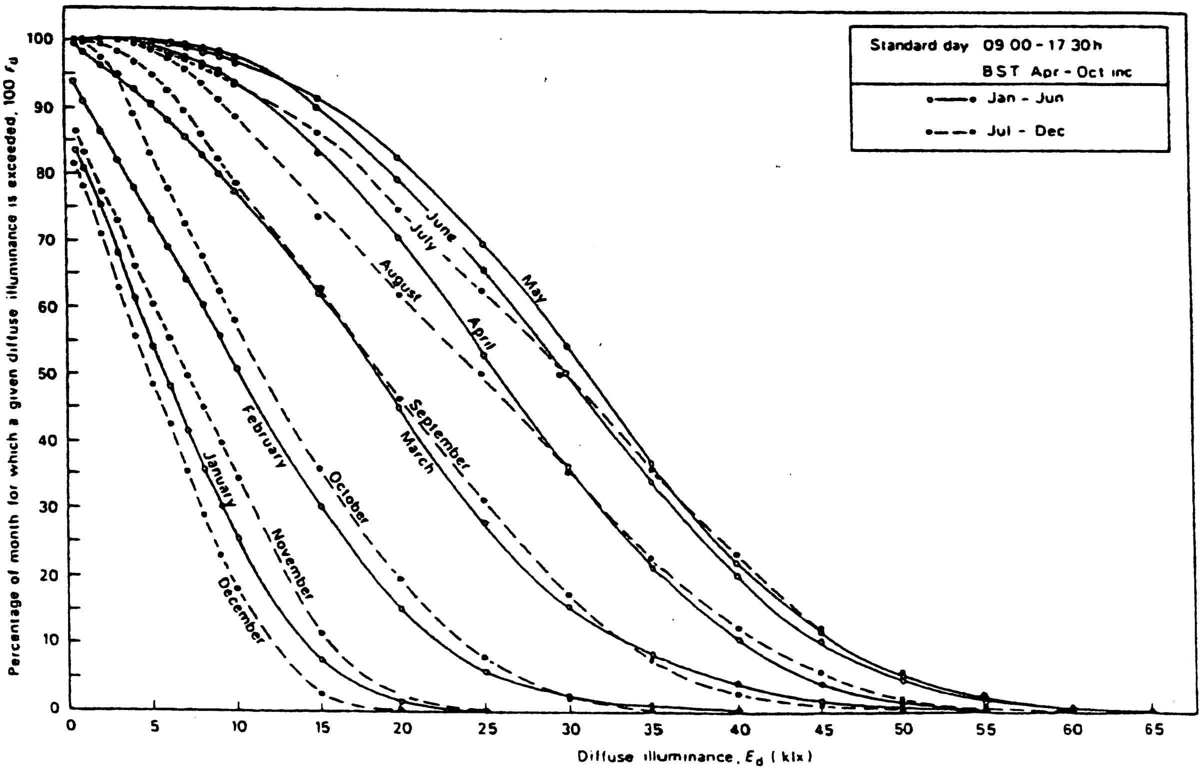
Typical luminous efficacies (lumens/Watt) : tungsten filament (GLS) 12, tubular fluorescent 60, low pressure sodium 180, daylight 115.

(c) Daylight

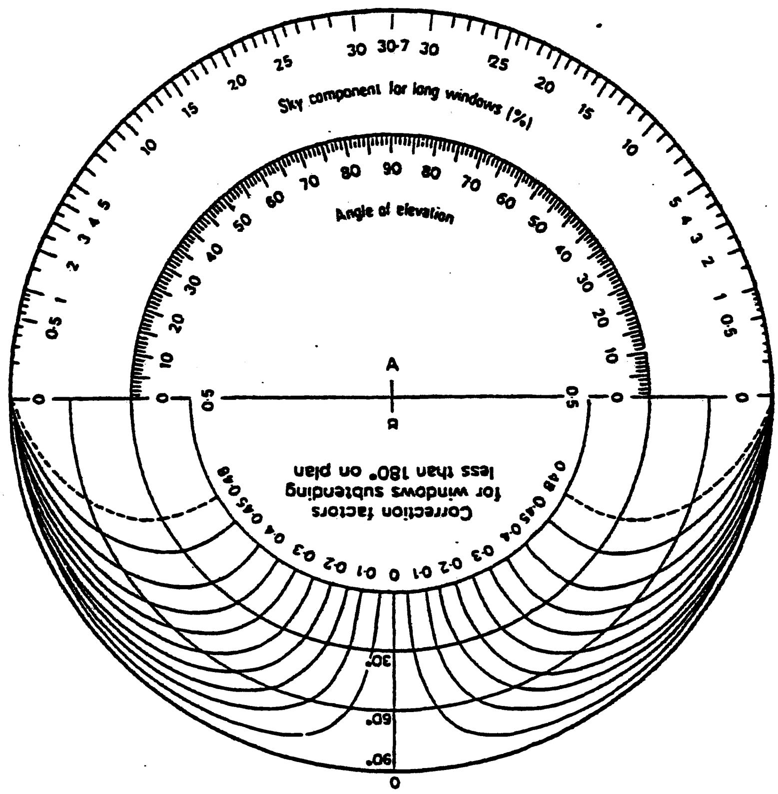
Sky as a diffuse source : sky luminance B_θ from elevation θ above horizon, where B_z is luminance at the zenith:

$$B_\theta = B_z(1+2\sin\theta)/3 \qquad \text{"CIE sky"}$$

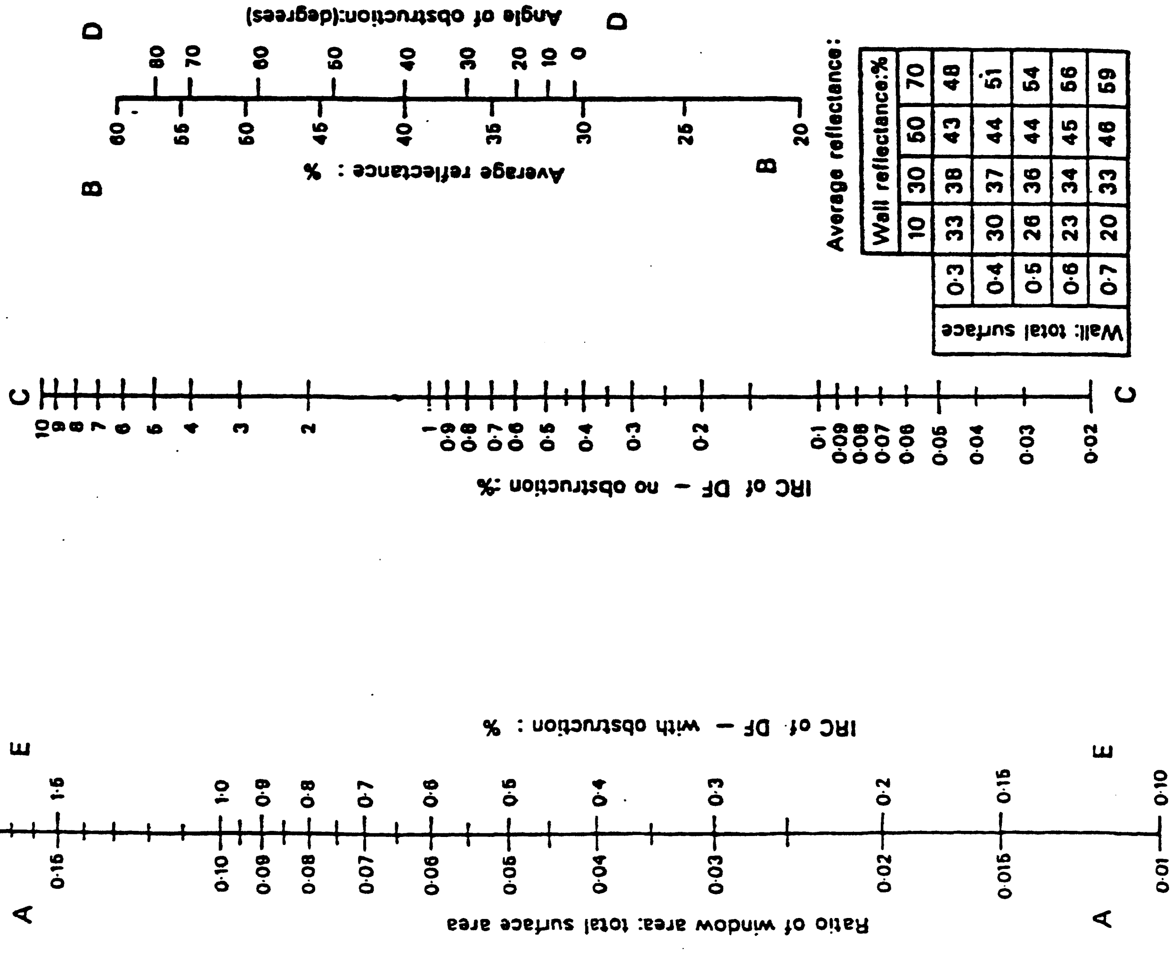
Example of monthly daylight availability curves: cumulative diffuse horizontal illuminance for Bracknell;



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)



2. Thermal matters

(a) Temperatures

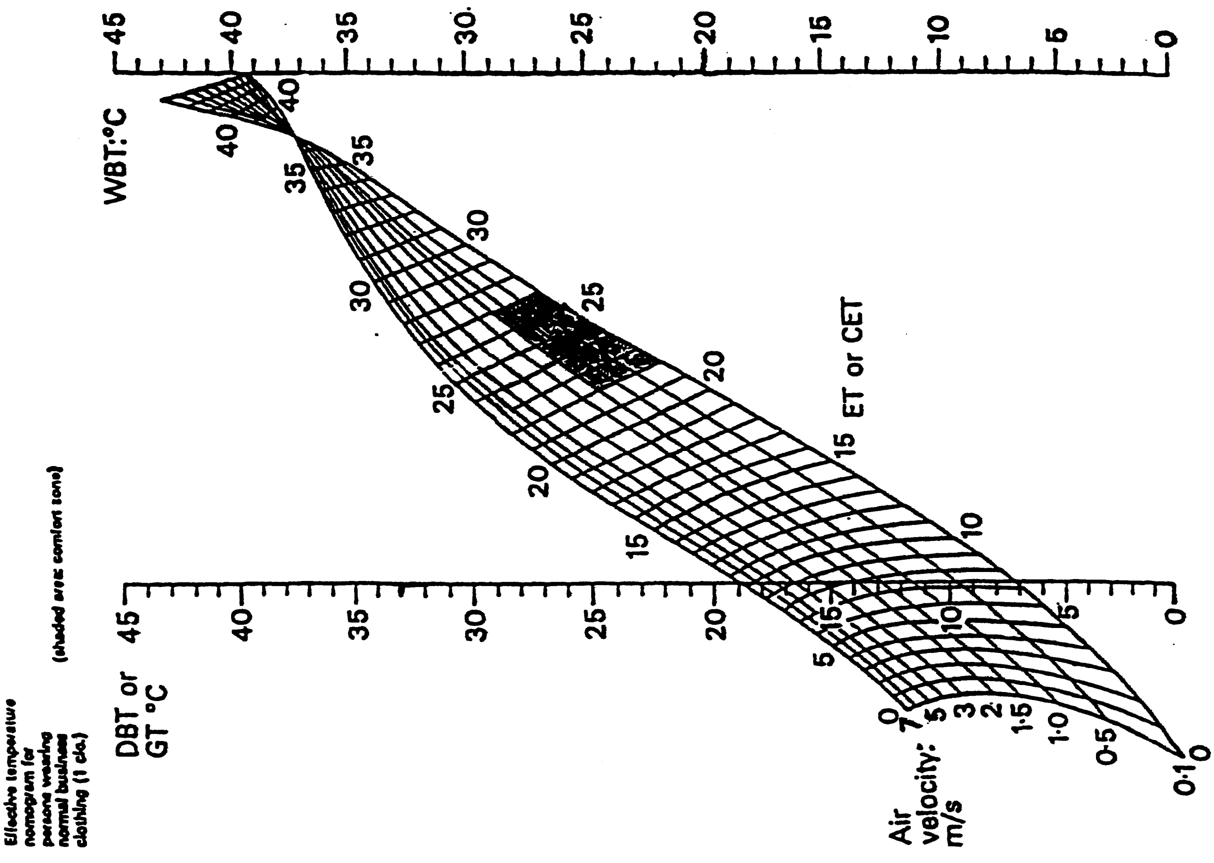
Air temperature in shade (= dry bulb temperature).

Wet bulb temperature (taken with dry bulb, indicates humidity).

Mean radiant temperature (theoretical: mean of temperatures of surfaces radiating to point in question weighted according to solid angle subtended and surface emissivity).

Globe temperature (measured inside a small black sphere - related to mean radiant temperature and air temperature).

Corrected effective temperature (CET) - depends on globe and wet bulb temperatures, and air velocity - see nomogram.



Neutral temperature (CET at which most people comfortable)

$$T_n = 11.9 + 0.534\ T_o \pm 2.5°C \qquad (Humphreys)$$

for a sedentary occupation, where T_o is mean monthly temperature.

(b) Thermal comfort

Metabolic rate M ranges from 70 watts when sleeping through 150 watts when typing, 300 watts for fast walking to 650 watts for hard sustained work.

Heat loss H depends on radiation, convection and evaporation (and on clothing level: 0.1 clo for shorts only, 1.0 clo for a business suit, 2.5 clo with heavy overcoat).

Fanger's equations: heat loss (watts)

$$H = R + C + (E_{diff} + E_{sw} + E_{res}) + C_{res}$$

"Predicted mean vote" on scale -3 to +3 , cold to hot:

$$PMV = 0.303\ (0.28 + \exp(-0.036M))\ (M-H)$$

"Predicted percentage dissatisfied"

$$PPD = 100 - 95 \exp \{ - (0.34\ PMV^4 + 0.22\ PMV^2)\}$$

(c) Heat loss calculations for buildings

By conduction $Q_c = (\Sigma UA)\ \Delta T$ watts, where A is area of wall, roof, windows etc., and ΔT is air temperature difference between inside and outside. The "U-value" for a wall in W/m^2K is given for layered construction by

$$1/U = R_i + \Sigma rt + R_c + R_e$$

where R_i and R_e are thermal resistances at internal and external surfaces (depending on convective heat transfer) and R_c is for cavity, and r and t are reciprocal of conductivity, and thickness of the various materials.

By ventilation, Q_v depends on room volume, number of air changes per unit time, and the appropriate coefficient for air ($C_v = \rho c_p \approx 1200\ J/m^3K$ at 20°C).

Total loss $Q = Q_c + Q_v$, giving a 'Specific Heat Loss' in watts per degree of temperature difference.

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

(d) Thermal solar gains, and utilisation

Published monthly data on irradiation on horizontal surfaces (diffuse plus sunlight) in W/m^2 not lumens. Convert to irradiation on vertical surfaces - dependent on orientation relative to South. Then allow for absorption or transmission coefficient of surface material (often by a 'Solar Gain Factor'). Typical gains 700 W/m^2 for South-facing window.

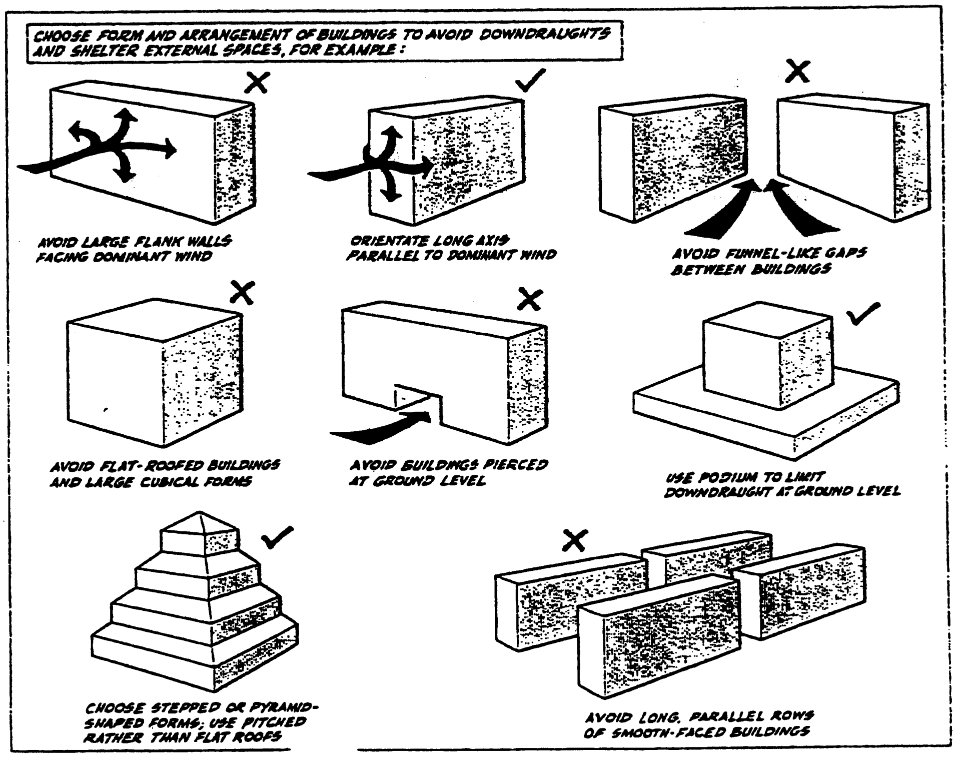
Then on average, energy required for heating building

$$H_{req} = Q - (G + S) \times UF$$

where G is casual gains (machines, people etc.), S is solar gain, and UF is a 'Utilisation Factor' dependent on thermal inertia of the building etc.

3. Ventilation

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



$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho U_{ref}^2} \; ; \qquad U_{ref} = U_{ambient}$$

$$= U(z = 10m.) \; typically$$

(b) Orifice flow

$$\Delta p = K(=1)\frac{1}{2}\rho U^2$$

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

Q (volume flow rate) = $C_D \times U \times Area$

C_D = discharge coefficient due to streamline contraction.

(c) Momentum jets

$$R \;\alpha\; x$$

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

(d) Buoyancy effects

Stack effect; $U = \sqrt{g \frac{\Delta\rho}{\rho} H}$ for two equal area vents

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 $\rho \simeq \rho_a$ and use ρ_a and T_a as reference conditions whenever necessary.

(e) Physical modelling

$$\frac{U}{\sqrt{g'L}} = f_1\left(\frac{\underset{\sim}{x}}{L}, \frac{F_o}{L^{\frac{5}{2}} g'^{\frac{3}{2}}}, \frac{t}{L^{\frac{1}{2}} g'^{-\frac{1}{2}}}, Reynolds\ ,\ Peclet\right)$$

$$\frac{\rho - \rho_a}{\rho_a} = \frac{T - T_a}{T_a} = f_2\left(\frac{\underset{\sim}{x}}{L}, \frac{F_o}{L^{\frac{5}{2}} g'^{\frac{3}{2}}}, \frac{t}{L^{\frac{1}{2}} g'^{-\frac{1}{2}}}, Reynolds,\ Peclet\right)$$

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):

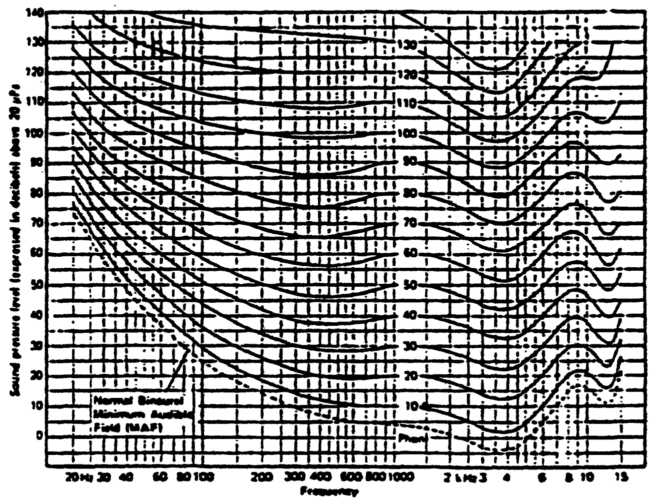
$$I = \frac{\bar{p}^2}{\rho c} \ : \ IL = SPL = 10 \log (I/I_o) \ : \ I_o = \frac{p_o^2}{\rho c} = 10^{-12}$$

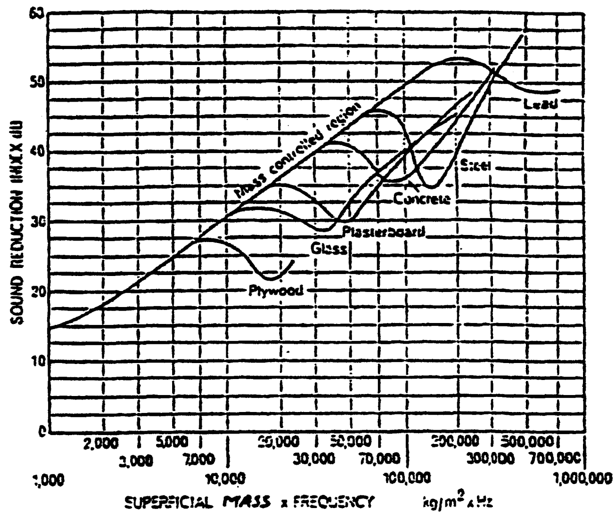
Sound energy density (energy per unit volume) :

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

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

Human ear : curves of equal perceived loudness (men) on left below





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 :

$$\text{direct SPL} = \text{SWL} - 10 \log 4\pi - 20 \log r$$

(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 terms area times absorption coefficient α , or $A = S\bar{\alpha}$ where $\bar{\alpha}$ 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 $A = - S \ln(1-\bar{\alpha})$.

Preferred values for T: speech 1.0 secs, orchestral music 1.8 to 2.2 secs.

In long or flat enclosures, need 'sound propagation' curve against distance in given direction from point source (SP = SPL - SWL). Simple geometrical acoustics for a point source considers reflections from ceiling and floor (coefficients ρ_1 and ρ_2), and effective images at distances r_i from receiver to obtain total steady-state energy density at receiver

$$D_{tot} = \frac{W}{4\pi c}\left[\frac{1}{r^2} + \sum_{n=1}^{\infty} (\rho_1\rho_2)^n \left\{\frac{2}{r_{2n}^2} + \frac{\left(\frac{1}{\rho_1}+\frac{1}{\rho_2}\right)}{r_{2n-1}^2}\right\}\right]$$

(c) <u>Noise control</u>

Barriers and screens: if uninterrupted wave travels distance d and diffracted wave a+b, wavelength λ, "insertion loss" on introducing an infinitely long barrier 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 a diffuse sound field R = 20 log (Mf)-47 dB.

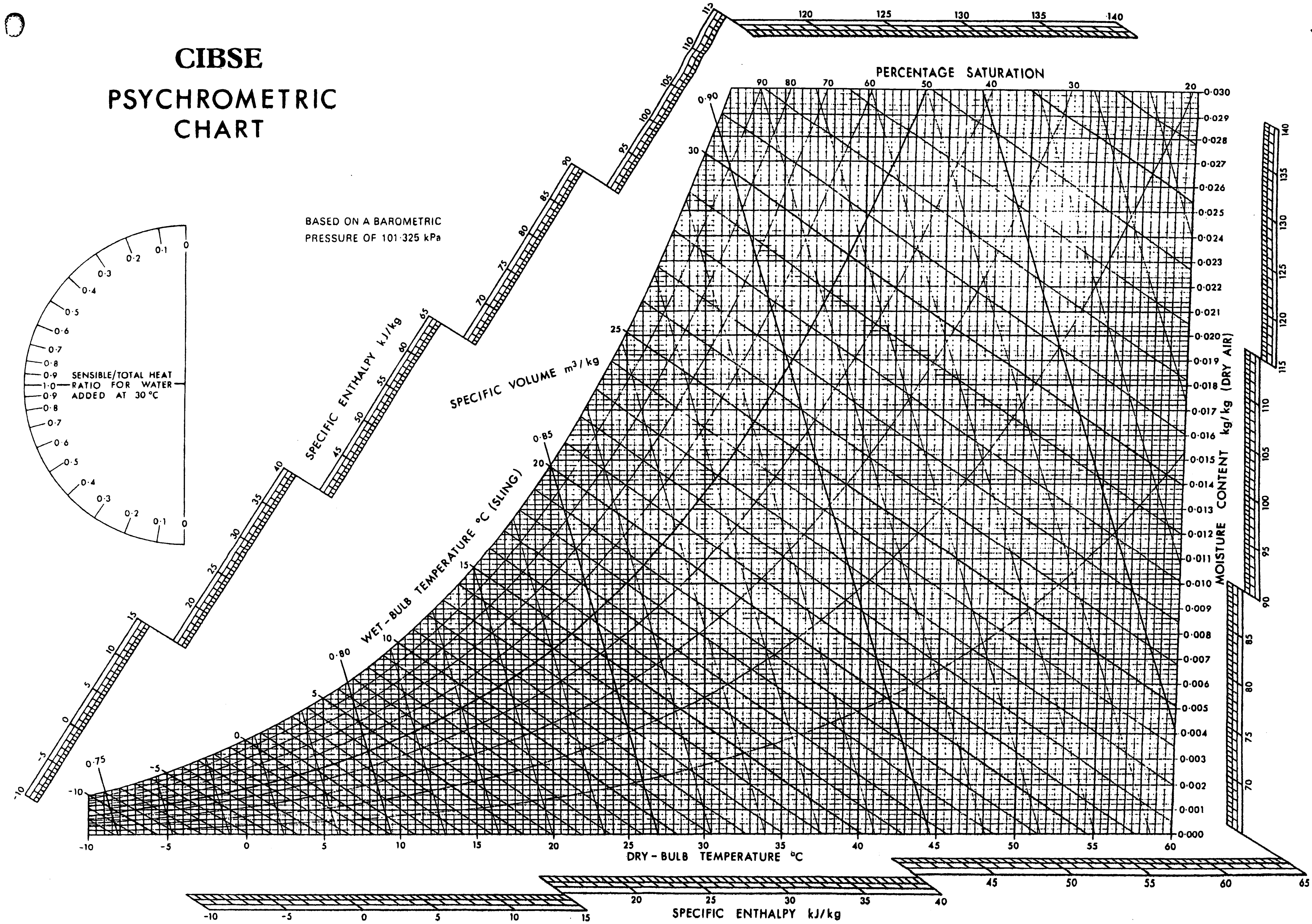
Problems with Mass Law: resonance effect at frequencies proportional to $\sqrt{B/M}$ and dependent on panel span, where B is bending stiffness per unit width; "coincidence effect", when speed of bending waves in panel equals speed of sound in air, at frequency proportional to $\sqrt{M/B}$ and independent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

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.

CIBSE PSYCHROMETRIC CHART



4D11 2005 Answers

1. (b) 24.3 °C 0.109 kg/s

2. (a) 0.569 W/m^2K
   (b) 23.1 %

3. (b) approx 4.2 % and 1.1 %

4. (a) 24
   (b) 70 % 830 MJ or 230 kWh

5. (b) about 115 m^2 of panel, 30 m^2 of porous, absorbers

6. (b) possibly 10 m from source, 8 m long, 5 m high