CET372 / FUNCTIONAL DESIGN OF BUILDINGS

COURSE MATERIAL

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MODULE-1

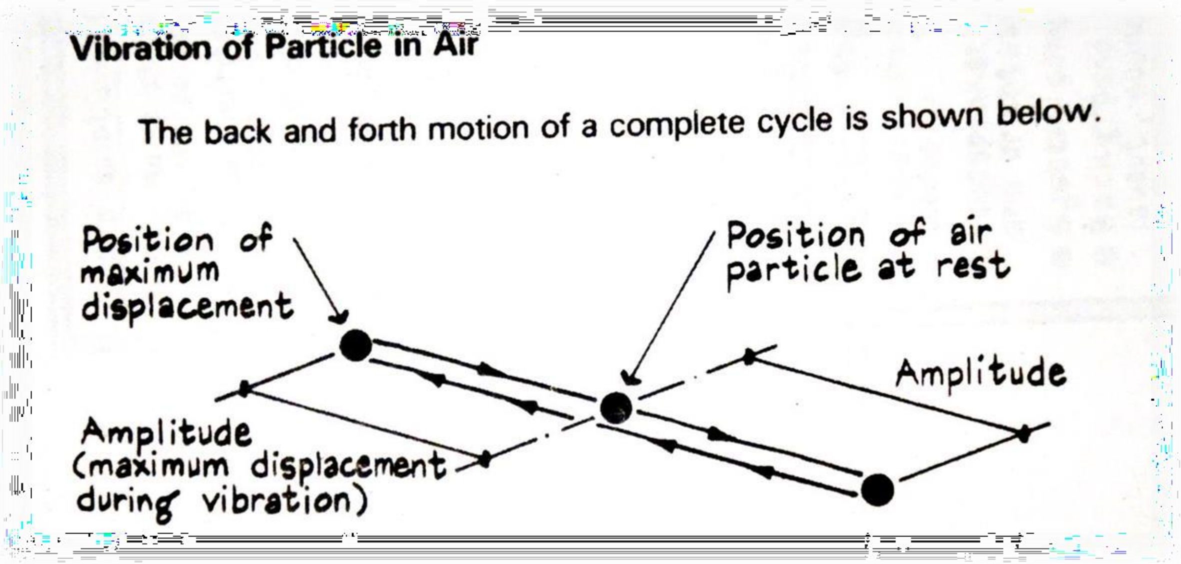
ACOUSTIAL / SONIC ENVIRONMENT AND ACOUSTIAL COMFORT

ACOUSTICS AND APPLICATIONS

Acoustic is the science of sound which deals with its production / generation / creation, transmission, absorption, reflection, decay etc.

Sound is a sensation caused on the ear by a vibration in an elastic medium such as air, water or a solid body. The source of sound normally is a vibrating solid body which in turn generates vibrations in the air or water which acts as a medium to convey it in to the ear.

Sound energy progresses rapidly producing extremely small pressure changes in the atmosphere. Though sound can travel great distances, each vibrating particle moves only small amounts to its normal position.

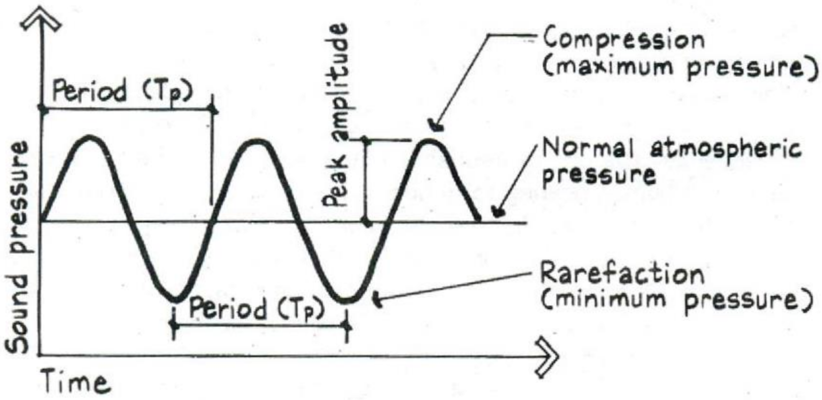


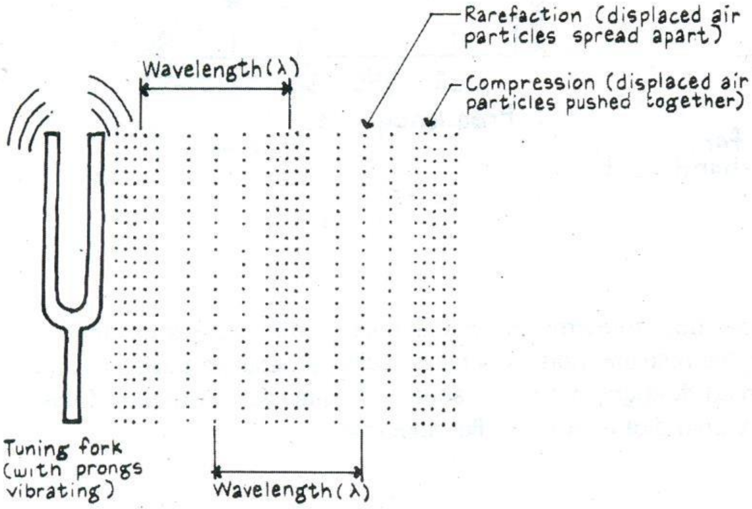
Pure tone: Pure tone is a vibration caused at single frequency. Eg. Sound produced by atuning fork.

SOUND WAVES

Shown below is the motion in the air of a sound wave produced by a tuning fork.

The fig. below shows various characteristic of a sound wave.





The time taken for one complete cycle is called a period (T_p). Frequency (f) is the rate of repetition of a periodic event. That is, the number of times per second a given molecule vibrates about its neutral position. The unit of frequency is Hz. The relation between period and frequency is: $T_p = 1/f$.

Wavelength (λ): is the distance a sound wave travels during one cycle of vibration. If "v" is the velocity of sound in the medium, and 'f' is the frequency, $\lambda = v/f$. λ will also be $= v * T_p$.

Velocity of sound in Different Media

In air:

At 0 ^oC, 332m/sec

At 20 ^oC, 344m/sec

At 30 ^oC 350m/sec

In water: 1437 m/sec

In salt water: 1541 m/sec

In steel: 6100 m/sec

In Timber: 5260 m/sec

In Brick: 3650 m/sec

Intensity of sound

In a carrying medium, the strength of sound is measured as intensity. The unit is Watts/m^2. The intensity of sound at a point "r" meters away from a point source of sound power "W" watts is equal to:

$I = W/4\pi r^2$ ($4\pi r^2$ is the surface area of the sphere having radius "r")

Inverse square law: If "I1" is the intensity of sound level at a distance d1 from the sound source and "I2" is the intensity at a distance d2;

$I1/I2 = d2^2/d1^2$

When d2= 2 times d1, the intensity will reduce to $1/4^{th}$. See fig. below.

Audible range of sound

Audibility of a sound depends on two factors 1) Its frequency 2) Its intensity. Sound waves of frequency below 20 Hz and above 20,000 Hz are not audible to human beings. Again on getting older, the ability to hear higher frequencies reduce considerably. A sound intensity of less than 10^{-12} watts per sq. m. is not audible and intensity above 1 watt/sq.m gives pain to ears.

Nearly all human sensations are proportional to the logarithm of the intensity of the stimulus. Human ears also respond to sound intensities according to exponential law.

For example, if the intensity is doubled ear gets an impression of only a slight increase not an increase of 100%. A young and healthy person can respond to air vibrations hardly greater than molecular size and it also responds without damage to a sound intensity of 10^{12} times

greater. Also a young and healthy person can respond to sound frequencies of 20 Hz to 20000 Hz.

Great scientist Alexander Graham Bel was the first one who tried to relate the intensity of sound to an intensity level that corresponds to the human hearing sensation. Hence "Bel" is used as the unit of sound intensity in honour of Alexander Graham Bel.

A sound intensity of l watts/m^2 is defined to be equal to $\log_{10} l/l_0$ Bel, where l_0 is the reference sound intensity which is taken as 10^{-12} W/m^2. If you refer to the fig. above, it can be seen that **zero** Bel will correspond to the lower limit of audibility and **twelve** Bels will correspond to the threshold of pain. Later on, it is found more convenient to use the unit dB (decibel) which is 1/10th of Bel for indicating sound intensities.

A sound intensity of l watts/m^2 is defined to be equal to $10 \log_{10} l/l_0$ dBExamples:

1 Intensity of a rock music programme is $8.93*10^{-2}$ watts/m^2. Find the correspondingintensity in dB scale.

$Li= 10 \log l/l_0 = 10 \log 8.93*10^{-2}/10^{-12}$

$= 10 \log 8.93*10^{10}= 10*10.95=110$ dB

2 A loud speech measured has a sound intensity level of 73 dB.

3 Find thecorresponding intensity in W/m^2.

$73=10 \log_{10} l/l_0$ $\log_{10} l/l_0 = 7.3$ $\log_{10} l/10^{-12}=7.3$ $l*10^{12}=$Antilog 7.3l$=2*10^{-5}$ W/m^2

4 Measured sound intensity of one trombone is 80 dB. Find out the sound intensity of76 trombones.

L_1= 80 dB

$80 = 10 \log l_1/10^{-12}$

$l_1/10^{-12} = 10^8$

$l_1 = 10^{-4}$ watts/m^2

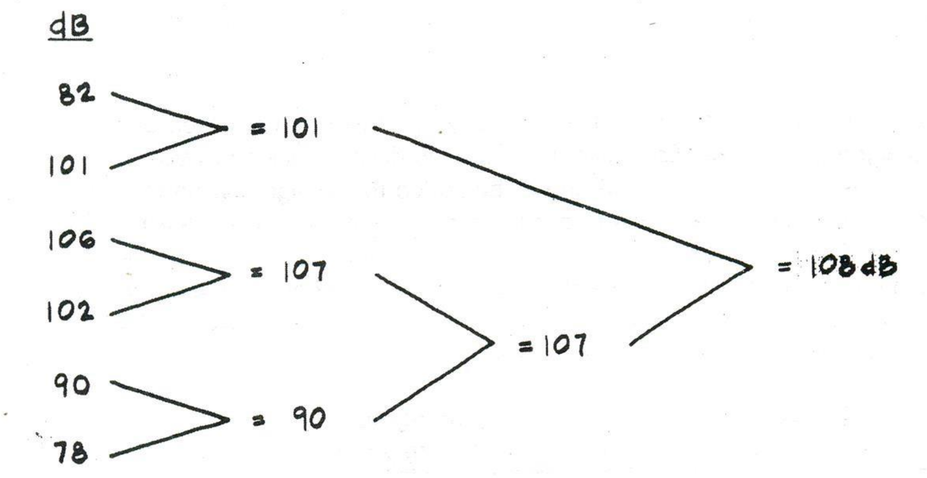
$l_2 = 10^{-4} * 76$ watts/m^2 $L_2 = 10 \log 10^{-4}/10^{-12} * 76$
$= 10 \log 10^8 + 10 \log 76 = 99$dB

Addition of sound levels

Sound levels in dB scales cannot be added up directly as it is in logarithmic scale. We can find out the corresponding intensities in w/m^2 (as described in example-2) add them up and then again convert to dB scale as described in example-1. There is an easier way of adding sound levels in dB.

L1 (higher sound level) - L2 (lower sound level) in dB	Add to L1
0 or 1	3 dB
2 or 3	2 dB
4 to 8	1 dB
9 or more	0 dB

Example: Find the combined sound level of 82dB, 101dB, 106 dB, 102 dB, 90 dB and 78 dB.



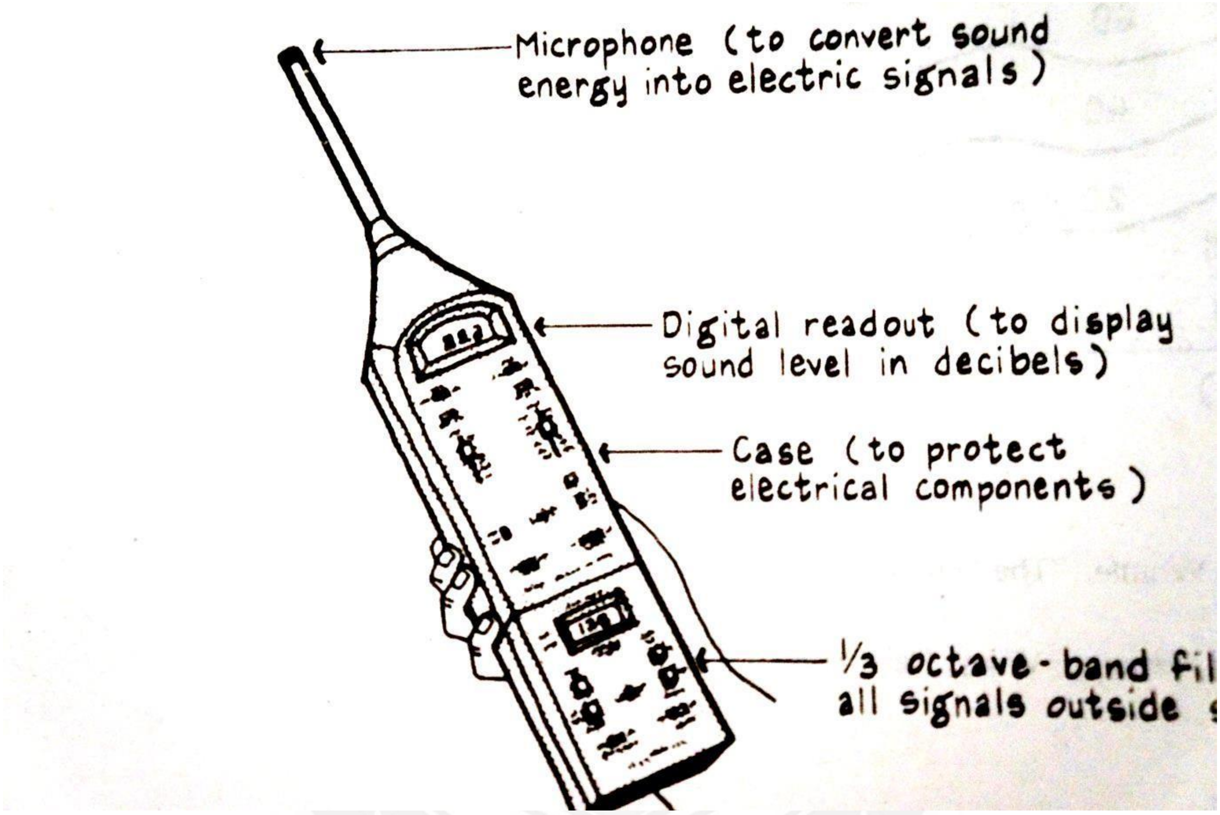
Based on the selection of combinations, there could be a difference of 1 dB in some cases which is acceptable.

Changes in apparent loudness with changes in dB

Change in Sound level (dB)	Change in apparent loudness
1	Not felt (except for pure tone)
3	Just barely felt
6	Clearly noticeable
10	About twice/half as loud
20	About 4 times or 1/4th as loud

SOUND MEASUREMENT (SOUND LEVEL METER)

Sound intensity is measured as sound pressure level using sound level meters. Sound level meter consists basically a microphone and an electric circuit including an



attenuator, amplifier, band filter, and a display unit.

Apparent loudness

The dB scale described above also tells only approximately the intensity of loudness felt by the human ear. The loudness also depends on the frequency of the sound waves. That is, a sound of frequency 100 Hz having intensity say 60 dB will be sensed as less louder than a sound having the same intensity and say having a frequency of 1000Hz. However it is very difficult to measure the loudness physically. Based on experiments with people having good hearing perceptions curves of equal loudness (contours) are developed as illustrated in fig below.

It can be seen that for 1000Hz, the db and the loudness (called phons) match. For lower frequencies the loudness is much less for the same intensity (dB) of sounds. The apparent loudness is slightly higher than what is indicated by the dB scale for frequencies of 2000- 6000 range and then it reduces for higher frequencies.

Another scale dBA is often used to get a better indication of this subjective effect. It is called "A-weighted measurement". While measuring sound, a band filter is used admitting only one octave band at a time. Then the sound levels are added up to get the apparent loudness in dBA.

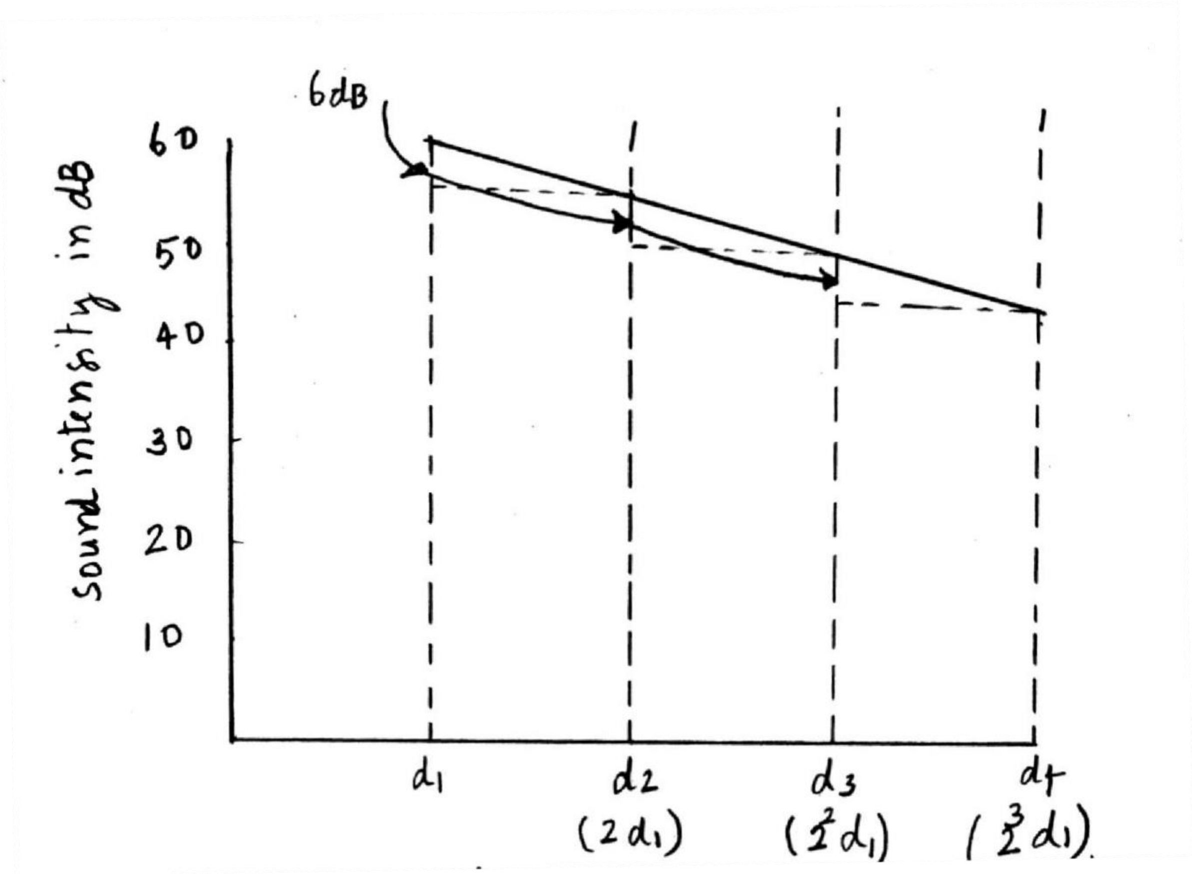
SOUND ABSORPTION

When sound energy impinges on objects like the walls, ceiling etc. of a room, a part of it gets absorbed. A part is transmitted and another part is reflected back. Sound is absorbed by a mechanism by which the sound energy is converted to other forms of energy. The effectiveness of a sound absorbing material can be expressed by its absorption coefficient. Theoretically it can vary from "0" (no sound energy is absorbed) and "1" (entire sound energy is absorbed). The part which is transmitted should also be considered as absorbed in case of acoustical calculations. The fraction not reflected is the fraction absorbed. An open window which transmits all sound energy falling on it is considered as a perfect sound absorber with absorption coefficient =1. Materials having absorption coefficients more than 0.50 are considered as good sound absorbers.

The sound absorbed by an open window (in fact the entire sound energy is transmitted) of size 1 ft X 1 ft is termed as 1 Sabine. Sound absorbed by a window of 1 sq. meter area is 10.76 sabins which is called 1 metric Sabine.

BEHAVIOUR OF SOUND IN THE FREE AND REVERBERANT FIELDS

Free field means open field where the sound waves are free from the influence of any reflective surfaces (like walls, ceiling etc.).



Distance from the source in exponential scale

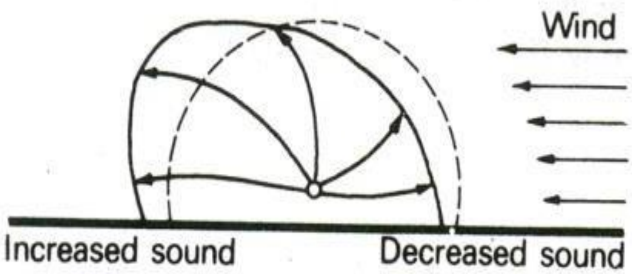
When the distance gets doubled, the sound intensity gets reduced by 4 times

(ie. By 10 log 4= **6 dB in decibel scale**).

When the distance increases 10 fold, sound deduction will be 20 dB.

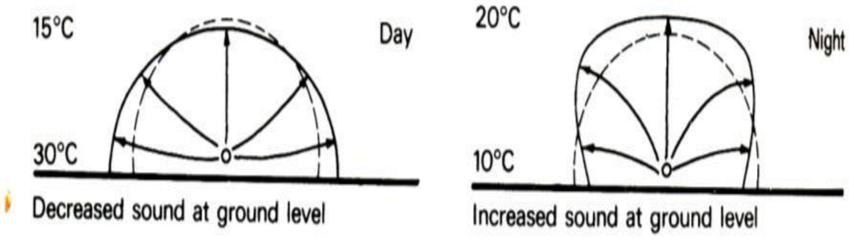
For line sources, i.e. for noise from railway track or busy road etc., the reduction will be only 3 dB with doubling of distances.

Also in free field; the wind direction and velocity, the ground and air-temperature etc



affect the propagation of sound.

For a wind velocity of around 16 kmph, at 150m away from a sound source, a 10 dB addition or deduction is possible compared to a condition having no winds.

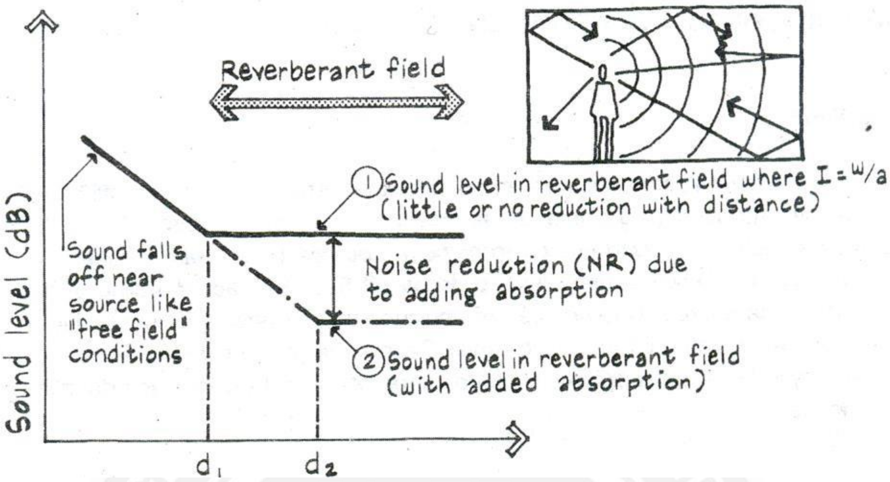


For a place 300 m away from the source, the difference in sound levels between day and night can be 10 dB.

Again loud noises from distances are heard at low pitch because the air absorbs sound at higher frequencies at higher rate than sounds at lower frequencies. For every 300 m, sound at 1000Hz is reduced by 1 dB while sound at 9000Hz is reduced by 40 dB. This is why, the thunder (from a long distance) is heard at low pitch (the higher frequency parts are mostly absorbed by the atmospheric air).

Reverberant field means the enclosed condition (inside a room or a hall), where the listener received both direct as well as reflected components of sound. In a reverberant field also, near the source the sound energy decreases as in the case of the free field, but the further (after about 1.5 metres or so in small rooms) decrease will be very little in cases of small rooms and will be at a lower rate than in the free field in cases of bigger rooms/halls.

By adding sound absorbents to the ceiling and wall, sound deduction can be achieved as shown in fig below. Deduction up to 10 dB can be achieved in a larger room toward the rear end by adding absorbents in the ceiling and another 6 dB by adding absorbents in the walls as well. If all the walls, ceilings and floors are perfect absorbers, the sound will behave just as it does in the free field (not possible practically). Normal total deduction possible is around 8 dB.



NOISE

The initial definition of noise was "an unpleasant sound". But the international committee for standardization of acoustical terms now defines noise as "an unwanted sound", i.e. a sound not desired by a recipient. The discrimination and differentiation between sound and noise also depends on the habit and interest of the person receiving it.

Noise could be of indoor or outdoor origin. It could be continuous or intermittent. If could be of any frequency.

The noise can also be classified into 1) Air-born noise and 2) Structure bon noise.

Air-born noise is the one which is originated in the air, transmitted through the air and reaches the receivers ear. Examples are noise generated by human speaking, noise from loud speakers, noise from fireworks at distant places etc.

Structure-borne noises are the ones generated in the body of the solid structures, mostly due to vibration of machines etc., and transmitted through the structures like columns beams, floors of buildings and finally transmitted to the air before reaching the human ears. Examples are vibrating mechanical equipments, footsteps of people walking/playing in the upper floors, sound from drilling in walls and structural components etc.

Effects of noise on human

1. Noise induces several impacts on human and living organisms. Some of the adverse effects are:
2. Annoyance: it creates annoyance to the recipients mainly due to fluctuations in sound levels. Non-periodic sounds, due to irregular occurrence, cause displeasure to hearing and causes annoyance.
3. Physiological effects: Breathing amplitude, blood pressure, heart beat rate, pulse rate, blood cholesterol etc are affected.
4. Loss of hearing: long exposure to high sound levels causes either temporary or sometimes permanent loss of hearing
5. Performance: working performance is affected due to loss of concentration.
6. Nervous system: it causes pain, ringing in eras, feeling of tiredness, and thus functioning of the whole system.
7. Sleeplessness: Affects sleeping, and thereby inducing people to become restless and lose concentration and presence of mind.
8. Damage to materials and buildings: Materials may get damaged by exposure to high intensity sounds even from the infrasound/ultrasound ranges of frequencies.

Up to 65 dBA noise level may cause only annoyance no physiological effects. Levels above this can cause both psychological and physiological effects.

Continuous exposure to 90 dBA or above sound may cause permanent hearing loss. Even short period of exposure to above 100dBA noise level, the hearing perception may be damaged temporarily and prolonged exposure may cause irreversible damages.

120 dBA causes pain even with short exposure. 150 dBA will cause instant loss of hearing temporarily or sometimes permanently.

The permissible exposure to different sound intensities as per OSHA (Occupational safety & Health Administration) regulations is given below. No sound above 115 dB is permissible.

Maximum allowable duration per day hours	Sound pressure level, dB (A)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.75	107
0.5	110
0.25	115

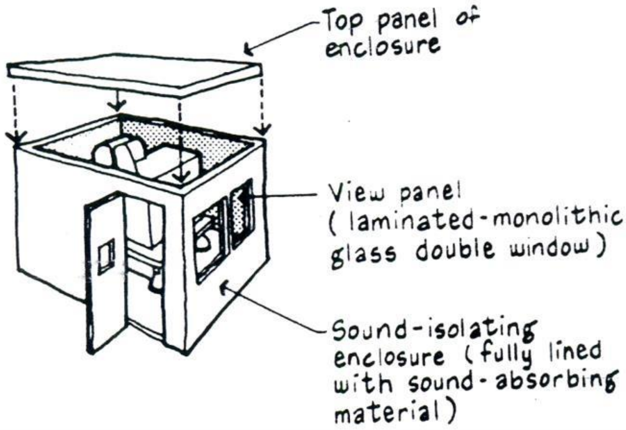
Dealing with noise related problems

Noise-problems generally consist of three inter related elements.

1) The Source 2) The path and 3) The receiving end.

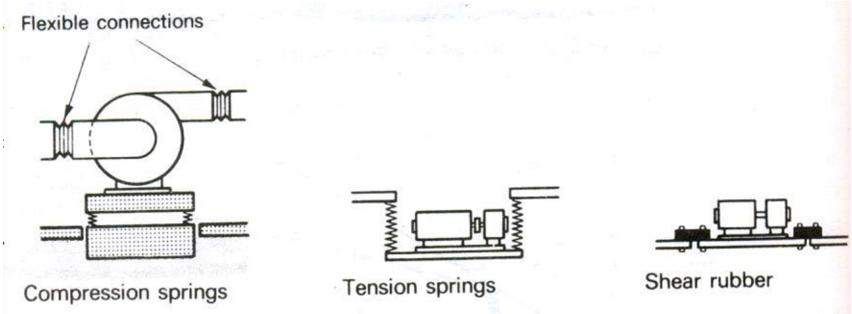
At and near the source: Reducing noise at source is very important. Taking proper care to educate people about the ill effects of noise and thereby making them conscious about the importance of avoiding the circumstances of producing unnecessary noise is an important step. Making inflexible rules and imposing severe punishment for breaching the same is very important.

When the source of production of noise is a machine, it can be located in isolated rooms or special enclosures as shown in fig. can be designed for individual machines

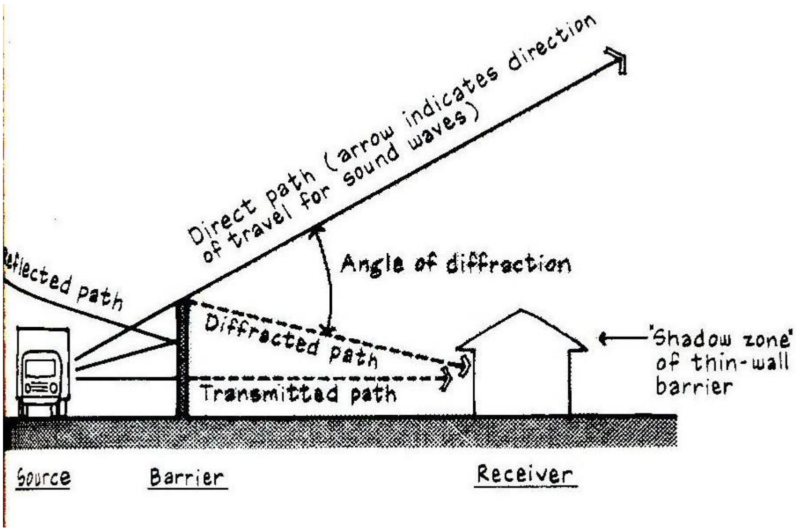


to reduce the air born noise from the machine.

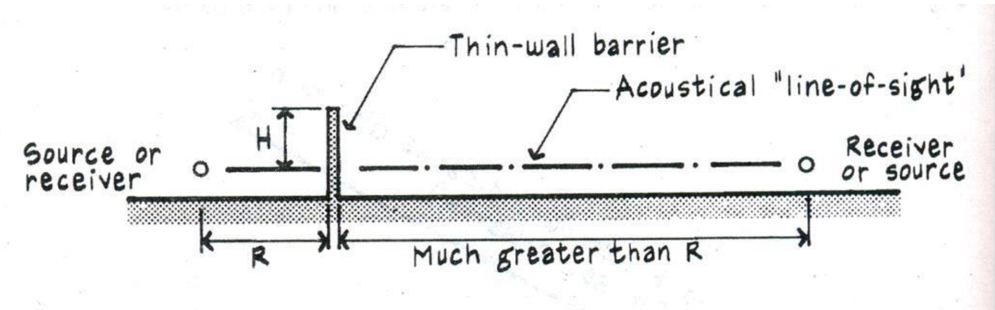
The structure born noise from machine can be prevented by providing flexible mountings.



In the path: outdoor barriers can be used to reduce environmental noises. See fig. below.



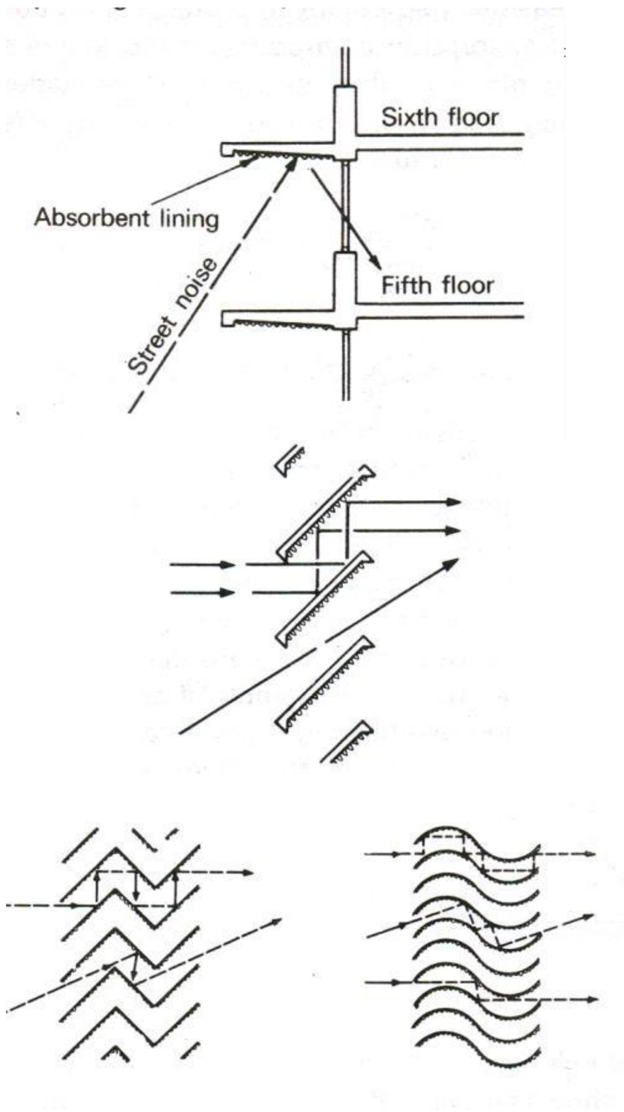
The barrier should be closer to the source for best results. The effectiveness depends on the value of H^2/R.



The barrier placed close to the receiver can also be effective. The effectiveness will be the least when the barrier is placed in the central area.

Providing discontinuity in structures is the best way to prevent transmission of structure born noises.

At the receiving end: Providing least amount of openings to the side from which noise is coming is a very effective way to reduce noise pollution. Treating the bottoms of the sunshades as shown in fig. below can be effective in noise reduction.



Further noise reduction (of the reverberant noise) is possible inside the room by adding suitable absorbents to ceilings walls etc. inside the room. This will be effective to the rear end of the room.

COMPUTATION OF ROOM NOISE REDUCTION (N.R.) WITH THE USE OF ABSORPTION MATERIALS

N.R. (Room noise reduction) is given by the equation N.R. =10 log a_2/a_1. Where "a_1" is the total absorption before treatment with sound absorbers
And "a_2"is the total absorption after treatment of surfaces with absorbing materials.

N.R. is the total noise (sound) deduction (of the reverberant noise) in dB.

Example: A class room of 20m X 10m X 4m has 4 windows of 2 sq.m each and one door of 3 sq. m, all kept open. The absorption coefficients of ceiling and wall are 0.04 and that of the floor is 0.02. Find out the total sound absorption in metric Sabine. If 50% of the wall and 50
% of the ceiling are treated with sound absorbing materials having absorption coefficient
0.50 and the floor is laid with carpet of absorption coefficient 0.70, find the reduction in reverberant noise level that can be achieved. Assume that the hall is occupied with 60 people having average absorption of 0.75 including that of the seat.

Room Volume= 20X10x4=800 cu.m Surface area of ceiling= 200 sq.m Surface area of the floor= 200 sq.m Area of openings=11 sq.m
Surface area of wall=2*(20*4+10*4)-11=229sq.m

Absorption by all the surfaces before treating= 200*0.04+229*0.04+200*0.02+11

=32.16 Metric Sabine

Absorption by the audience=0.75*60=45 Metric Sabine

Total absorption before treating the surfaces=32.16+45=77.16 Metric Sabine

Absorption by all the surfaces after treating=100*0.04+100*0.50+229/2*0.04+229/2 *0.50+200*0.7+11=266.83 Metric Sabine

Total absorption after treating = 266.83+45=311.83 Noise reduction (N.R)=10 log 311.83/77.16 =**6 dB Sound insulation and TL value.**

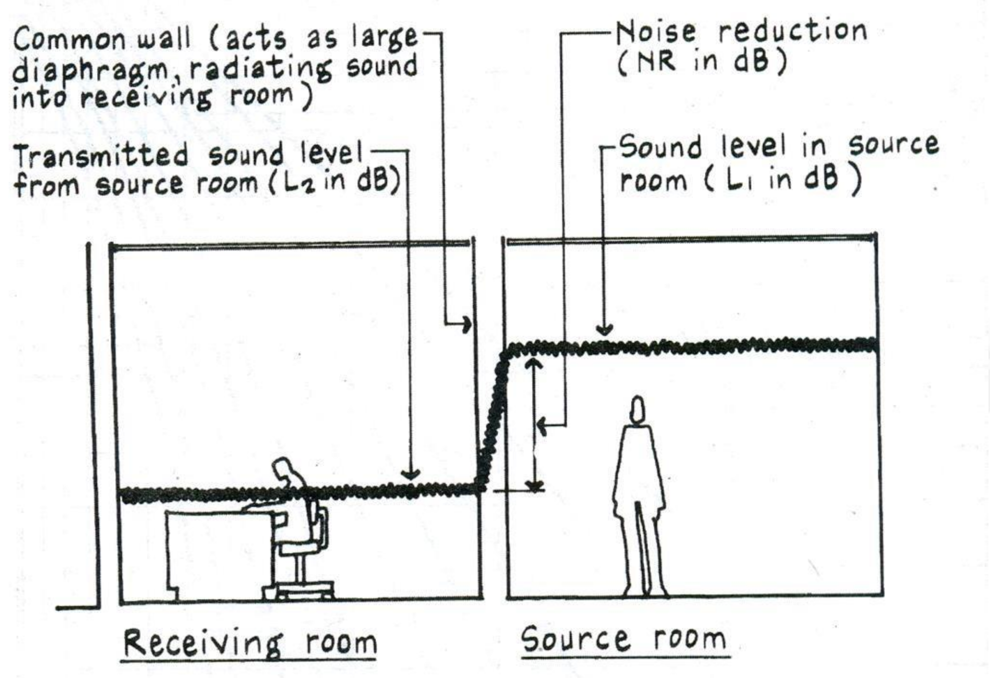
Sound insulation merit of a partition is generally expressed in transmission loss (in dB). Transmission loss is equal to the number of decibels by which sound energy incident on a partition is reduced in transmission through it. A wall of TL of 30 dB means the sound energy is reduced by 30 dB on passing through this wall.

If "t" is the transmission coefficient (a decimal fraction expressing the portion of the sound energy transmitted) TL= 10 log 1/t

For a solid homogeneous partition, TL value is a function of its mass. If M is the mass per unit surface area expressed in kg/m^2 (i.e., the mass density multiplied by the thickness ofthe partition), TL=18 log M +8 (approx) for M>100 and

TL=14.5 log M +13 for M<100.

Approximately for every doubling of wall thickness, TL will increase by around 5 dB. Even a very small opening in the wall will reduce the TL value considerably.



Example: Find the transmission loss value of a 12 cm solid brick wall of 12 sq. m. If there is asmall opening of 0.10m*0.10m is in that wall, find how much deduction will occur to the TL value.

M=0.12 *1800 = 216 kg/m^2 (1800 kg/m^3 is the density of brick) TL= 18* log 216 +8 = 50 dB

When 0.1*0.1=0.01m^2 opening is made in the wall TL of the solid wall=50=10 log 1/t1

Transmittance, t1= 1/10^5

Area of the solid wall =12-0.01=11.99 m^2t2= transmittance of the opening=1

Net transmittance (t) = [11.99*(1/10^5)+1*0.01] / 12 =0.0008433 TL value= 10 log 1/0.0008433 =31 dB

TL value is reduced from 50 dB to 31 dB even with this small opening.

If the opening size is 1 sq.m, it can be seen that the TL value will be just 11 dB

FLANKING PATH

Any path for sound transmission that bypasses or circumvents the primary path through the structure under consideration is called the flanking path. A/C ducts, PVC pipes used for electric wiring etc act as flaking paths between rooms separated by solid walls. Extreme care should be given in identifying and treating flanking paths properly, especially for rooms for which confidentiality is important.

Some general points to be made use of in tackling the noise problem

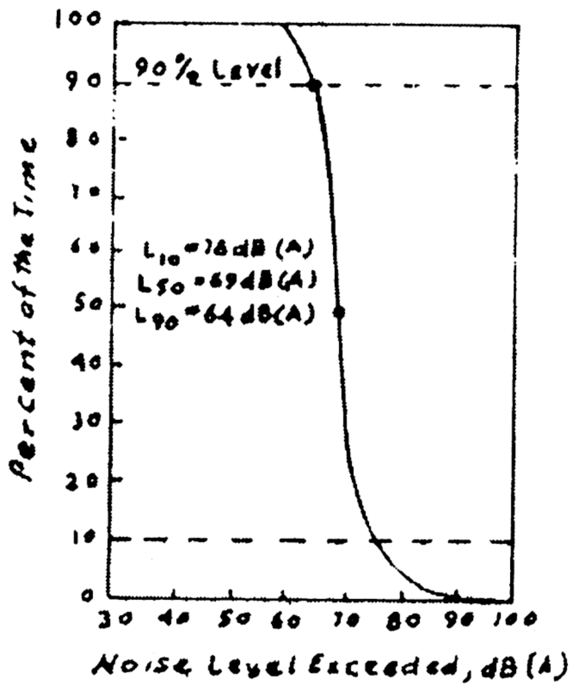
For external noise:

- Distance and screening
- Avoid zones of directional sounds
- Using non-sensitive areas of buildings as barriers
- Positioning of areas away from the noise source
- Noise insulating building envelope Internal noise:

- Reduction at source
- Enclosing or isolating the source
- Separating noisy space from quiet ones by placing non-critical areas in between
- Placing the noisy equipments in the massive part of the building like the basements
- Reducing impact noise by covering surfaces with resilient materials
- Reduce reverberant noise by absorbent materials
- Reduce sound transmission by air-tight and noise insulating constructions
- Reduce structure born sound transmission by discontinuity.

How to quantify noise from a particular environment like busy street busy junctions etc.

Here, the noise level will be constantly varying and it is difficult to fix up a single value (like certain number in dBA) to indicate the noise level. Hence a statistical approach is adopted. The sound level will be recorded for a fixed period. It can be 24 hours. It can be 15 hours from 6 a.m. to 9 p.m (Day time for acoustical calculations)



or 9 hours, 9 p.m. to 6 a.m. (Night time for acoustical calculations). See the fig. below for a graph plotted from such measurements.

Whatever is the time of measurement, the percentage of the same is plotted in Y-axis and the noise level in dBA is plotted in X-axis. The three important terms in connection with this are L90, L50 and L10. L90 means, the sound level which is exceeded 90% of the time L50, the sound level which exceeded 50% of the time and L10, the sound level which exceeded only during 10% of the time. L90 is the sound level persists in the region for most of the time and hence is the background noise level of the region. The fluctuation value in an interval of time is called the Noise climate of the region and is given as NC=L10-L90 per sampling time.

The equivalent sound level denoted as L_{eq} is given by the equation $L_{eq} = L50 + (L10-L90)^2/60$

In the example shown in the graph, L90=64 dBA, L50= 69 dBA and L10= 76 dBA

Suppose it is based on a 24 hr. measurement, the Noise climate= 76-64=12dB for 24 hours. L_{eq}=69+(76-64)2/60=71.4 dBA

Indian standards for ambient noise levels

Area	Noise Limits, Leq, dB (A)	
	Day Time [2]	Night Time [3]
Silence zone [4]	50	45
Residential area	55	45
Commercial area	65	55
Industrial area	75	65

1. Ministry of Environment and Forest (MOEF) Guidelines vide Environment (Protection) Act, 1986 third amendment rules, dated 26/12/89 (Ref. 6)
2. Day time from (600 hrs to 2100 hrs, IST)
3. Night time from (2100 hrs to 600 hrs IST)
4. Silence zone: Up to 100m around hospitals, educational institutions and courts. The zones are to be declared by competent authority. Use of vehicle horns, loud speakers and bursting of crackers shall be banned in these zones.

Sometimes there could be huge differences between the day time (6.a.m.-9.p.m.) and night time (9.p.m.-6 a.m.) sound levels. To take care of this, instead of L_{eq} another parameter called L_{dn} (day and night equivalent sound level) is often made use of.

L_{dn}= 10 log [15/24*$10^{Leq-d/10}$ +9/24*$10^{Leq-n/10}$]

REVERBERATION

The concept of reverberation was first introduced by Prof. Wallace Clement Sabine in 1895. In 1895, the newly constructed Fogg Art Museum Auditorium being found totally useless, Prof. W.C. Sabine was consulted for finding solutions to make it useful. Sabine made a two year long study in the auditorium. He conducted several tests (mainly between 2 a.m. and 5 a.m.) with the help of people having good perception of ears. Prof. Sabine finally rectified the faults of the auditorium. It was during this study that he established the very important acoustical phenomenon, the reverberation. Reverberation is the persistence of sound in a closed environment, even after the stoppage of the original sound. Reverberation time defined by Sabine is the time taken by the sound to decay to one millionth (1/10, 00,000) of its original intensity (i.e. the time taken to decay by 60dB).

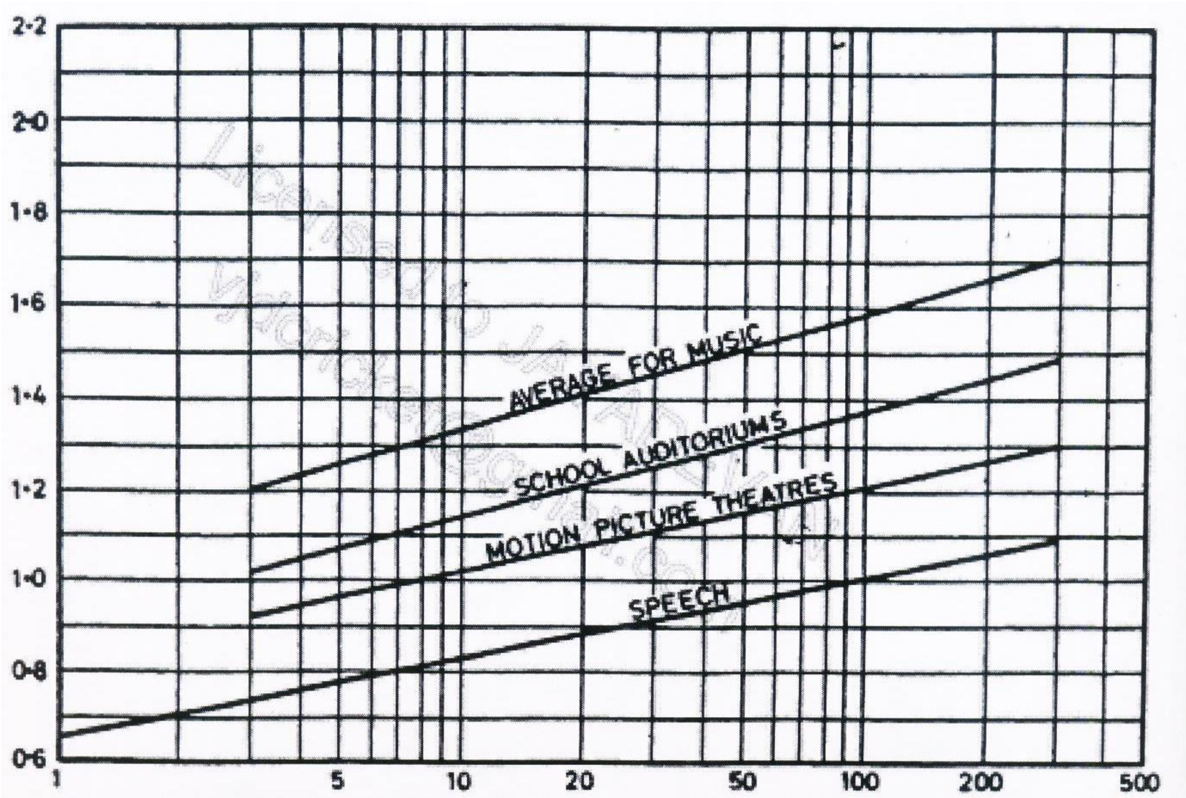
The empirical relation that Sabine derived and proved is

T= 0.049 V/A Where "V" is the volume of the room in cubic feet, and **"A" is the total absorption ($\Sigma a_i S_i$)** in Sabine. **("a_i" and S_i are the respective absorption coefficients and surface areas of different surfaces of the room**, S_i will be in sq. ft.).

The equation in metric units will be **T= 0.16 V/A**

A= **$\Sigma a_i S_i$** and the unit will be metric Sabine ("V" will be in m^3 and "S" will be in m^2)

For satisfactory functioning of a hall or auditorium, the reverberation time should be within certain limits. Excessive reverberation will create overlapping of sounds and results in loss of clarity. Inadequate reverberation will make the hall lifeless. For speeches etc., comparatively less reverberation is required whereas for music more reverberation is required. The time of reverberation required also varies with the size of the hall. For larger halls slightly higher reverberation is preferred compared to



smaller halls. IS-2526-1963 gives the following graph to determine the required reverberation time for various activities based on the size of the hall. The X-axis gives the volume in 100 m^3 and the Y-axis gives the reverberation time in seconds.

When we speak about absorption coefficients, we have to remember that the absorption also varies with the frequency of the sound. The more the frequency normally the more it gets absorbed (there are some exceptions). Hence the absorption coefficient corresponding to 500 (or 512) Hz is usually taken as the representative absorption coefficient for sound absorption calculations. Another term called N.R.C (Noise reduction coefficient) which is the average of absorption coefficients of frequencies, frequencies 250, 500, 1000 and 2000 is also sometimes used for sound absorption calculations.

Absorption Coefficients.

	Octave-Band Center Frequency (Hz)					
	125	250	500	1000	2000	4000
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03
Carpet on foam rubber	0.08	0.24	0.57	0.69	0.71	0.73
Carpet on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Floors, concrete or terrazzo	0.01	0.01	0.015	0.02	0.02	0.02
Floors, resilient flooring on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Floors, hardwood	0.15	0.11	0.10	0.07	0.06	0.07
Glass, heavy plate	0.18	0.06	0.04	0.03	0.02	0.02
Glass, standard window	0.35	0.25	0.18	0.12	0.07	0.04
Gypsum, board 0.5 in.	0.29	0.10	0.05	0.04	0.07	0.09
Panels, fiberglass, 1.5 in. thick	0.86	0.91	0.80	0.89	0.62	0.47
Panels, perforated metal, 4 in. thick	0.70	0.99	0.99	0.99	0.94	0.83
Panels, perforated metal with fiberglass insulation, 2 in. thick	0.21	0.87	1.52	1.37	1.34	1.22
Panels, perforated metal with mineral fiber insulation, 4 in. thick	0.89	1.20	1.16	1.09	1.01	1.03
Panels, plywood, 3/8 in.	0.28	0.22	0.17	0.09	0.10	0.11
Plaster, gypsum or lime, rough finish on lath	0.02	0.03	0.04	0.05	0.04	0.03
Plaster, gypsum or lime, smooth finish on lath	0.02	0.02	0.03	0.04	0.04	0.03
Polyurethane foam, 1 in. thick	0.16	0.25	0.45	0.84	0.97	0.87
Tile, ceiling, mineral fiber	0.18	0.45	0.81	0.97	0.93	0.82
Tile, marble or glazed	0.01	0.01	0.01	0.01	0.02	0.02
Wood, solid, 2 in. thick	0.01	0.05	0.05	0.04	0.04	0.04
Water surface	nil	nil	nil	0.003	0.007	0.02
One person	0.18	0.4	0.46	0.46	0.51	0.46
Air	nil	nil	nil	0.003	0.007	0.03

Note: The coefficient of absorption for one person is that for a seated person (m^2 basis). Air absorption is on a per cubic meter basis.

Example: In the problem discussed in page 14. Find out the reverberation time before and after treatment of surfaces.

Solution: Volume of the room = 800 cubic meter

Total absorption before treatment =77.16 Metric Sabine

Reverberation time= 0.16*800/77.16= 1.66 seconds [high value for speech but good for music]

Total absorption after treatment= 311.83

Reverberation time= 0.16*800/311.83= 0.41 seconds [Quite low, alright for speeches]

While designing Auditorium etc., for the computation of absorption by the audience, normally it will be assumed as 2/3rd full. I.e. if the hall is intended for a seating capacity of 300, sound absorption of 200 people and 100 vacant seats will be considered for reverberation calculations.

LIMITATIONS OF SABINE'S FORMULA

Sabine's formula though very effective in most of the cases, has some limitations. The reverberation computed is not so reliable when the average absorption coefficient ($\bar{a}$) is more than 0.20 or so.

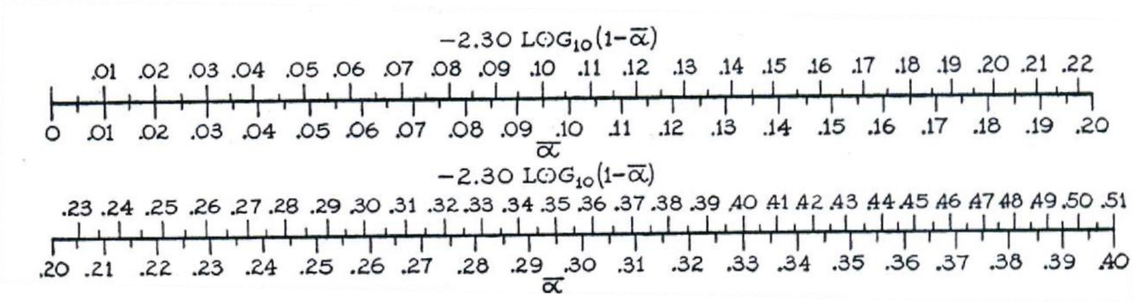
$\bar{a}$ is defined as $\Sigma aiSi/\Sigma S_i$

We have to use Eyring's formula to get more reliable values of reverberation time when $\bar{a}$ exceeds 0.20.

Eyring's formula

$T= 0.16\ V/S\ [-2.30 \log_{10} (1- \bar{a})]$

Charts are available to read the value of $[-2.30 \log_{10} (1- \bar{a})]$ from the value of $\bar{a}$.



COMMON ACOUSTICAL DEFECTS

A good knowledge about different acoustical defects is a prerequisite before attempting to design a building for good acoustics. The common defects observed are:

1 Excessive/Inadequate reverberation (measured as reverberation time)

Depending up on the activities to be performed, the space should have the reverberation within certain limits. Too low reverberation will affect the liveliness of the space whereas too high reverberation will affect the intelligibility. Generally for speeches a reverberation time of 0.5-0.85 seconds is fine where as for musical activates a reverberation time of 1.2 to 1.6 seconds is more appropriate. A reverberation of over 2 seconds is not usually preferred except for prayer halls in Churches. The halls shall be properly sizes and the surfaces shall be properly treated to achieve optimum reverberation time.

2 Echoes

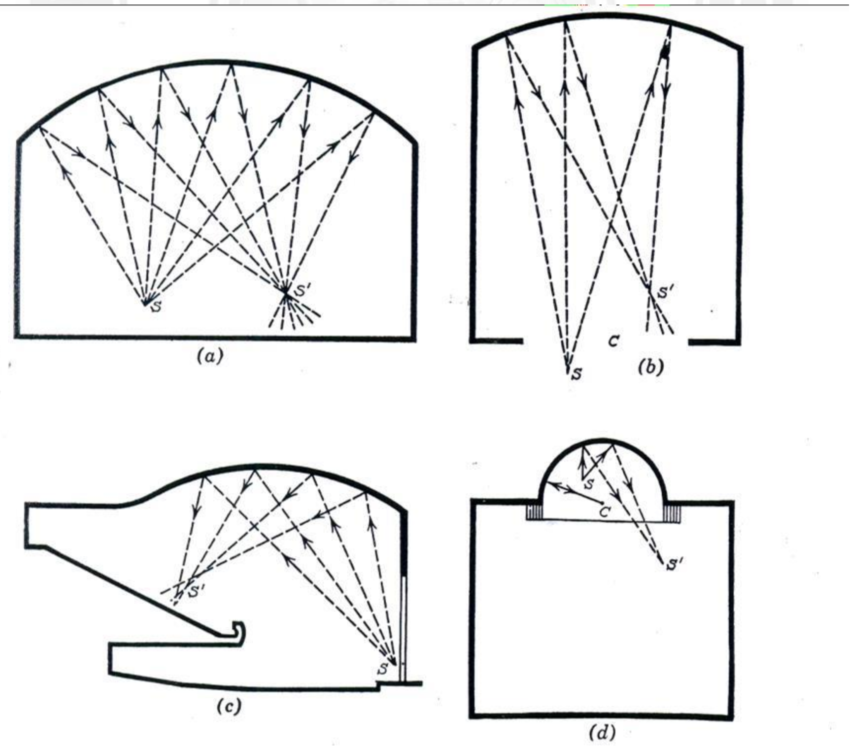
An echo is a distinct repetition of the original sound which is sufficiently loud to be heard over the reverberant sound and the background noise. Echoes occur when the reelected sound is heard after $1/10^{th}$ of a second after the original sound is heard. Since the velocity of sound in air is approximately 340 m/sec, the possibility of hearing an echo occurs only when the reflected sound travels 34 m more than the direct sound before reaching the listener. If the length of the hall is less than 17 metres, there will not be any echo problem. If it is more than 17 m, the rear wall and the surfaces, from which the reflected sound can be expected, should be treated with sound absorbing materials to eliminate echo.

3 Flutter echo

If the hall consists of two parallel walls with highly reflective surfaces, the sound waves get reflected back and forth repeatedly causing a disturbance called flutter echo. A single hand clap for example will be heard as multiple claps slowly fading way. This can be avoided by finishing the parallel walls with sound diffusing surfaces or sound fixing absorbing materials. Making slight inclination to make the sidewalls non-parallel is also works to eliminate flutter echo.

4 Sound foci

If the room consists of concave surfaces, sound after reflection will concentrate on certain spots producing excessive loudness. See fig. Hence, concave surfaces should be avoided as far as possible to create good acoustical environment. If they are absolutely unavoidable, shall be treated with good sound absorbing materials.



5 Dead spots

Due to the presence of concave surfaces, sound tends to concentrate on certain spots and due to this reason certain other spots suffer lack of intensity. These areas, where the sound intensity is not adequate for satisfactory listening, are called dead spots.

6 Whispering galleries

The sound waves sometimes takes the path through concave surfaces and makes even a whisper to be heard at a distant spots in the hall very clearly. This phenomenon has become popular in connection with the St. Paul's Cathedral, London, where a whisper at some spots could distinctly be heard at some other places so far as 200 ft away.

"THE ACOUSTICS WERE SPLENDID – I COULD HEAR EVERY WORD THE WOMEN BEHIND ME WERE SAYING!"

ACOUSTICAL DESIGN OF AUDITORIUMS AND CONFERENCE HALLS

The various steps involved in connection with the design of an auditorium are:

1. Examining the site with respect to noises
2. Limiting the size of the auditorium
3. Designing/deciding the shape
4. Providing optimum reverberation in all parts of the hall
5. Conducting tests like articulation testing etc. to ensure that the design objectives are achieved.

1. Examining the site with respect noises

The site selected for the auditorium shall be very quiet as far as possible. The normal background level inside should be limited to 35 dBA. To achieve this, the building envelope should be so designed with walls and partitions having adequate TL (transmission loss) values which would bring down the noise level to the required limits. In noisy areas, it may not be possible to go for natural ventilating as small openings itself reduce the TL value considerably. Corridors or lobbies may be interposed between the auditorium and the source of noise. Such lobbies treated with sound absorbing materials are sometimes called sound locks.

2. Limiting the size of the auditorium

The size of the auditorium is governed by the required seating capacity. From the economy point of view smaller sizes are always preferred but the size should not be so small that it would be difficult to achieve the required time of reverberation. Usually a size of 3.5 to 5 m^3 per seat will be sufficient. The lower limit may be used for conference halls and the upper limit for larger multipurpose auditoriums. A volume of 5.7 m^3 per seat should not be exceeded in any case.

3. Shape of the Auditorium

It is necessary to get direct sound as well as reflected sound for the listener to get a good feeling of listening. The direct sound beyond 9 m will be unintelligible. Too much of path difference between the direct and indirect sound is also not appreciable. To limit the path difference to about 12 m or less is ideal for good listening. Designing the shape of the auditorium means

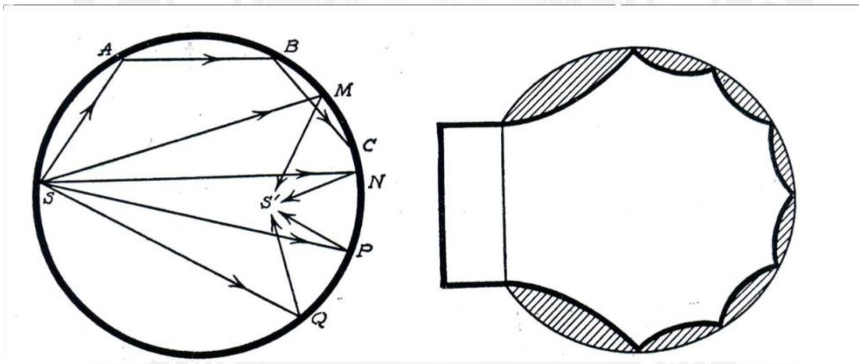
1 Designing the Floor plan, shape and rises

2 Designing the side walls

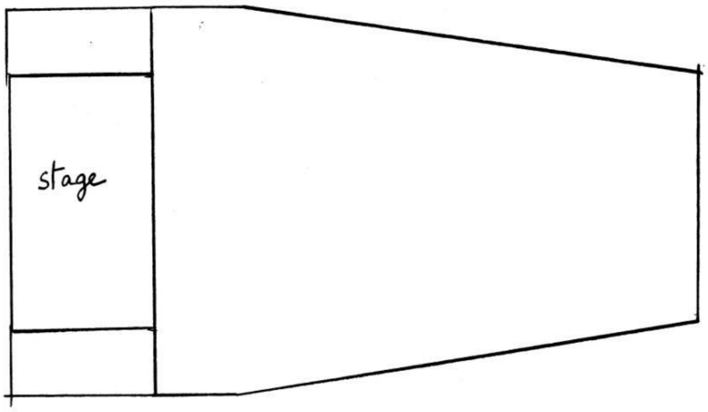
3 Designing the ceiling

4 Designing the rear wall

Among the variety of shapes, the rectangular and fan shaped ones are mostly preferred. The advantage of the rectangular shape is that it makes the reflection paths short. The fan shape brings the audience nearer top the stage. Parabolic and concave shapes should be avoided as they could produce sound foci and dead spots. If a circular plan is unavoidable on some other consideration, the inside can be treated as shown in fig below to avoid the effects of focusing of sound.



In general a rectangular plan is ideal for small halls and a fan shaped (wider near the stage) plan is ideal for larger auditoriums.



FAN shape

Design for good line of sight is considered to be good for receiving direct sound also. As the sound source will normally be elevated, for the first few rows, the seats need not be elevated for good line of sight (and hence for direct sound). There is an empirical formula available to calculate the distance from which the sloping of the floor is to be started. The formula is:

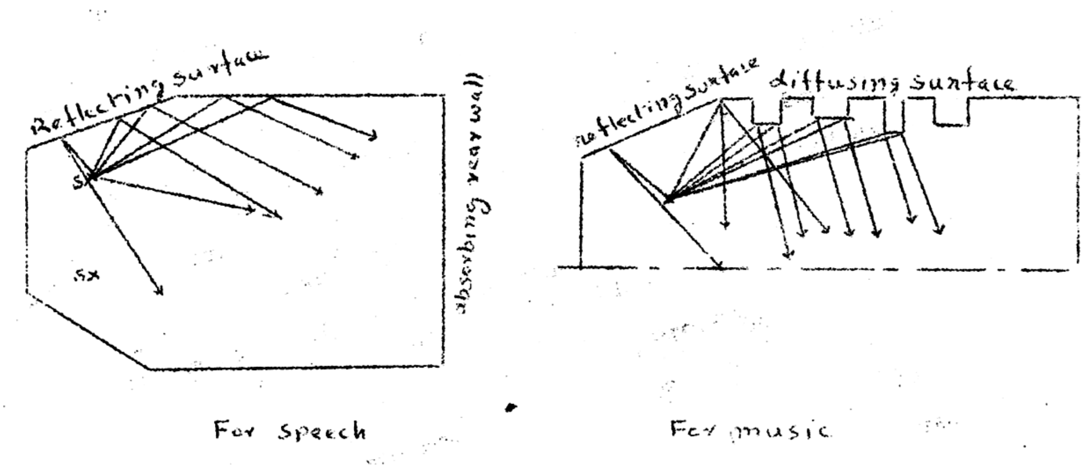
d = r (2.5 h-1)

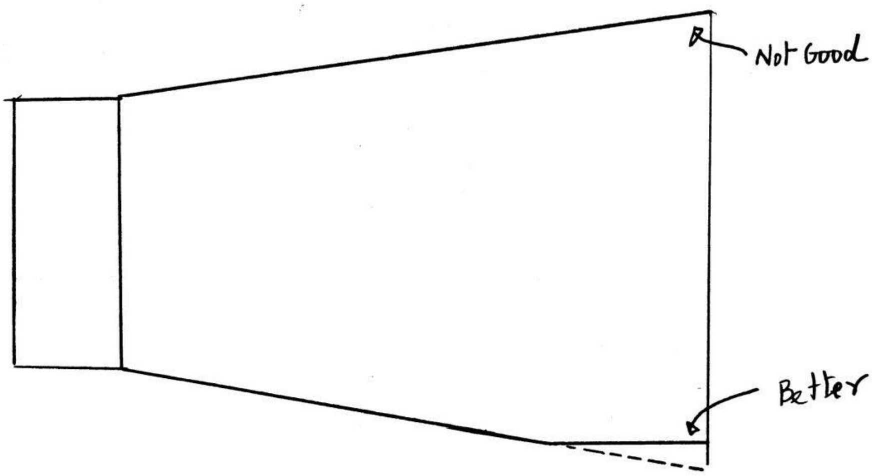
"d" is the distance from the source to the last row not elevated. "r" the distance between the rows and "h" height of the source from the floor level. (**d, r, h are in feet)**

Beyond the distance "d" an elevation of 8^0 is normally provided for auditoriums. For lecture halls a slope of even 15^0 is sometimes provided.

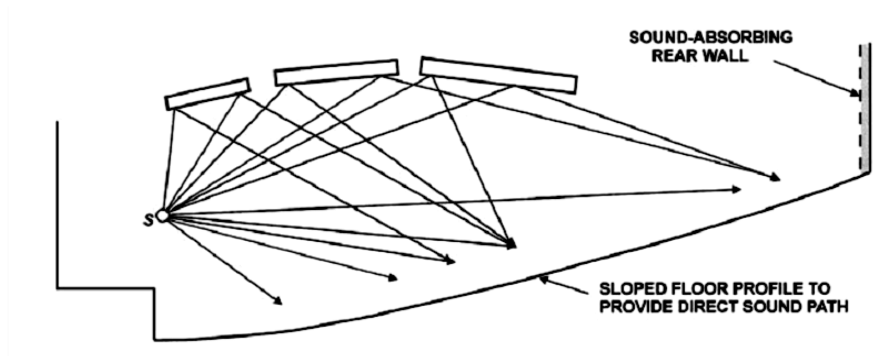
Design of side walls

Position of side walls depends on the floor shape selected. For speeches, strong reflections of path difference of not more than 9 meters is preferable. For music, more a kind of sound disusing treatment is preferred (as shown in fig.). Convex surfaces are also good sound diffusers. At points where the side walls join the rear wall, acute angles should be avoided.



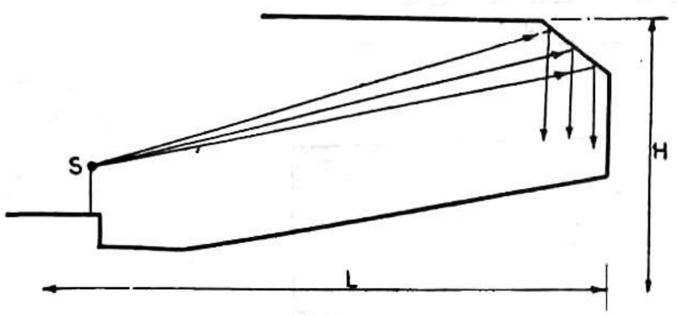


Ceiling

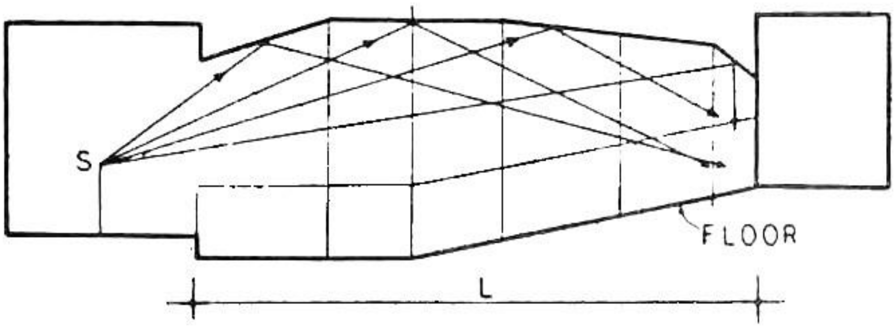


It is essential to shape the ceiling of the auditorium to get favorable reflected sound without much path difference. The ray method is normally adopted to do that.

The fig shows how the ceiling can be shaped to achieve good reflected sound. Regarding height of the ceiling, 1/3rd to 2/3rd of the hall width is normally adopted. Ceiling height should not be too much as it creates undesirable path difference. For an auditorium of 40 metre length and 20 metre width, a height of 10-12 metres will be satisfactory. Again concave surfaces should be avoided as far as possible and the ceiling should not be parallel to the floor throughout to avoid flutter echo. Towards the rear end where the ceiling need not serve as reflectors, the surface should be treated with sound absorbers. Where the ceiling joins with the rear wall it shall be made as shown in fig below.



The fig. below shows an acceptable shape for an auditorium.



Rear walls

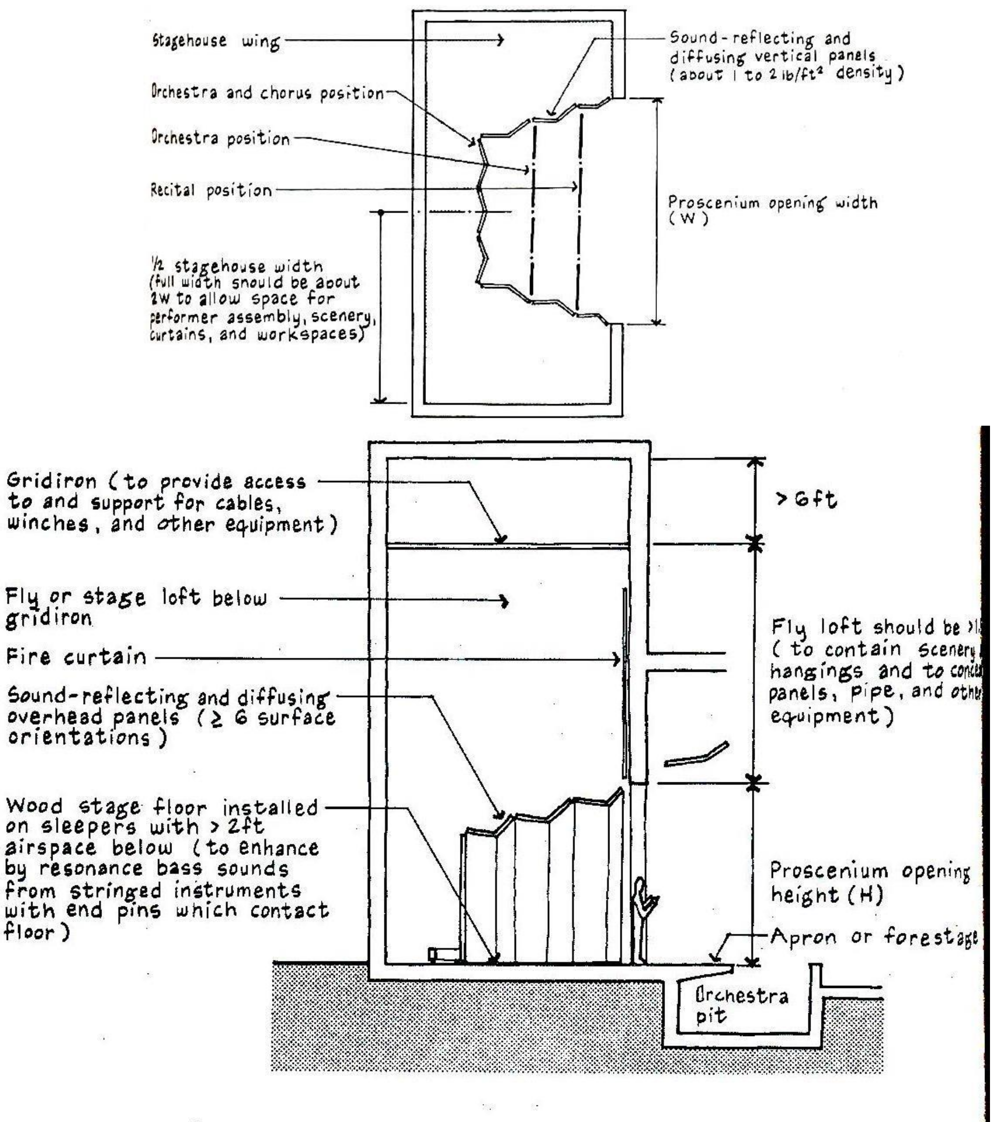
Rear walls are usually treated with sound absorbing materials. Normally concave shape should be avoided. Slight curvature (large radius of curvature) can be tolerated. If needed, if it helps to improve the loudness in the back seats without giving other problems, rear walls also can be made reflective. This may be needed in large auditoriums below the balcony recess.

Balcony

If the auditorium is having a balcony, care should be taken to see that the cantilever projection is not greater than twice the depth (opening) under it. If it is more than twice, it will act as a separate space and separate determination of reverberation will be required for this region. Also special measures will be required to feed the back seats by means of soundwaves reflected from ceiling and balcony soffit.

Stage

Proscenium stage is the one in which the performing area is coupled with a stage house. There are other types of stages called open or thrust stage, Arena stage etc.



Note: The fixed height of the proscenium opening *H* usually varies from 20 to 35 ft (and higher for opera). The fixed width of the proscenium opening *W* varies from 30 to 80 ft, depending on the type of theatrical or orchestral production.

4. Providing optimum reverberation time

Fix the optimum reverberation time from the chart based on the volume of the hall and the type of activity to be performed.

Find the total absorption required, using Sabine's formula.

The total absorption includes the absorption from audience and vacant seats also. Usually the hall is considered to be 2/3rd full for this purpose. The absorption per person including the absorption from the seat he is occupying can be taken as 0.46 m^2 Sabine. The absorption of vacant seats should be computed based on the type of seat coverings used. Find out the absorption of all surfaces based on the absorption values available in standard tables (Values corresponding to 500/512 Hz or the NRC values may be taken).

Find out the balance absorption required

Place suitable absorption materials at suitable locations to get the required total absorption to maintain the reverberation time.

For multipurpose halls removable or changeable fittings may be used to get the required reverberation times based on the activity to be performed.

5. Check for a completed Auditorium

Even when the hall is designed based on the principles described above, it is essential to make a check to ascertain its performance.

Hand clap is an effective test for echo and room flutter. Persons with good ear perception should be used for tests. A single clap should be made standing at the position of the sound source and these persons will be able to detect defects if any. It is more difficult to check the reverberation time. Measuring the decay of sound using instruments and study the reverberation characteristics based on that is a bit tedious job though not impossible. But a Well trained person having very good auditory perception can find out defects with his ears.

Another important test that can be conducted if poor listening conditions are suspected at some part of the auditorium is "Articulation test". In this test, a person standing at the position of the sound source will call out a list of mono syllabic speech sounds. The observer seated at positions where the intelligibility is suspected will write down the same. If the speaker calls out 1000 words and the observer hears 850 of them correctly, the percentage articulation is 85. A value above 85% is considered to be good. 75% and above is satisfactory and below 65% is poor.

ACOUSTICAL DESIGN OF SMALL LECTURE ROOMS

For lecture rooms, intended for less than 100 people, a rectangular shape with level floors and ceilings is good enough

Volume should be kept around 3.5 m^3 per person

A ratio of 4:3:1 (length: breadth: height) is good enough Reverberation time should be around limited to 0.85.

The background noise level shall be 35-40dBA. If it is a noisy area, it may not be possible to provide natural ventilation through openings like windows and ventilators. If artificial ventilation is provided, the ventilation ducts which can act as flanking paths must be adequately attenuated with sound absorbers.

ACOUSTICAL CONSIDERATIONS IN OFFICES

To create a silent and efficient work atmosphere, offices shall be located in quiet areas.

If it is not possible, then care should be taken to see that, walls or partitions of sufficient TL value are provided for the facades facing the noisy areas. Even small openings can reduce the TL value considerably; in very noisy areas it may not be possible to provide natural ventilation.

Locating spaces those are not of acoustical importance as barriers and thus preventing sound to penetrate into the sensitive areas is a very effective step.

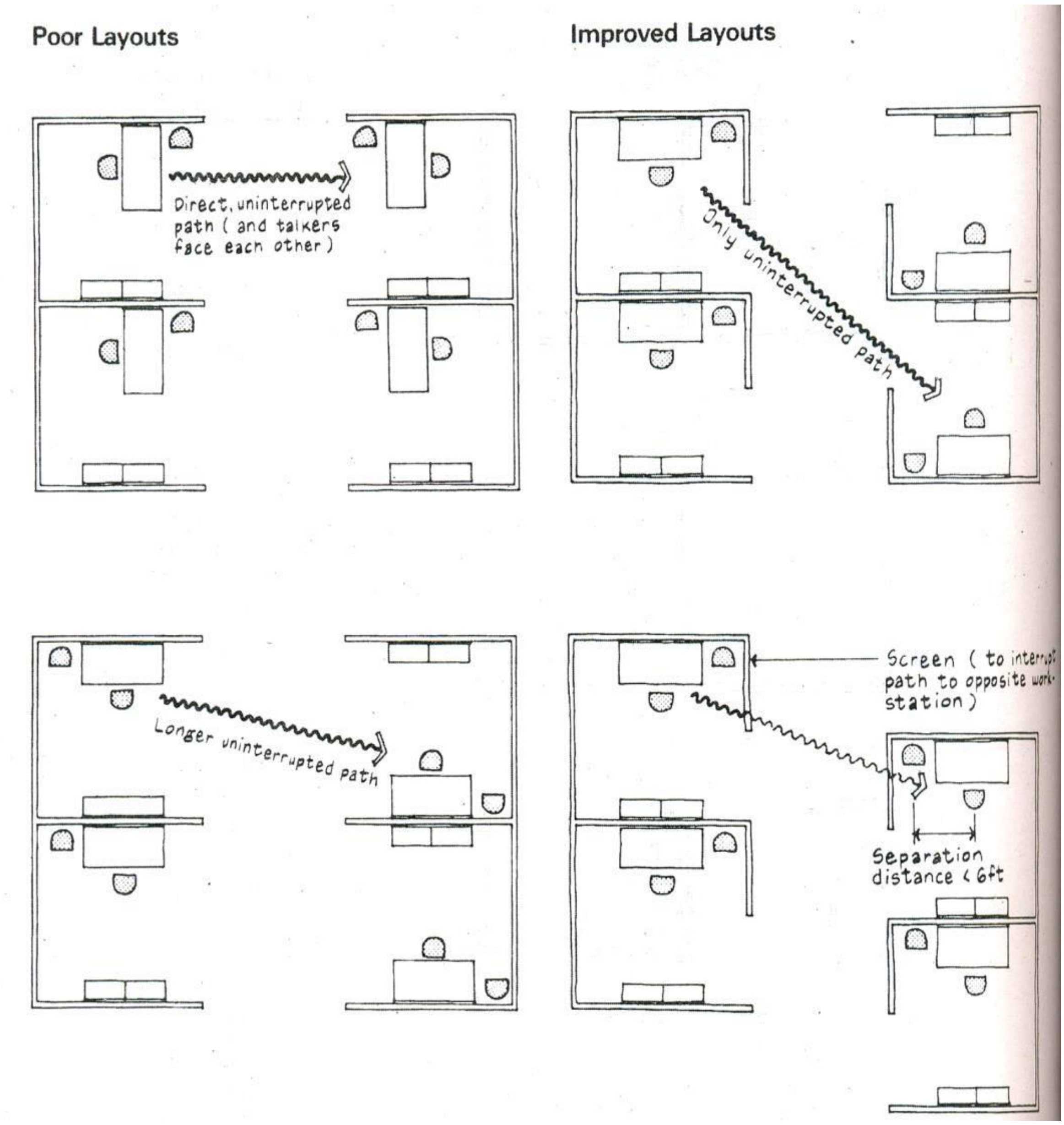
In case of artificially ventilated rooms, the surfaces are to be treated with adequate sound absorbing materials to reduce the reverberant sound level and hence the overall sound level in the inside space. This also helps to reduce the reverberation time to a minimum, less than 0.50 or so. In artificially ventilated spaces, the A/C ducts etc act as flanking paths and hence should be treated with sound absorbing materials inside.

There are sources of sound generation inside the office also. Areas which are sensitive should be kept away from the areas those produce noise. Again non-sensitive areas can be placed in-between as barriers. Sound generating machines should be isolated as far as possible.

In open offices the workstations should be positioned to get greater distances between the talker and the listener. The side walls or ceilings which could be strong reflectors of directional sound shall be treated with sound absorbers.

Increasing the room background sound level is a very effective method to provide good acoustical condition inside by reducing the effect of noise. A very soft instrumental music of sound level less than 50 dB may be provided as uniformly distributed background sound inside the open office space. If it is more than 50dB, it may annoy the occupants.

Spaces were continuous walking or movements of occupants are expected and possibility of falling of objects etc. are suspected, carpeting of floors may be done to prevent the structure born sound. Proper care should be taken to reduce the propagation of structure born sound by providing dampers and discontinuities.



ACOUSTICAL CONSIDERATION OF RESIDENCES AND APARTMENTS

Insulation against unwanted sound is an all important problem in the acoustical design of homes and apartments. The most important acoustical problem in the design of residences is the insulation against outside noise. The main sources of outside noises are traffic, children playing, service deliveries, road rapiers, blaring loud speakers, machineries from the neighborhoods etc.

As far as internal noises are considered; conversations of the occupants, sound from television, music systems, banging of doors, shifting of furniture, operation of the cisterns of water closets etc. are the important sources. For apartments the noises from other flats and staircases are to be seriously considered.

The most ideal way is to keep the building away from noisy areas like busy streets, railway lines, airports, Temples & Churches etc.

Attention should be given while planning to put the layout in such a way that sensitive areas are located away from the path of the noises. Also windows should be placed towards quieter sides and they should be tightly closable. The inner surfaces of the louvers shall be treated with sound absorbing materials to reduce the sound intrusion through windows. Great care should be taken in cases of bathroom fixtures. The sound created while flushing

of water closets should not disturb the sleep of people in the bedrooms of the same house or of the other apartments in the case of flats. Bath rooms should not come right above the bedrooms.

As far as reverberation is concerned, staircases and living halls are the most problematic. They act as speaking tubes. Adequate insulation should be given to bring down the reverberation to below 1 sec. High reverberation will affect the intelligibility of telephonic conversations.

The TL value between two rooms in the same house shall not be less than 30 dB. Between living rooms of two apartments and between bed room and living room of other apartment shall not be less than 50 dB. Between any other rooms of two apartments shall not be less than 45 dB.

Ventilation ducts and air transfer openings provided should be designed to allow minimum noise penetration.

Structure born noise due to the footsteps and falling of objects in the upper floors is a major problem in apartments which is difficult to be managed. Wherever possible, installations for damping of sound shall be provided to reduce the structure born sound propagation.

ACOUSTICAL CONSIDERATIONS IN INDUSTRIAL BUILDINGS (FACTORIES ETC.)

Factories are producers of noise rather than receivers of noise. Noises in industrial buildings are mainly of indoor origin. Noises in factories are classified into

1 Impact noise

Impact noise is the most intense and widespread of all industrial noises. Impact noises are normally intermittent and impulsive but sometimes can be continuous as well

2 Frictional Noise

It is produced mainly due to sawing, grinding, etc. Lathes, breaks bearings etc. also produce friction noise. They generally are of high frequencies and extremely unpleasant.

3 Rotation or reciprocation noise

Rotating or reciprocating machines produces noises due to unbalanced forces/pressure fluctuations in fluids inside the machine. Interaction of rotating components with the fluid streams can also produce noise. Again these are normally of high frequency range and can be quite annoying.

4 Noise from air-turbulence

Noise may be generated by rapid variation of air pressure by turbulence from high velocity air. Intensity increases rapidly with the velocity of the air-stream.

5 Humming noise from transformers and turbines

Whining noise from turbines and humming noise from transformers are of this category.

The sound levels observed in these industrial buildings are not only just annoying but regular exposure to such atmosphere could also temporarily or even permanently damage the ears. A sound level of 120 dB should not be exceeded at any time. If possible the sound level should not be exceeded even 100 dB. Continuous noise should never exceed 80 dB. Feasible engineering controls have to be adopted to limit the sound level to this level. Whenever this is not possible, ear protecting masks should be given to the employees who are constantly exposed to these levels of sounds. A good ear plug when properly used can reduce the sound up to 30dB.

Noise control by location and noise control by layout are two effective ways to isolate critical areas from noises.

Noise reduction at source by covering the noisy equipments, keeping them in rooms with highly insulated surfaces, reduction of structure born noise by damping and providing discontinuities are the other options to reduce the noise problems inside industrial buildings. Again ventilating ducts and pipes for electric wirings should be critically observed as flanking paths and treated properly. Carpets may be used where impact noise due to falling of objects are expected in large scale.

ACOUSTICAL CONSIDERATIONS OF STUDIOS

Studios and broadcasting stations should have perfect acoustical environment. Hence it requires special precautions.

1. The noise level should be brought down to 20-30 dB
2. Echoes should be completely eliminated
3. Outside surface of the recording room should be treated with sound reflecting materials
4. The walls and partition walls should be rigid to avoid resonance
5. Inside surface should be treated with absorbing materials, probably with provisions to change the degree of absorption.
6. Provisions of windows should be minimized
7. The entry to the recording room should be through two doors opening one by one so

that possibility of external noise entering the room will be the minimum as at least one door will be in closed position mostly.

8. When more than one studio are functioning, it is better to locate them in the same floor
9. Heavy acoustical curtains with provisions for adjustments may be used to achieve the optimum reverberation required for different programmes.
10. Hinged panels (one side absorptive and the other side reflective) in walls and rotatable cylinders in ceilings shall be used to make changes in the amount of absorption required.

Types of sound absorbents

Absorbents are special materials used to increase the absorption of sound. Typical sound absorbing materials will have a loose structure due to which the sound energy will be lost in their pores. Based on the ways it is applied, it can be classified into:

A) Porous Absorbents

Here the absorption (conversion to heat) takes place due to the friction between the porous walls and the sound waves.

1) Pre-cast acoustical boards or tiles which are manufactured in factory, brought to the site and fixed to the existing wall and ceilings. Since they are factory made products, they provide uniform absorption throughout. The required absorption can be precisely achieved by using these types of factory made products.
   Compressed cane or fiber board/Tiles (perforated or non-perforated), Wood particle boards/Tiles, Mineral/compressed glass wool tiles etc are the examples.
2) Acoustic plasters: These are applied in-situ. This includes granulated sound insulation materials with cement or fibrous materials combined with a binding agent. Normally these plasters are sprayed on to the walls with blowers or air-guns. The effectiveness largely depends on the skill of the worker. It is comparatively cheap. It is suited for corridors etc.
3) Acoustical blankets: Materials used most commonly in fabrication of acoustical blankets are mineral wools, hair felt, wood fibre and glass fibre. Generally the thickness varies from 2.5 cm to 10 cm. Increasing the thickness will increase the sound absorption in the lower frequency range. Absorption of higher frequency waves increases only marginally with thickness. These types of absorbents are very effective where a balanced absorption is required, e.g. for recording studios.

B) Resonant panel Absorbents.

These are semi-hard materials on wooden frames with air-gap. When sound waves strike these panels, vibrations takes place and absorption takes place mainly due to damping.

C) Cavity resonators.

These are containers with small openings. Resonance of air in these containers dampens the sound. They are ideally suited to absorb sound from air-conditioners and individual machines.

D) **Composite type absorbents**.

This is basically a combination of different types of absorbers described above. Composite units of hardboard backed by perforated fibre board. Composite units of perforated board backed by mineral or glass wool quilt. Special absorbers constructed of hard board, teak ply etc backed by air.

The acoustical materials used should have adequate fire resistance, should have good appearance, sufficient strength and resistance to abrasion, should be easy to handle, should economical and also should have only minimum maintenance cost, should not lead to any health problems.

MODULE 2

NATURAL LIGHTING AND ARTIFICIAL LIGHTING

NATURAL LIGHTING

Natural lighting refers to the light that comes from the Sun. **Artificial lighting** is used to produce light when the Sun goes down, e.g. electric lights, candles and lamps.

Filament Lamps:

• The filament lamp consists of a **tungsten** filament that is enclosed in a glass envelope (the bulb).

• When an electric current flows through some metals, it heats the metal and the metal becomes hot enough to glow white. Tungsten is used for the filaments in lamps because it can be heated to high temperatures without melting.

• The filament is usually in the form of a coil because coiling reduces heat loss.

• The air is taken out of the glass envelope (bulb) and a small quantity of an **inert gas** is placed in the bulb.

• At high temperatures evaporation of the metal takes place, particles of tungsten are released from the coil and condense on the inside of the bulb. This gradually darkens the bulb.

• Placing the inert gas inside the bulb slows down the rate of evaporation of the tungsten.

Fluorescent Lamps: When ultra-violet (UV) light falls on certain materials, they glow brilliantly and this is the principle used in the fluorescent tube.

• A fluorescent lamp consists of a **cylindrical glass tube** with **electrodes** at both ends.

• **Mercury vapour**, at a low pressure, is inside the glass tube.

• When an electric current is passed through the Mercury vapour, it emits a bluish light as well as UV radiation.

• The inside of the bulb is coated with a phosphor powder and when UV light hits this coating, it is absorbed and visible light is emitted.

A comparison of the two lamps:

The fluorescent lamp is **more efficient** than the filament lamp. Although the initial cost of a florescent lamp is more than that for a filament lamp, its energy use is more efficient.

Unlike the filament lamp, the fluorescent lamp does not waste a lot of electrical energy as heat. Fluorescent lamps are preferred to filament lamps in many situations, because they give a light that is **similar to daylight.**

The fluorescent lamp's bulb is long and extended, and **does not cast sharp shadows** as filament lamps do.

Lighting is very important in the home and in the workplace. If you are working in poor lighting accidents can occur e.g hammering a nail in the dark may result in damage to your finger. Reading in poor lighting can adversely affect you vision.

White light and colours

White light consists of a mixture of colours. If you put a **prism** in the path of white light you will see a mixture of colours which is known as the **visible spectrum**. This process by which white light is separated into its colours is called **dispersion.** The colours of the spectrum are: **Red Orange Yellow Green Blue Indigo Violet**

The **colour** of an object depends on:

1. The colour of the light falling on it and
2. The colour it transmits or reflects.

The colour that we see when light shines on an object is the colour of the light that is reflected from the surface of the object. All the other colours are absorbed by the object and are therefore not visible.

An object appears white if it reflects all the light that falls on it. An object appears black if it absorbs all the light that falls on it.

The speed of light is slower in various materials than it is in a vacuum or outer space.

When the light passes into a material at an angle, the light beam is bent or **refracted** according to Snell's Law and the index of refraction of the material. But also, the speed of light through a material varies slightly with the wavelength or frequency of the light.

Thus, each wavelength is refracted at a slightly different angle when passing through a material at an angle. This spreading out of the beam of light is called **dispersion.**

The velocity of light in a material--and thus its index of refraction--depends on the wavelength of the light. In general, the index of refraction is greater for shorter wavelengths. This causes light inside materials to be refracted by different amounts according to the wavelength or color.

Sunlight is often called white light, since it is a combination of all the visible colors. Since the index of refraction is different for each color, the angle of refraction will be different for each color when the light passes from air into glass or other transparent material. ***If the material is shaped like a prism, the angles for each color will be exaggerated, and the colors will be displayed as a spectrum of light.***

When colours of the visible spectrum are recombined using a second prism, or a lens, white light is produced.

Primary colours

Red, blue and green are called **primary colours**, because adding various amounts of these colours produces any other colour in the visible spectrum.

• Red and blue give magenta (purple).

• Green and red give yellow

• Blue and green give cyan (blue-green)

The colours produced by combining any two primary colours are called **secondary colours**. Magenta, yellow and cyan are secondary colours.

The diagram above shows what happens when you add together combinations of the primary colours.

Blue + Green = Cyan Red + Green = Yellow Red + Blue = Magenta.

If you add the three primary colours together you would get WHITE as shown in the center of the diagram.

Pigments

The three basic, primary colours of pigments are magenta, yellow and cyan. The secondary colours of pigments are red, blue and green.

• Yellow and magenta give blue.

• Magenta and cyan give red.

• Yellow and cyan give green.

• Adding all three primary pigments together gives BLACK.

Applications of colour mixing

1. **Printing:** To print a colour picture, four printing plates are produced to give different sets of dots. To reproduce a colour picture the paper is printed with a yellow plate followed by a red plate, followed by a blue plate and finally by a black plate. The mixing of the four colours produces a coloured picture. If you examine a colour picture in a magazine with a magnifying glass, you willl see that the overlapping dots of the three colours and black give the appearance of many colours.

2. **Painting:** A person can obtain a particular colour of paint for a house or car by using the principles of colour mixing.

3. **Colour television**.

4. **Stage lighting**: To produce different colour effects on stage, filters are used. Combining lights covered with filters produces many coloured scenes.

5. Photography.

6. **Dyeing**.

ARTIFICIAL LIGHTING

The components of the visual environment

The goal of lighting is to make the environment visible, the visual environment is a visible environment. The aim of lighting is to create an adequate visual environment.

The internal visual environment comes into being by illuminating a room. Thus, there are two components of the visual environment - one is a usually furnished room with surfaces reflecting light to a greater or lesser extent , - this is a basically passive component- and - the other is light, which (as an active component) makes the room visible.

The surfaces of the interior can be characterized by their reflectance, while the use of light can be described by the illuminance of the surfaces.

LIGHT AND ITS QUALITY

Light is the visible part of the electromagnetic spectrum between the wavelengths of l = 380- 780 nm. Its symbol is Φ**e**, its unit is Watt [**W**]

Each wavelength corresponds to a given colour as shown in the following figure. Colours at shorter wavelengths are called cool (colours like purple and blue), colours at longer wavelengths are called warm colours (like orange and red).

We use so called **white light** for lighting, as the natural light that human vision developed by was white light, too.

It is a peculiarity of white light that it contains radiation at every wavelength of the visible range, and that the intensity of radiation at the different wavelengths vary to a certain extent. Thus, white light may vary. White lights differ from each other in colour combination, so white lights may differ in quality.

The **quality of white light** can be characterized with its spectral distribution.

There are two aspects of the quality of light that are important in practice.

The quality of white lights may differ because they may contain consecutive colours in varying ratios. The quality of a white light can be characterized in practice from this point of view with the help of **colour temperature.** The c*olour temperature of a given* *light is the temperature of the black body, at which the spectral distribution of its radiation is nearly the same as that of the given light,*

A lower colour temperature means warmer light, a higher colour temperature indicates cooler light. The ratio of red is higher in warm light, while the ratio of blue is higher in cool light.

The colour temperature of the incandescent lamp shown in Figure 0.2 is 2 900 K.

The quality of white light may also vary according to how much the colour of the surfaces illuminated by the light appear to be different when illuminated by artificial light compared to the colour they appear to be when illuminated by natural light.

From this point of view, the quality of white light can be given with the help of **colour rendering**. The better the colour rendering of a white light, the less difference the colour of the surface shows when illuminated by it and by natural light.

The degree of colour rendering can be given with the help of the colour rendering index in %, whose symbol is Ra . Ra = 100 % when colour rendering is perfect.

THE QUALITIES OF SURFACES

The reflection of surfaces can be characterized in an exact way by the reflection factor expressed as a function of wavelength $\rho(\lambda)$.

Surfaces can be classified into two groups:

1. The group of non-coloured surfaces. It is typical of these surfaces that they reflect nearly the same portion of light at every wavelength as shown in the following figure.

When illuminated with white light, that is to say with a light containing all the colours in nearly the same proportion, these surfaces seem white, black or various shades of grey.

2. The other is the group of coloured surfaces. It is typical of these surfaces that their reflection varies greatly at different wavelengths.

As wavelengths correspond to colours, the above surfaces seem to be the colour at whose range their reflection is dominant when illuminated with white light. It is essential to note that the colour of a given surface is not an inherent quality, existing independently of everything, but it is a quality affected by both the characteristics of the surface and the quality of the light that illuminates it. Consequently, what colour a surface seems to be depends on the colour distribution - the quality - of the illuminating light as well.

Still, people attribute natural colours to materials. Those are the colours the materials have by natural lighting. As natural light is a white light, and its quality may vary, people associate many different natural colours with a given material.

The colour of a surface is the perception generated by the spectral distribution of the light reflected from it $\Phi\rho(\lambda)$. It depends on the reflection factor of the surface as a function of wavelength - $\rho(\lambda)$ - and on the spectral distribution of the illuminating light - $\Phi\mathbf{i}(\lambda)$ – as illustrated by the following equation $\Phi\rho(\lambda) = \rho(\lambda) * \Phi\mathbf{i}(\lambda)$

The colour of a given surface may vary. The colours associated to surfaces (materials) in our minds are the colours that they seem to have by natural lighting, so - grass is green, as natural light contains all the colours, including green, grass reflects the green part of the light, and absorbs the rest of the light. The same grass is practically black if it is illuminated with red light. - milk is white, as it reflects every part of the natural light in nearly equal measure, so the reflected light is white light. When milk is illuminated with red light, it reflects only red light, and it looks red.

The spectral distribution of natural light is always changing, the ***components*** of direct sunlight, of the light of an overcast sky, that of a clear or partly cloudy sky are different, and different colours are present in these lights to differing degrees. As a result, different natural colours are associated with the surfaces and materials of the environment. We consider grass green by different sky conditions, whether the sun shines or not.

THE CHARACTERISTICS OF THE VISUAL ENVIRONMENT

We see the elements of our environment as having some colour and brightness. The brightness of a surface is the so called **L luminance.** The lighter the surface, the greater its luminance is. In a word, it is the luminance and the colour of certain elements of the surfaces we perceive. The greater the reflection (ρ) and the illuminance (**E**) of a surface is, the lighter it is, in other words

$\mathbf{L} = \rho * \mathbf{E}$

The visual environment is the spatially arranged surface elements of our field of view, that is

Σ ρ * **E**

(field of view)

The visual environment is a product of the passive environment (ρ) and of active illumination (**E**). The two components are inseparably involved in the result. The brightness of a darker, but better illuminated surface may be the same as the brightness of a dimly illuminated lighter surface. To sum it up, the visual environment is a three dimensional coloured image of the field of view, a spatial arrangement of luminances and colours.

It follows from the fact that the visual environment is a product of the environment and of illumination, that -a good visual environment is a product of a well formed interior and of adequate illumination, -neither a badly formed environment, nor inadequate illumination, can result in a good visual environment.

The goal of lighting is to create an appropriate visual environment. What constitutes an adequate visual environment can vary from case to case.

The visual environment has to meet a double requirement: -on the one hand, we require background information from our environment, we would like to know what is, and what is happening around us. This requirement has to do with the actual field of view.

-on the other hand, we require a more or less accurate picture of a certain part of our environment. This requirement is based on the activity done in the room, and it has to do with the centre of the field of view.

Usually the latter requirement, the requirement to see details clearly is more exacting.

Being able to get exact information on the environment means being able to differentiate the dimensions, luminances, colours and spatial positions of the details.

THE CHARACTERISTICS OF VISION

The visual environment is created for people, therefore its peculiarities have to be taken into account when forming it. From the point of view of lighting, the following qualities of human vision have to be taken into account :

1. Human eyes can see nearly a hemisphere, but only a relatively small part of it, in the axis of the field of view, is perceived exactly.

2. We can see colours only in light environments. If it is dark, we can only see the environment in black and white.

3. The sensitivity of the human eye depends on the wavelength (colour) of the perceived light as shown in the figure of **V**λ(λ).

If the intensity of the radiation reaching the eye is the same at every wavelength, we perceive as the lightest colour - the yellow-green colour at 555 nm in a light environment, - the blue-green colour of 505 nm in a dark environment.

The name of **V**λ(λ) is the curve of spectral luminous efficacy.

It follows from the above, that light seen by the eyes, as a physical effect, is not the same as the **luminous flux,** the sense of light.

The luminous flux is the part of radiant light that produces a visual impression, its symbol is Φ, its unit is lumen [**lm**].

Although only the term of "luminous flux" should be used, the term "light" is often used carelessly in everyday practice.

4. The human eye can adapt its sensitivity to light. This process is called adaptation. Different levels of adaptation correspond to environments lit to various degrees.

The adaptability of vision does not mean we are able to see equally well in every environment.

Our vision is better in brighter environments than in darker environments.

When the environment changes, when it gets brighter or darker, our vision has to adapt to it, which takes time. The time required for full adaptation is nearly one hour.

5. We are able to see clearly objects at various distances. This quality of vision is called accommodation.

6. We perceive the ratios of brightness logarithmically. Consequently, - relatively unevenly illuminated homogeneous surfaces seem to be of nearly the same brightness, - nearly evenly illuminated, non-homogeneous surfaces seem more homogeneous, - in order for a surface to be twice as bright as another, the ratio of their brightness has to be 1:10.

THE VISUAL TASK AND THE VISUAL ENVIRONMENT

When forming an adequate visual environment, two essential questions have to be answered:.

1. What constitutes an adequate visual environment in the given circumstances?
2. How can the visual environment be made adequate?

The question of "What constitutes an adequate visual environment in the given circumstances? " can be answered on the basis of the characteristics of vision and on those of the visual task originating from the activity performed in the interior.

A given visual task requires a certain visual ability. Visual ability is the accuracy and speed of visual processing.

The measurable parameters of visual ability are the following:

- visual accuracy,
- contrast sensitivity and
- speed.

Visual accuracy is the reciprocal of the minimum angle α**min**, at which two points can be differentiated from each other.

Contrast sensitivity is the reciprocal of the minimum contrast **Cmin** that can be perceived.

Speed is the speed of visual processing.

Visual ability is affected by the visual environment. The visual environment is characterized by its average luminance. The conditions of a well-defined visual ability are a product of a certain level of average luminance of the visual environment. In order to achieve the desired visual ability, the visual environment, as a possible field of view, has to have a certain level of average luminance.

The relationship between the characteristics of visual ability and the average luminance of the field of view is illustrated by the following figure.

In any visual task, the size of the part of the object to be seen as well as the distance between the object and the viewer defines a minimum angle of α*. That is the minuteness of detail we have to see the object with in order to get adequate information. The visual environment has to provide visual accuracy appropriate for 1/ α*.

Contrast C* between the brightness of an object and its surroundings defines a contrast sensitivity of 1/C*, which is required in a given visual task in order to get the correct visual information.

The above two parameters (1/α*and 1/C*) determine the minimum visual ability for a given task.

As the above figure shows, the average luminance of the field of view has to be a L* that is larger than both Lα* and Lc*.

How can the visual environment be changed to achieve an adequate L*, as the average luminance of the field of view?

As the luminance of a surface is the product of the reflection factor (ρ) and the illuminance (**E**) of the surface , i.e. **L = ρ * E** the luminance of certain elements of the field of view can be changed either by changing the reflectance of the surfaces, or by changing their illuminance. Lighter surfaces and higher illuminances equally result in better visual ability, that is to say, they enable us to perceive smaller details and smaller contrasts.

Moreover, it follows from the above equation that there are two ways of changing visual ability and/or the visual environment:

- one is changing the ρ reflectance of the surfaces architecturally,
- the other is changing the illuminance E by means of lighting engineering.

The interior space is usually given prior to designing its lighting system. Consequently, it is the duty of lighting to provide an adequate visual environment (visual ability - average luminance of field of view) for a given activity or visual task.

In order to provide the surfaces of a room with adequate illuminance, it is necessary to "put" enough light into the room. The amount of luminous flux generated and distributed in the interior has to be sufficient to illuminate certain surfaces to the required degree.

LIGHT SOURCES

Light sources are instruments of producing light. Light sources are technical devices which convert usually electric energy into radiation - partly to light.

Based on the way they work, light sources are divided into two types of lamps:

- incandescent, and
- luminescent.

In incandescent lamps, light is produced by the radiation of a filament at high temperature.

The spectrum of the light generated in this way contains radiation at every wavelength and its spectrum is monotonous. A considerable amount of heat is generated at the same time as light.

Incandescent lamps used in practice are

- filament incandescent lamps,
- tungsten halogen lamps for mains voltage, and
- low voltage tungsten halogen reflector lamps.

In luminescent lamps light is generated by excited electrons. An electric arc excites light in a socalled arc tube or on the surface of the envelope, as the case may be.

The spectrum of the light generated this way is not necessarily continuous, radiation is much larger in certain narrow bands than in others, and the spectrum is not monotonous. Luminescent lamp used in practice are

- fluorescent lamps,
- compact fluorescent lamps,
- mercury lamps,
- mercury tungsten blended lamps,
- metal halide lamps, and
- high pressure sodium lamps.

From the point of view of their practical use, light sources can be characterized by their:

- construction and operation, and their
- technical data:

rated voltage: is the voltage that the base of the lamp can be connected to for normal operation. In incandescent and main voltage tungsten halogen lamps, it is the same as the rated voltage of the building's network, in other cases it may be different.

nominal input: is the electric power consumed by the lamp alone under rated circumstances. If auxiliaries are needed for the operation of the lamp, the input of the light source - auxiliary unit is larger than that of the lamp alone.

type of base: the type of technical design by which the lamp is connected to the electric network.

MODULE 3

THERMAL COMFORT

INTRODUCTION

Are you comfortable? When your state of mind and physical body are at ease, i.e., with the body heat generation in equilibrium with the heat loss to the surroundings, you would likely feel comfortable; is the technology for providing occupant thermal comfort, sheltering one from the unpleasant outdoor environment. Or, more correctly, HVAC is meant to ensure denizens thermal comfort in the midst of the highly-fluctuating weather. As it focuses on supplying and maintaining an indoor environment that is thermally comfortable to the occupants, indoor temperature and humidity are two deciding parameters that need to be regulated.

Almost universally, the comfortable indoor temperature falls between 20°C and 25°C, with a corresponding relative humidity in the range of 40–60%. Depending on many other determinants, these ranges of conditions furnish the befitting heat sink for removing the right quantity of heat per unit time from our body, maintaining it comfortably at 37°C. Other than temperature and humidity, some minimum air movement is needed for appropriate heat convection and for supplying adequate fresh air to the occupant.

Furthermore, lighting and backdrop, including background melody and scenery, etc., are also necessary to sooth the soul.

Historically, the quest for more comfortable living near the North Pole can be clearly seen from the ingenious creation of Igloos from snow by the indigenous inhabitants.

The very representation of coldness, snow, is surprisingly an excellent insulator. Therefore, there is a certain amount of truth in the Chinese proverb, "fighting poison with poison." The parallel saying in North America is "fighting fire with fire." In heating, ventilation, and air conditioning (HVAC) context, the indigenous people fight cold with cold, or, more correctly, snow. Igloos not only resist the outdoor coldness from penetrating indoors via conduction but also retain the occupant-generated heat indoors. The highly-reflective snow also keeps radiation heat transfer in check. Moreover, the design of the igloo is such that the portal is positioned away from the prevailing wind and, hence, minimizes convection heat loss. In short, an igloo keeps out the wind, the snow, and the cold. It keeps you warm.

Other than the igloo that is built from naturally-available snow near the North Pole, inhabitants farther away from the poles have traditionally resorted to fireplaces to beat the long, cold winter. Closer to the equator, on the other hand, trying to stay cool has been a more important striving. It is interesting to note that the first air conditioning units operated by passing warm air over an array of ice blocks.

The energy (oil) crisis of the 1970s led to the emerging of well-sealed and highly insulated buildings, especially in North America. Later in the 1980s, the indoor air quality (IAQ) became a concern. Consequently, minimum air exchange between the indoor stale air and outdoor fresh air came into place. For larger buildings, this is ensured via central air distribution systems, with or without cooling or heating capability. It is interesting to note that we are yet to figure out exactly what is needed for a healthy indoor environment, namely, the value of the minimum required air exchange is still being debated and altered every now and then. Nonetheless, the rule of thumb is approximately 0.5 ACH1 (air change hour).

Undoubtedly, ASHRAE (the American Society of Heating, Refrigerating and Air Conditioning Engineers) is all over the map on HVAC and/or thermal comfort.

Recently, ASHRAE, having been a global, beyond just American, professional association for many years since its inception, is trying to dissociate itself from the original terms making up the acronym. Along this effort to make the first letter of the acronym, A, not signifying American, ASHRAE is thus declared to stand for nothing.

Even though ASHRAE no longer stands for the American Society of Heating, Refrigerating and Air Conditioning, its mandate, nevertheless, remains at advancing heating, ventilation, air conditioning, and refrigeration, and, if the author may add, for human thermal comfort. Concerning the establishment of ASHRAE, the following milestones are worth highlighting.

1894 Hugh J. Barron founded the American Society of Heating and Ventilating Engineers (ASHVE).

1904 Refrigeration engineers formed the American Society of Refrigeration Engineers (ASRE).

1954 ASHVE and ASRE merged to become ASHRAE.

Among others, also founded was ARI (the Air conditioning and Refrigeration Institute). ARI is a national trade association representing manufacturers of over 90% of United-States-produced central air conditioning and commercial refrigeration equipment.

Back to the question of thermal comfort, conventionally, predicted mean vote (PMV) index has been employed to predict the mean response of occupants according to the ASHRAE thermal sensation scale Keep in mind that the neutral or comfortable PMV value of zero falls around the neighborhood of 22°C and 50% relative humidity. The word "predicted" here relates to the large number (more than one thousand) of "guinea pigs," originally all college students, who participated in climate chamber experiments, from which statistical votes were deduced to represent the general population at large.

Deviations from 1ACH signifies the air change rate, i.e., the rate of replacing the indoor air with outdoor air, in terms of volume of the building of interest per unit hour.

Temperature, humidity, occupant activity level, local air flow, radiation, and clothing are key influential parameters affecting PMV either side of the neutral comfortable condition (temperature) are predicted to lead to a progressively larger percentage of the population being dissatisfied. This is illustrated in Fig. 1.5 in terms of predicted percentage of dissatisfied (PPD) versus PMV, where 100% of the population is predicted to be dissatisfied when it is too cold or too hot. As expected, it is impossible to satisfy every person with one comfortable setting. Admittedly, this, in part, is because of some amount of variation in personal physiology; certain people are more "warm-blooded" or "hot," whereas some tend to be "cold-blooded" or "cool." To irritate everybody, on the other hand, is very doable. Pushing the thermostat setting adequate up or down will aggravate the entire population. This can be seen in Fig. 1.5, which indicates that the PPD quickly approaches 100 when it is very cold or very hot.

It should be mentioned that there has been a surge of newer publications of thermal comfort assessments in recent years. Cheung et al. [2019] found that the accuracy of PMV-PPD, when applied to the entire population in the ASHRAE Global Thermal Comfort Database II is only 34%, as compared to 43% accurate when relating occupant's thermal sensation (satisfaction) to the air temperature alone. This is somewhat perplexing because four environmental parameters, air temperature, mean radiant temperature, relative humidity, and air speed, and two personal parameters, metabolic rate and clothing insulation, are involved in PMV.

One key reason why the PMV-PPD approach failed to provide a better prediction is this classical study conducted by Fanger [1970] was based on a group of participants who were all college students from a temperate climate. The ASHRAE Global Thermal Comfort Database II [Földváry Ličina et al., 2018], on the other hand, consists of a much more diverse and significantly bigger data set that crosses age, culture, climate, etc. For instance, an older person who has spent his entire life in a hot and humid tropical climate will likely feel more comfortable in a warmer and more humid environment surrounded by vegetation than a youngster from a frigid climate/zone who enjoys playing in the snow. Also worth mentioning is that the range of participant activities covered in Fanger's experiment is quite limited. Wang and Hu [2018] found that people start to sweat while undergoing moderate activities, and their mean thermal sensation vote tends to increase.

In other words, the level of physical, mental, and spiritual activities can noticeably alter the thermal comfort settings.

There is definitely some weighty amount of art and subjectivity, within the science of thermal comfort. To cite but one example is the debate disclosed by Chappells and Shove [2005], which eludes to the notion that thermal comfort is a highly negotiable social–cultural construct. An analogous everyday example is buffet. It is an universal challenge to not overeat at a buffet, where we are tempted with all the food choices. On the other hand, a healthy banquet has the set amount of food, and in general, we are more satisfied after a quantity-controlled banquet than a buffet.

In the same token, we can alter the unsustainable trajectories of the need and technologies associated with thermal comfort into sustainable ones. Adaptive thermal comfort [Carlucci et al., 2018] is one probable undertaking along the path to more sustainable HVAC.

The role of an hvac&r engineer

What does an HVAC&R engineer do? Being compensated for solving heating and cooling problems may be a short answer. The air conditioning fable given by Pita

[1998] is timely. Here is a paraphrase: On a record-breaking summer day, the air conditioning system in a skyscraper stopped functioning, turning the offices into steam saunas. Without operable windows, computers began to break down, office workers started to leave, and tenants threatened lawsuits for damages. Not knowing what to do, the managerial team became frantic. Just when the world seemed to collapse on them, someone shouted, “There is this HVAC wizard going by the name Rupp just a block away.” In desperation, they called Rupp. Within minutes, Rupp showed up and briefly examined the complex 7000-ton HVAC system and muttered, “Hmm.” He took out a small wrench and tapped a valve. Immediately the system started running and soon thermal comfort was restored. The building manager thanked Rupp and asked him how much he owed him. “$3705,” Rupp responded. “Are you nuts?” the manager shrieked, “$3705 for beating up a valve?” “The tapping costs only $5,” Rupp responded, “The $3700 is for knowing which valve to tap.”Folio:8

Returning to the question concerning the role of HVAC engineers, in general, the tasks of HVAC engineers are to calculate the demands for heating, cooling, and ventilation; to choose the necessary equipment and controls; and to ensure that the components are correctly integrated into the building. As mentioned earlier, thermal comfort depends on:

Temperature. Both dry-bulb and mean-radiant temperatures are important. The dry-bulb temperature more-or-less dictates the convection heat transfer between our body and the surrounding air. On the other hand, our skin and the outer surface of our clothing exchange heat with the ambient surfaces via radiation.

Humidity. A relative humidity in the ballpark of 50% is a good guideline.

Air Motion. Near-stagnant air is never a comfortable environment. Respiration, body odor diffusion, burping, and tooting are all healthy bodily functions. Some of these may amplify when our body endeavors to adjust to become more comfortable with its environment. Some minimum air movement is needed to convect and diffuse these chemicals to ensure proper functioning of our mind.

Air borne Contaminants. Both gaseous species and particulate need to be kept in check. The many happenings indoor such as the usage of a multitude of beauty sprays can adversely impact the IAQ.

State of Mind. Individuals such as the spiritual gurus and world-class magicians can control their mind to a large extent. The lowering of their heart beat leads to reduced metabolism followed by heat generation, and hence, thermal comfort condition. Some magicians can convince their mind that they are on a warm sunny beach when they are enclosed in ice.

The HVAC design process involves basically iterating the following steps:

Calculation of peak loads.

Specification of equipment and system configuration.

Calculation of annual performance.

Calculation of costs.

Why Do We Bother with this Low-Tech Field of HVAC&R?

The human species is not very adaptive, and the situation may be getting progressively worse, especially with the progressive entitlement mentality along with climate change. We need individual air-conditioning adjustment units even when we travel over short distances in a minivan! It cannot just be 21°C with a little breeze for everybody anymore. On the flip side, depending on the day and the mood of the person, a regular sauna visitor could be the very one who insists on a comfortable temperature of no more than 18°C with 70% or higher relative humidity! The bottom line is that HVAC&R is everywhere!

One can get a sense of the ever-importance of this field from the review on human thermal comfort in the built environment by Rupp et al. [2015]. Keep in mind that globally more than 40% of total building energy is spent in thermal comfort, i.e., totally some 49,000 PJ in 2016 [IEA, 2017]. This ratio and more so, the absolute quantity, will escalate as developing countries advance into widespread indoor thermal comfort engineering. In addition, climate change is expected to add a heavy load to the cooling demand.

THERMAL DESIGN OF BUILDINGS

Thermal balance definition

Thermal balance occurs when the sum of all the different types of heat flow into and out of a building is zero. That is, the building is losing as much heat as it gains so it can be said to be in equilibrium.

To establish the thermal balance, we need to identify the different sources of heat losses and gains, in order to sum them up in an equation:

Qi + Qc + Qs + Qv + Qe = change in heat stored in the building, nil if thermal balance exists, where

Qi = internal heat gain or loss resulting from internal heating or cooling sources = primary heating/cooling (active heating, air-conditioning) + secondary heating/cooling (people, appliances…)

Qc = conduction heat gain or loss when outside or inside heat flows through the envelope

Qs = solar heat gain when additional heat is provided by solar radiation

Qv = ventilation heat gain or loss when outside air enters the building

Qe = evaporative heat loss when water is changed into vapor (typically if you have a pond in your building to help cool it down)

This equilibrium actually strongly depends on the season and is usually assessed for a whole year to be statistically valid.

Application to design project

For your design project it will be assessed only for a given period: beginning of March and over a representative period of 24 hours considered as a sequence of 4 separate time intervals:

- morning conditions
- mid-day conditions
- afternoon conditions
- evening and night conditions (no solar irradiation, no appliances running, no one in the building (except if residential housing)).

For each of these 4 periods, we will consider the conditions as steady-state i.e. both indoor and outdoor conditions fixed to reasonable average values for this time of the year and this location.

Therefore, you will have to determine reasonable indoor and outdoor temperatures, solar irradiation values (for each façade and accounting for obstructions) etc for each of these 4 periods and keep these as fixed parameters.

Typically, we will be in a heating period i.e. it will be colder outside than inside, therefore Qi will be positive, Qc negative, Qs positive (always), Qv negative and Qe negative (always).

The idea in your design project will be to determine the active heating or cooling requirements knowing what is gained and lost passively, i.e. determine the "primary heating" component in the Qi term that will make the sum equal 0.

Practically, you will have to identify and assess the different sources of heat gains and losses, using the heat transfer and ventilation equations we have studied, the tables and data sheets provided in your textbook or found in literature, and the information you found on your particular building from various resources.

More specifically, you will, for each of the 4 time periods:

- for Qi: estimate the heat input provided by the average number of people living in the building (depending on what they do there), and the appliances (computers, …) and lights (depending on the type of luminaires), knowing the indoor temperature and humidity
- for Qc: knowing the materials that make up the building envelope and the windows (wall layers, frame and glazing), estimate the heat transfer to get a total heat loss accounting for each one's area and the temperature difference between the inside and outside of these walls/windows
- for Qs: knowing the orientation of the different façades and, roughly, the obstructions created by the surroundings (and a sun course chart to determine the impact of these obstructions on the actual irradiation1 as well as the time periods they will mostly affect), estimate a reasonable value for solar irradiation and, knowing what the windows are made of, the solar heat gain we get through these windows

- for Qv: knowing the volumes involved and the recommended air renewal rates, maybe also accounting for air leaks or wind conditions if relevant, estimate the heat losses due to air movement
- for Qe: as you probably don’t have enough information about the building to assess the heat loss due to evaporation, we will just neglect this term

Once you have an approximate value for all these terms, you will be able to estimate the heating requirements for the building you have chosen.

Don’t worry if you cannot get precise numbers. Once more, what counts is only to have the right order of magnitude and to base your conclusions on correct suppositions and method.

DESIGN APPROACHES

Introduction

The constant and increasing environmental degradation, along with the consequent potential hazards, is listed among the most serious and urgent problems humanity has to deal with. The environmental problem, caused by, among other things, large-scale industrial activities, is related to the consumption of conventional energy sources. This consumption, already too large to be covered by the existing conventional sources, is constantly growing, since the needs for energy keeps multiplying. What seems to be the answer to this rather crucial challenge is the use of renewable energy sources, such as solar, wind and geothermal energy, in combination with the rationalized use of conventional energy sources, especially in those domains of human activity where large amounts of energy are demanded. One of these domains is the built environment, in a broader sense this includes the building industry, building operation and maintenance etc. The renewable energy source that has been widely used in the building sector is the sun. The use of solar energy has always been a challenge for architects and engineers. The use of sunlight for lighting the interior spaces of a building and for provided heat by solar energy for warming them has been an objective towards the fulfillment of which many techniques have been applied. The selection of window area of a façade taking into account the orientation of this façade, the application of the principles of bioclimatic architecture and the use of passive solar systems are some indicative examples (Kontoleon et al. [15]). During recent decades, the development of photovoltaic technology has led to the possibility of the direct use of solar energy for the production of electricity. A photovoltaic conversion attempts to directly transform all photon energy in light into electricity by taking advantage of the intrinsic photo-effect. Photovoltaic elements can either be building integrated (façade or roof integrated) or not. They can produce large amounts of electricity.

Their output depends on various parameters such as temperature, solar radiation on site, effective area (m2), shadowing etc. Generally, large-scale, effective use of photovoltaic technology could cover a large part of the world's energy demand.

As a new design concept, ecological building has been emphasized all over the world, and it has become an important subject in the building field. It is the end-result for the ecological building to sufficiently use natural energy such as solar energy, wind energy, and the like, which will lead to the reduction of the dissipation of fossil energy. Solar energy systems therefore have an important role to play. The way solar systems are used is different from what it used to be, however. Buildings are no longer designed to use just passive solar systems or active ones. As a matter of fact, the words passive and active don't make sense any more, as the newer ecological buildings combine several of these technologies. The quest to achieve a safe and comfortable environment has always been one of the main preoccupations of the human race. In ancient times people used experience gained over many years to make the best use of available resources to achieve adequate living conditions. Florides et al. [15] pointed out that as late as the 1960s though, comfortable house conditions were only for the few. From then onwards central air conditioning systems became common in many countries due to the development of mechanical refrigeration and the rise of the standard of living. The oil crisis of the 1970s stimulated intensive research aimed at reducing energy costs. Also, global warming and ozone depletion and the escalating costs of fossil fuels over the last few years, have forced governments and engineering bodies to re-examine the whole approach to building design and control. As a result, it is of great importance in the building field to reconsider the building structure and exploit the renewable energy systems, which can minimize the energy expenditure and improve thermal comfort. The ecological building concept came into being as an extension of the emphasis on the natural ecosystem balance, and the ecological building concept is the reflection of consanguineous interdependence between the human and the natural environment. As a new design concept, ecological building emphasizes human nature, resource economization, energy conservation and environment protection. By using recycled materials and renewable energy, the sustainable development of living spaces can be achieved. Accordingly, people will live in harmony with the natural environment.

Solar energy is abundant and clean; therefore, it is meaningful to substitute solar energy for conventional energy, which is one of significant characters of ecological building. Solar energy therefore has an important role to play in the building energy system. However, as Hestnes [15] mentioned, the way solar systems are used is different to what it used to be. Buildings are no longer designed to use just passive solar energy systems, such as windows and sunspaces; or active solar systems, such as solar water collectors. In fact, the words passive and active no longer make sense, as the newer buildings combine several of these technologies. They may be energy efficient, solar heated and cooled, and PV powered, i.e. they are simply “solar buildings”. Recently, solar water collectors have undergone a rapid development; they are installed with the main purpose of preheating domestic hot water and/or to cover a fraction of the space heating demand. However, this application mainly for obtaining hot water through solar energy is not very consistent with the order of nature. In winter, it is convenient to combine the hot water system with the space heating system just through increasing the collector area. Whereas, for summer with high solar radiant intensity and high ambient air temperature, the demand for air-conditioning and refrigeration is in preference to hot water, this phenomenon is especially obvious in the south. As has been shown from mass media, the prevalence of air-conditioners has brought great pressure upon energy, electricity and the environment. Consequently, solar-powered air-conditioning system would be a perfect scheme because it not only makes the best use of solar energy, but also converts low-grade energy (solar energy) into high-grade energy for comfort. In addition, it is meaningful for energy conservation and environmental protection. Solar cooling has been shown to be technically feasible. It is a particularly attractive application for solar energy, because of the near coincidence of peak cooling loads with the available solar power. The future development trend is building integration of solar energy systems. Hestnes [15] classified solar cooling systems into three categories namely: solar sorption cooling, solar-related systems and solar-mechanical systems. The former two systems are based upon solar thermal utilization and the latter one utilizes a solar-powered prime mover to drive a conventional air-conditioning system. The solar-powered prime mover can either be a Rankine engine or an electric motor based on the solar photovoltaic principle. Kazmerski [15] reported that the photovoltaic panels have a low field efficiency of about 10–15%, depending on the type of cells used, which results in low overall efficiencies for the system. Wang [15] showed that, at otherwise identical refrigerating output, the solar mechanical systems are 4~5 times more expensive than those powered by solar thermal utilization. Therefore, the majority of solar-powered air-conditioning systems at present are solar sorption and solar related systems based on solar thermal utilization. According to Grassie and Sheridan [15], in most solar cooling systems, hot water driven single-stage lithium bromide absorption chillers are commonly used. Evacuated tubes or other high-grade solar collectors are adopted to provide a hot water temperature of 88–90ºC as a heat source to drive the chiller. Experimental data on the performance of such systems were reported by several researchers, such as Bong et al. [15], Li et al. [15], and the like. Although a large potential market exists for this technology, existing solar cooling systems are not competitive with electricity-driven or gas-fired air conditioning systems. The major problems facing solar absorption cooling systems are its high initial cost, low system performance, and solar energy usage for only a short period during each day of operation. Another potential solar powered air-conditioning system is the solar adsorption cooling system.

Adsorption cooling is the other group of sorption air conditioners that utilizes an agent (the adsorbent) to adsorb the moisture from the air (or dry any other gas or liquid) and then uses the evaporative cooling effect to produce cooling. Solar energy can be used to regenerate the drying agent. Solid adsorbents include silica gels, zeolites, synthetic zeolites, activated aluminas, carbons and syntheticpolymers. Liquid adsorbents can be water, triethylene glycol solutions of lithium chloride and lithium bromide solutions.

Wang [15] suggested that for the mini type solar air-conditioning system, the solar adsorption cooling system may be a better option.

Up to now, the solar-powered adsorption systems have mostly beenintermittent and used only for ice making applications. For applications such as air conditioning, when the chilled water temperature requirement is only around 6–8°C, two or more adsorption beds can be used to produce a cooling effect continuously. Li et al. [15] established a lumped parameter model to investigate the performance of a solar powered air conditioning system driven by simple flat plate solar collectors. As for working pairs, Dieng et al. [15] described that compared with adsorption systems that require heat sources with temperatures above 100°C (zeolite-water systems, activated carbon-methanol systems) and conventional compressor chillers, a silica gel/water adsorption refrigerator useswaste heat at below 100°C, which would be suitable for a wider range of solar thermal collector types. In this paper, a hybrid system of hot water supply, heating, natural ventilation and air conditioning based on solar energy, which was designed for the ecological building of the Shanghai Institute of Architecture Science, was introduced in detail.

INTRODUCING SUN AND ITS RADIATION ENERGY

The earth absorbs a small part of the sun’s energy that is 5 to 10 times more than the fossil energy that exists on earth. Iran is situated in a highly appropriate location so the use of solar systems can be economical.

Sun radiation

When sun radiation passes through the earth’s atmosphere it divides into two different parts: direct radiation and diffusing radiation. The direct radiation is the part of this radiation that reaches earth without any changes and causes special shadows. The diffusing radiation is the part of the radiation that diffuses when it passes through the atmosphere or it changes its direction. We call both direct and diffusion radiation combined the total radiation. Our common units in evaluating radiation, with attention to its primary parts, are calories on one square centimeter for one minute. For radiation calories we use one square centimeter for an hour or a day or a year, a kilowatt on one square centimeter and for the total radiation, a kilowatt on one square centimeter in one hour.

The radiation of the sun occurs with two different wave lengths. The short wave length consists of 3.3 micrometers. The wave length that is important is
2.5–2.9 and it is called infra red.

Solar system

These systems are the ones used for creating human societies. The different solar systems that exist today are given in the following:

1- Photobiology systems: in this system, solar energy is saved by the photosynthesis of plants and with burning and the fuels such as alcohol or metal is regained.

2- Chemical systems: that are divided into two different groups:

a- Photochemical systems that use the sun's radiation in chemical operations.

b- Hilo metric systems that use the sun as a resource of temperature.

3- Photovoltaic systems: this is a process that converts solar energy to electrical energy without using a movable mechanism. The factor that is used in this system is called solar energy. This system is not economical in many ways because of its high price and vast application which are difficult to overcome. However, much research about solar energy is devoted to this subject.

4- Thermal systems: these systems are the most economical and can be divided into the following groups:

a- cooling and heating systems

b- water heating systems

c- cooling and drying systems

d- pumping systems

e- electricity producing systems

f- green space producing systems

ACTIVE AND PASSIVE SOLAR SYSTEMS

Active solar systems are the systems that have the equipment to absorb and use solar energy. This equipment can be determined for different conditions automatically but inactive systems or natural systems are used for designing buildings in a way, which without using mechanical equipment, they cannot use solar energy for cooling and heating inside the building. Examples are solar walls, the solar room and the thermal diode.

The active solar systems

The active solar systems, dependent on the kind of collectors that are used inside, are of different kinds. These collectors divide into three total groups:

1- Centralized gathering

2- Pipe vacuum gathering

3- Flat gathering.

There are two types of gainer:

1- A gainer with fluid air or gas:

Advantages:

- Highly appropriate for warming the house
- The system and the way it works is very easy
- It doesn't need the change phase for heating (we can send hot air through the place directly)
- It doesn't need maintenance
- It doesn't need fluid prediction, and the subjects such as boiling, freezing and change of its properties
- System leakage doesn't cause damage

Problems:

- They are not appropriate for heating water
- Leakage decreases the output. Finding the source of the leakage is difficult
- A large space is needed for the system (unit of compression with the watery systems)
- It needs electrical energy for changing air (in a watery system, we have to install more pumps inside and the amount of electricity also increases)

2- A gainer with fluid water or other liquids:

Advantages:

- Highly appropriate for apartments and multi unit complexes
- System needs less mass for installing

Problems:

- Its design is highly complex
- If a leakage exists, many financial problems occur.

- The necessity for the existence of precautionary actions in order to prevent building, corrosion and freezing
- System needs maintenance

Parts of system

Collectors

The solar collectors are simple means that can be built on the building site or in a factory. The base of their work is to use the sun's radiation for heat absorbing and transforming it by an inter mediator for the diffusion of heat in buildings.

This heat diffusion can be done directly by the collector or by a heat storing unit.

The solar collector with the greenhouse effect gathers the heat and uses it for internal consumption of the building. The sun's radiation passes through the glass and a part of it is absorbed by the absorbing surface that then increases its temperature. With an increase in temperature, the absorbing surface starts to create an electric magnetic wave with a high wave length. However, glass is dark for these waves and doesn't let them pass, so heat is trapped behind the glass and its temperature increases. In this part of the paper, we try to explore the total properties of collectors, paying particular attention to the existing equipment, and some proposals for choosing a system are given.

Absorbing surface

The absorbing surface can be made from any kind of material that can absorb or transmit solar radiation. Usually metal, which has high conductive property, is highly suitable for this purpose. For absorbing much greater heat, a black color is used for covering metals such as copper, aluminum brass and galvanized iron, which have the highest heat conductivity. Therefore, these are the most appropriate materials for the absorbing surface.

Absorbing plate with air fluid

In air heating systems, we should pass air from near the absorbing plate.

One of the simplest absorbing plates is metal lance. In this kind of system the air is passed appropriately through the lances and it heats the absorbing plate, which consists of one galvanized plate, which has a thickness of 0.5 millimeters with some trapezoid grooves on it. They are installed on a thin wood plate. Air is heated by passing this absorbing plate and goes out from the possible exits.

Absorbing plate with liquid fluid

The connection of a heat transition pipe with the absorbing plate is very important (in design f-e-h) and so much attention is necessary for installing the pipes to the absorbing plates in this design. Designs (e-f) can be applied with two different connections. One is a parallel pipe connection and the other is series a connection. Since design (d) of has small diameter pipes that have a great loss of pressure, in this design two mental plates are pressed to each other and the fluid movement system is open inside them.

In design (d) two different metal plates are welded to each other. All the designs (g-h) are the simplest given designs that can be applied for industrial and residential use.

Covering plates

Glass is the commonest. It is transparent against the wave length of 2.9–3 micrometers that is important for solar energy. Some kinds of plastics are also used as a covering plate but we should note that they don't have the same property from the point of view of the greenhouse effect. Two kinds of plastic named Teflon and lemon have properties like glass – lemon having a high resistance against breakage. Although it is more expensive than glass, the use of plastic is highly effective in places that the solar gainers are near to breaking or are damaged.

Angles and the orientation of installation for collectors

The effectiveness of these collectors depends a great deal on the time of the year so that the system can be used for collecting the maximum amount of solar energy. In summer the steeple of the collector should be 10 or 15 degree less and in winter it should be 10 or 15 degrees more than the latitude of the location.

The most appropriate solar azimuth angle is zero degrees, in front of south for the northern hemisphere. However, research shows that the diversion degree doesn't have a great effect when using solar collectors. It is necessary for the plate of the collectors to be changed according to the climate and its orientation.

Different kinds of flat collectors

• Parallel connection – direct return.

• Parallel connection – inverse return.

• The series connection.

Thermal fluid transportation

The necessity for using solar energy is that there is a means for transmitting and distributing energy from the collectors to the saver unit. This action is usually carried out by the gases or liquids as a result of the obligation currency that is caused by the sail in the gas system and pumps in liquid systems. The amount of fluid flow in pipes or channels of the collector should be as much as the gained heat for transmitting. On the other hand, heat, which is absorbed in the plate, increases and reaches the point that the amount of heat loss for the environment is equal to the absorbing heat. The best situation occurs when the atmosphere of this plate is at the minimum amount, which is possible.

THERMO PHYSICAL PROPERTIES OF BUILDING MATERIALS

Introduction

In thermodynamics and building physics, a good knowledge of the main material properties that play a major role in the heat, air and mass (HAM) transports is crucial to conduct proper design, sizing and simulations, and verify experimental measurements.

In this dataset, 7 material properties are collected:

- Density [kg/m3]
- Thermal conductivity [W/m.K]
- Specific heat capacity [J/kg.K]
- Volumetric heat capacity [kJ/m3.K]
- Thermal diffusivity [mm2/s]
- Relative gas diffusivity [-]
- Effective gas permeability [m2]

The dataset focuses on building materials used in the built environment and composing construction elements of buildings and infrastructures. The data entries are grouped into 17 distinct material categories:

- Insulating vacuum panel (although not being a material category per se)
- Aerogel
- Bio-based insulation

• Mineral insulation
• Polymer insulation
• Cellular glass/mineral
• Textile
• Paper / cardboard
• Wood
• Plastic/polymer
• Plaster
• Ceramic
• Structural material
• Natural stone
• Soil
• Metal
• Carbon structure
• Fiber/particle composite

Except if stated otherwise in the name of the material, the reported properties of the materials are assumed to be for ambient (room) temperature (10 °C−40 °C), with normal conditions of pressure (atmospheric pressure) and relative humidity of around 50%. One should keep in mind that the thermo-physical properties of materials (especially porous materials) can be highly dependent on temperature and humidity.

Density Dependency of Many Building Material Properties

Many building materials are porous to some extent, meaning that they contain a certain fraction of pores that can be filled with dry or humid air (or other gases) or liquid water. The fraction of pores relative to the solid phase of the material and whether these pores are filled with dry air, humid air or liquid water can thus largely influence the density of the material but also its thermal conductivity, volumetric heat capacity, thermal diffusivity, relative gas diffusivity and effective gas permeability.

There is a strong correlation between the density and thermal properties of porous materials such as thermal conductivity (bulk metals and ceramics are not porous and thus do not present such a trend). The thermal conductivity of porous building materials is mainly determined by the solid phase fraction/porosity (and thus density), and the air and water content of these pores. Higher porosity materials (lower density) with air-filled cavities have fewer and smaller solid-phase bridges that conduct heat better than air/gas, and many air/gas-filled cavities with low thermal conductivity. This drives the overall effective thermal conductivity of the porous material down. If the conductive solid-phase fraction is larger, the density and the thermal conductivity tend to increase. If the cavities of the materials are filled with liquid water, the overall humidity content of the material increases together with its density (because liquid water is much denser than air/gas) and its thermal conductivity (because liquid water is much more conductive than air/gas and forms highly conductive bonds/bridges within the solid-phase matrix of the porous material). One can thus observe that, in general, building materials with a high density have larger thermal conductivity than building materials with a lower density (some exceptions are discussed in this report).

Because of this general correlation between density and other material properties, the data is presented in this report as a series of figures showing a given material property as a function of the density. However, one can note that the correlations between the density and the other material properties are not always positive, linear and/or monotonic. Although much weaker, these correlations can hold when looking at the overall dataset, but can change significantly or disappear when looking at the data points within a specific material category: e.g., the correlation between density and thermal conductivity is negative for ceramics and very weak but negative for metals.

Density

One can see that the density of building materials spans over a very wide range of several orders of magnitude. However, the figure provides information about the range of possible density for each material category.

Thermal Conductivity

One can see in *Figure 2* that the thermal conductivity of building materials spans over a very wide range of several orders of magnitude. However, the figure provides information about the range of possible thermal conductivity for each material category

Specific Heat Capacity

One can see in *Figure 9* that the specific heat capacity of building materials is often within the 300 – 2500 J/kg/K range. The figure provides information about the range of possible specific heat capacity for each material category.