8. ACOUSTICS OF ROOMS AND ENCLOSURES

8.1 Introduction

This section covers the acoustics of enclosed spaces. Upon completion, the reader should have a basic understanding of how to design spaces with suitable acoustic characteristics for a particular use.

The two fundamental qualities that determine a room's suitability for a particular use are:

- Reverberance or Liveliness: primarily a function of the sound absorption in the room and quantified by the *Reverberation Time*
- Background Noise Levels: predominantly HVAC noise, quantified by the NC or RC value

Typical applications:

- Acoustical spaces such as concert halls, classrooms, churches, offices, etc
- Industrial Environments - occupied spaces, or enclosures around noise sources

8.2 Sound Fields in a Room

Important Concepts:

Near Field
Far Field
Free Field
Reverberant Field
Diffuse Field

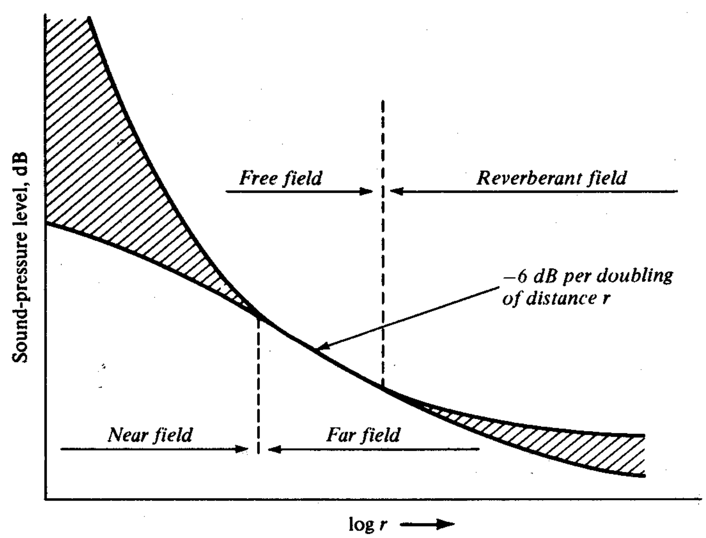


Figure 1. Sound pressure level variation with distance from the source

8.3 Sound Absorption

As sound strikes a wall, some of it is reflected, while some is absorbed by the wall. A measure of that absorption is the absorption coefficient α, defined as:

$$\alpha = \frac{I_{absorbed}}{I_{incident}} = \frac{I_{incident} - I_{reflected}}{I_{incident}} \quad \text{Equation 1}$$

$\alpha = 1$ if totally absorptive
$\alpha = 0$ if totally reflective

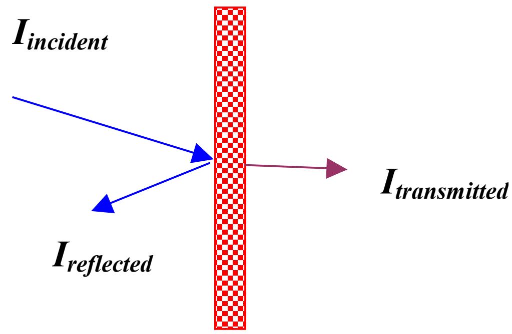


Figure 2. Sound striking an absorbing wall

α is a function of the material, the frequency, and incidence angle

While some of the absorbed sound is dissipated as heat in the material, some re-radiates from the other side. The amount of energy that gets into the next room is quantified by the transmission coefficient: (more on this in Section 9)

$$\tau = \frac{I_{transmitted}}{I_{incident}} \quad \text{Equation 2}$$

Absorption can be obtained by three primary mechanisms:

- porous materials,
- panel resonators or
- volume resonators:

Porous materials: Energy dissipation occurs due to acoustic pressure fluctuations at the surface which pump air into and out of the material. Friction between this air flow and the tortuous passages of the material dissipate energy as friction, and ultimately heat. Materials in this category include fiberglass, open cell foam, carpet and fabric. The frequency dependence for felt (a common absorption material) is shown in Figure 3.

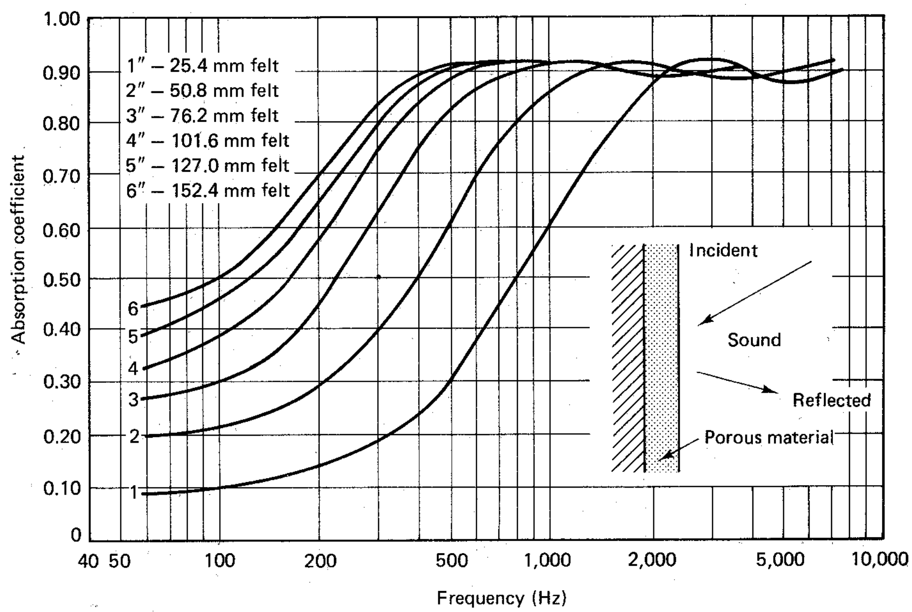


Figure 3. Variation of absorption coefficient with frequency for a porous material – felt

As seen in Figure 3, porous materials are more effective for absorbing high frequency sounds. The effectiveness depends on the thickness, relative to the sound wavelength. In order to be effective (nearly anechoic) at a given frequency, the material thickness must equal to at least ¼ of a wavelength. It is difficult to obtain low frequency absorption with porous materials (they would have to be very thick).

Rule of thumb: the lowest frequency that will be effectively absorbed by a porous material has a wavelength of **four (4)** times the absorbent thickness

Example: 152.4 mm (6″) thick material will effectively absorb all frequencies above approximately 565 Hz. ($f = c/\lambda = 343/.608$)

Panel Resonators: Any flexible panel which vibrates in response to incident sound will transmit some sound energy to the other side (and therefore decrease the reflected sound). The effect is most pronounced at low frequencies. Typical examples include drywall, plywood, glass panes, sheet metal panels, metal roof decks. Low frequency absorption is usually highly desirable and this is sometimes the only way to achieve it.

Volume Resonators: These are all some variant of a Helmholtz resonator, the characteristic of which is a narrow band of high transmission loss. Bass trap closets are one example which can be designed into a room. Another example is SoundBlox, a commercially available concrete block shown in Figure 4. These are designed to provide low frequency absorption as seen in Figure 5. They work well if you can include them in the original construction, but are not well suited for retrofit.

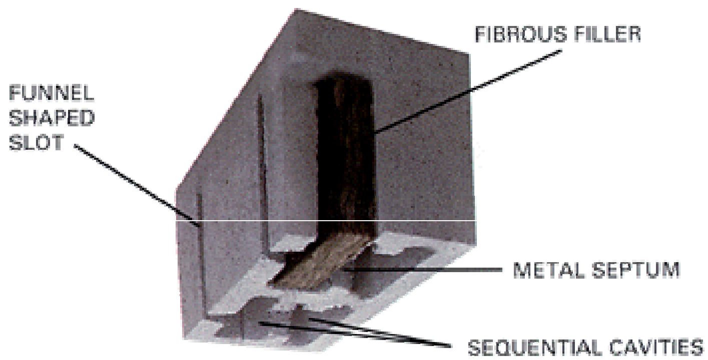


Figure 4. SoundBlox type RSC, a concrete cinder block with enclosed volume resonators for low frequency absorption

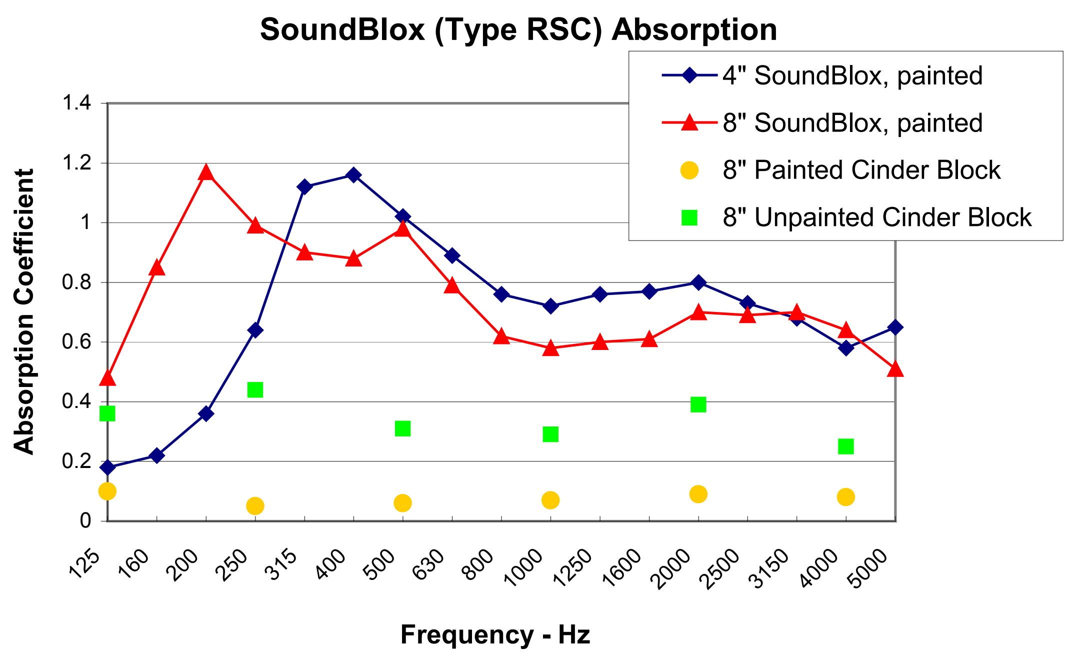


Figure 5. Absorption coefficient of SoundBlox compared to ordinary solid blocks (SoundBlox data from Proudfoot Company).

Published Absorption Coefficient Values

Absorption coefficients for commercially available materials are measured and published by manufacturers. A typical tabulation is shown in Table 1. It is possible to have absorption coefficient values greater than 1.0 for finite sized panels due to diffraction effects at the edges, and the additional absorption caused by the exposed area along the sides.

Table 1. Absorption coefficients of common building materials (ref. NIOSH Compendium of Noise Control Materials, 1975)

COEFFICIENTS OF GENERAL BUILDING MATERIALS AND FURNISHINGS

Complete tables of coefficients of the various materials that normally constitute the interior finish of rooms may be found in the various books on architectural acoustics. The following short list will be useful in making simple calculations of the reverberation in rooms.

Materials	*Coefficients*					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Brick, unglazed	.03	.03	.03	.04	.05	.07
Brick, unglazed, painted	.01	.01	.02	.02	.02	.03
Carpet, heavy, on concrete	.02	.06	.14	.37	.60	.65
Same, on 40 oz hairfelt or foam rubber	.08	.24	.57	.69	.71	.73
Same, with impermeable latex backing on 40 oz hairfelt or foam rubber	.08	.27	.39	.34	.48	.63
Concrete Block, coarse	.36	.44	.31	.29	.39	.25
Concrete Block, painted	.10	.05	.06	.07	.09	.08
Fabrics						
Light velour, 10 oz per sq yd, hung straight, in contact with wall	.03	.04	.11	.17	.24	.35
Medium velour, 14 oz per sq yd, draped to half area	.07	.31	.49	.75	.70	.60
Heavy velour, 18 oz per sq yd, draped to half area	.14	.35	.55	.72	.70	.65
Floors						
Concrete or terrazzo	.01	.01	.015	.02	.02	.02
Linoleum, asphalt, rubber or cork tile on concrete	.02	.03	.03	.03	.03	.02
Wood	.15	.11	.10	.07	.06	.07
Wood parquet in asphalt on concrete	.04	.04	.07	.06	.06	.07
Glass						
Large panes of heavy plate glass	.18	.06	.04	.03	.02	.02
Ordinary window glass	.35	.25	.18	.12	.07	.04
Gypsum Board, ½″ nailed to 2x4's 16″ o.c.	.29	.10	.05	.04	.07	.09
Marble or Glazed Tile	.01	.01	.01	.01	.02	.02
Openings						
Stage, depending on furnishings			.25 — .75			
Deep balcony, upholstered seats			.50 — 1.00			
Grills, ventilating			.15 — .50			
Plaster, gypsum or lime, smooth finish on tile or brick	.013	.015	.02	.03	.04	.05
Plaster, gypsum or lime, rough finish on lath	.14	.10	.06	.05	.04	.03
Same, with smooth finish	.14	.10	.06	.04	.04	.03
Plywood Paneling, ⅜″ thick	.28	.22	.17	.09	.10	.11
Water Surface, as in a swimming pool	.008	.008	.013	.015	.020	.025
Air, Sabins per 1000 cubic feet @ 50% RH				.9	2.3	7.2

ABSORPTION OF SEATS AND AUDIENCE

Values given are in Sabins per square foot of seating area or per unit

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Audience, seated in upholstered seats, per sq ft of floor area	.60	.74	.88	.96	.93	.85
Unoccupied cloth-covered upholstered seats, per sq ft of floor area	.49	.66	.80	.88	.82	.70
Unoccupied leather-covered upholstered seats, per sq ft of floor area	.44	.54	.60	.62	.58	.50
Wooden Pews, occupied, per sq ft of floor area	.57	.61	.75	.86	.91	.86
Chairs, metal or wood seats, each, unoccupied	.15	.19	.22	.39	.38	.30

The **Noise Reduction Coefficient** (**NRC**) is an attempt to get a single number to quantify a material. It is the numerical average of the absorption coefficients in the 250, 500, 1000 and 2000 Hz bands.

$$NRC = (\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000})/4 \qquad \text{Equation 3}$$

8.3 Experimental Determination Of Absorption

Absorption may be determined by experimental procedures, either:

- normal incidence coefficient α_n using an impedance tube (Figure 8.3)
- random incidence coefficient α_{sabine} using a reverberation chamber

A third theoretical quantity sometimes used in equations is the statistical energy absorption coefficient α_{st} It is defined as:

$$\alpha_{ST} = \frac{\text{Sound Energy absorbed by infinite surface in diffuse sound field}}{\text{Incident Sound Energy}} \qquad \text{Equation 4}$$

This is an idealized quantity which cannot be measured directly.

8.4 Normal Incidence Coefficient α_N

The normal incidence absorption coefficient is the ratio of energy absorbed/energy incident, for a plane wave, normally incident on an absorptive surface. It is easy to determine using a "standing wave tube" (sometimes called an "impedance tube"). It uses a small sample (typically 4" diameter) and has limited validity and usefulness due to the small sample size and the difference between a true normal incidence condition, and the actual incidence conditions (nearly random) seen in most real installations. But it is still useful for comparison purposes. The diameter of the tube must be smaller than ½ wavelength to insure plane wave sound propagation. A 4" tube is good up to about 3300 Hz. For higher frequencies, a smaller diameter tube is used.

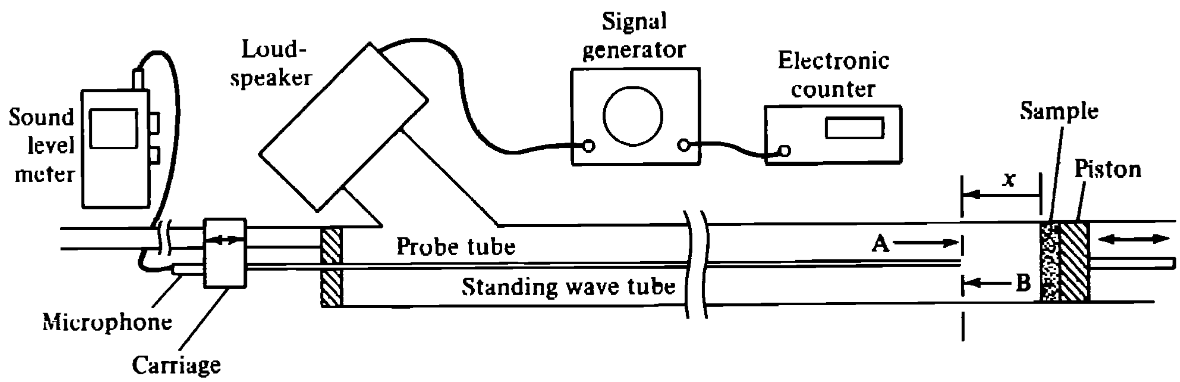


Figure 6. Impedance tube for measuring normal incidence absorption coefficient

We input a pure tone (or band of noise) using a loudspeaker. The incident wave from the speaker combines with the reflected wave from the end of the tube to form a standing wave. The depths of the minima are directly related to the absorption of the sample at the end of the tube. If the sample were perfectly reflective, total cancellation would occur ¼ wavelength from the end, and a pressure maximum would occur at ½ wavelength. A totally absorptive sample (anechoic) would exhibit a uniform pressure over the entire tube length. So, the difference in the maximum and minimum pressures is an indication of the absorptive characteristics of the sample.

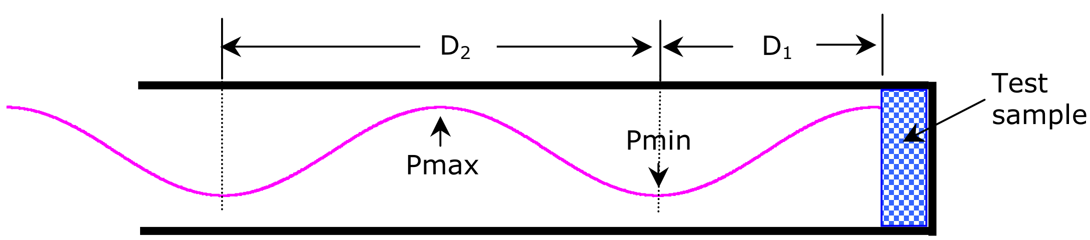


Figure 7. Interaction between incident and partially reflected waves result in a standing wave pattern in an impedance tube. D_1 is the distance from the sample to the first minimum. D_2 is the distance between the first and second minima (equal to 1/2 wavelength)

We experimentally measure the maximum and minimum pressures inside the tube by sliding a microphone along the centerline, from which we can calculate the normal incidence absorption coefficient, α_n .

$$\alpha_N = \frac{4\dfrac{P_{\max}}{P_{\min}}}{\left(1+\dfrac{P_{\max}}{P_{\min}}\right)^2} \qquad \text{Equation 5}$$

Additionally, if we measure the distance from the sample to the first minimum D_1, and the distance between consecutive minima (or consecutive maxima) D_2, the magnitude of the acoustic impedance can be calculated (ref. pg 57 L,G&E). A good check on the data is that D_2 should be equal to one half of a wavelength.

$$|Z| = \left|\frac{P}{u}\right| = \left(\frac{1+2R_0\cos\theta + R_0^{\,2}}{1-2R_0\cos\theta + R_0^{\,2}}\right)^{\frac{1}{2}} \rho\, c \qquad R_0 = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} \qquad \theta = \frac{2\pi\, D_1}{D_2}$$ Equation 6

8.5 Sabine Absorption Coefficient α_{Sabine}

A patch of material is placed in a large, highly reverberant room having a diffuse field. α_{sabine} is calculated from measurements of sound decay (reverberation time) in the room both with and without the material sample in place. It is a better approximation to real installations of absorptive materials, where the incidence angle can be anything.

(reference standards: ISO R354-1963, ASTM C423-84 & AS 1045-1971)

8.6 Room Averaged Coefficient $\overline{\alpha}$

Most real rooms have a variety of surfaces with different materials. The total effect of all these surfaces can be approximated by the average:

$$\overline{\alpha} = \frac{\sum_{i=1}^{N} \alpha_i S_i}{S} \qquad \text{where: } \alpha_i = \text{absorption of the i}^{\text{th}} \text{ surface}$$ Equation 7

S_i = Area of the i$^{\text{th}}$ surface S = Total surface area

N = Number of absorbing surfaces

Assuming a uniform intensity (a diffuse sound field) $I\,\overline{\alpha}S = I\sum \alpha_i S_i$
(the absorbed acoustical energy/unit time = the absorbed power)

If the distribution of α is highly uneven, a better approximation is:

$$\overline{\alpha} = \frac{S}{\dfrac{S_x}{\overline{\alpha_x}} + \dfrac{S_y}{\overline{\alpha_y}} + \dfrac{S_z}{\overline{\alpha_z}}} \qquad \text{where } S_{x,y,z} = \text{ area of x, y, z faces}$$

$\overline{\alpha_{\text{x,y,z}}}$ = average absorption of each face

8.7 Sound Buildup In Rooms

If a sound source with power of W is suddenly turned on, acoustic energy flows into the room, with maximum intensity occurring near the source. Waves travel outward and eventually bounce off walls (with partial absorption) back into the room. After several reflections, the sound field approaches diffuseness (if α is low).

Energy builds up until an equilibrium is reached. At equilibrium, the total power input (W) is exactly balanced by the power absorbed by the walls. The power absorbed by the walls is determined by the incident sound intensity:

$$W_{input} = W_{absorbed} = I\bar{\alpha}\,S$$

Since intensity is proportional to the square of sound pressure, this gives the result that the sound pressure in the room (in the reverberant field) is proportional to the input power and inversely proportional to the amount of absorption present.

$$p^2 \propto \frac{W_{input}}{\bar{\alpha}S}$$

Another way to think about it is the sound pressure (and intensity) in the room continue to build up until the power absorbed by the walls equals the input power. The higher the absorption, the lower the overall level which results.

A good analogy for this is a leaky water tank filled with a faucet (Figure 8). As the water level in the tank increases, more leaks out of the holes because the head (pressure) which forces water out the leaks is proportional to the water level. Eventually, the level will reach a steady height, where the inflow from the faucet is exactly equal to what leaks out. Now to complete the analogy to our acoustic problem, think of the water level as the sound pressure, the leaks are the sound absorption, and the flow from the faucet is the input sound power.

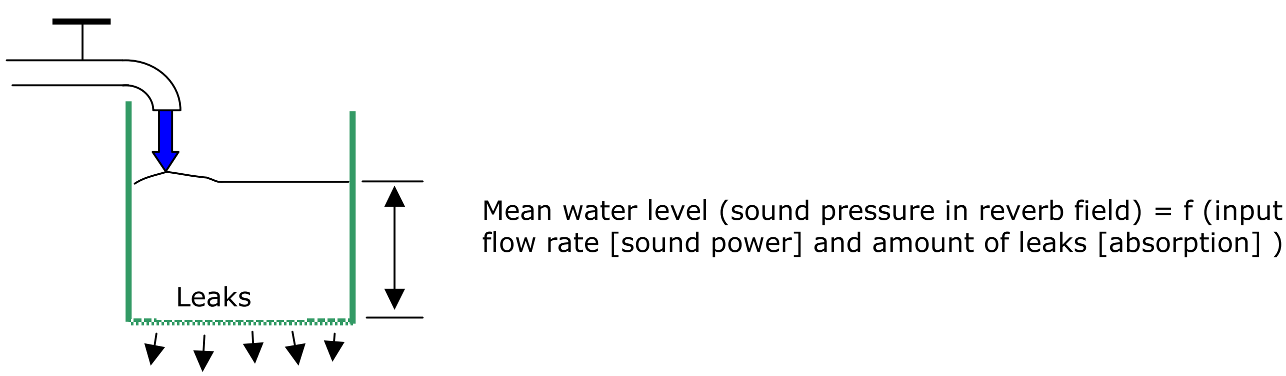


Figure 8. Leaky tank analogy for sound pressure buildup in an absorptive room

8.8 Sound Decay, Reverberation Time

If we now turn off our noise source, the sound level will decay linearly with time. Qualitatively, it's easy to understand that the more absorption a room has, the quicker the sound will decay. We can (and will) use this decay rate to experimentally measure the overall room absorption.

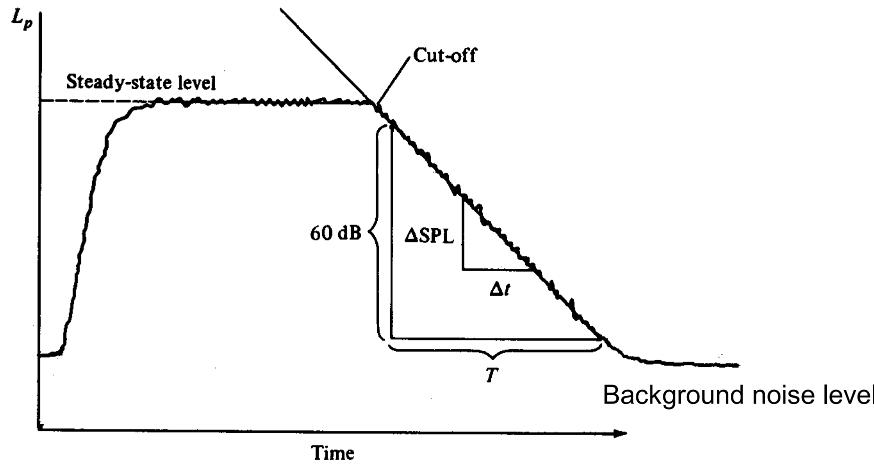


Figure 9. Typical decay of sound in a reverberation time test

The time required for the sound level to decay 60 dB is called the **reverberation time**, or T_{60}. It is often difficult (particularly at low frequencies) to put enough sound energy into a room to raise the level 60 dB over the background noise. The typical approach is to fit a straight line to the actual decay and extrapolate to 60 dB. Methods to excite the room include impulse sources such as popping balloons (ok for small rooms) or starter pistols; or a steady source – white or pink noise from amplified speakers.

Reverberation time is the single most important parameter for judging the acoustical properties of a room and its suitability for various uses. (Note, RC or NC criteria are measures of the background noise level of a room)

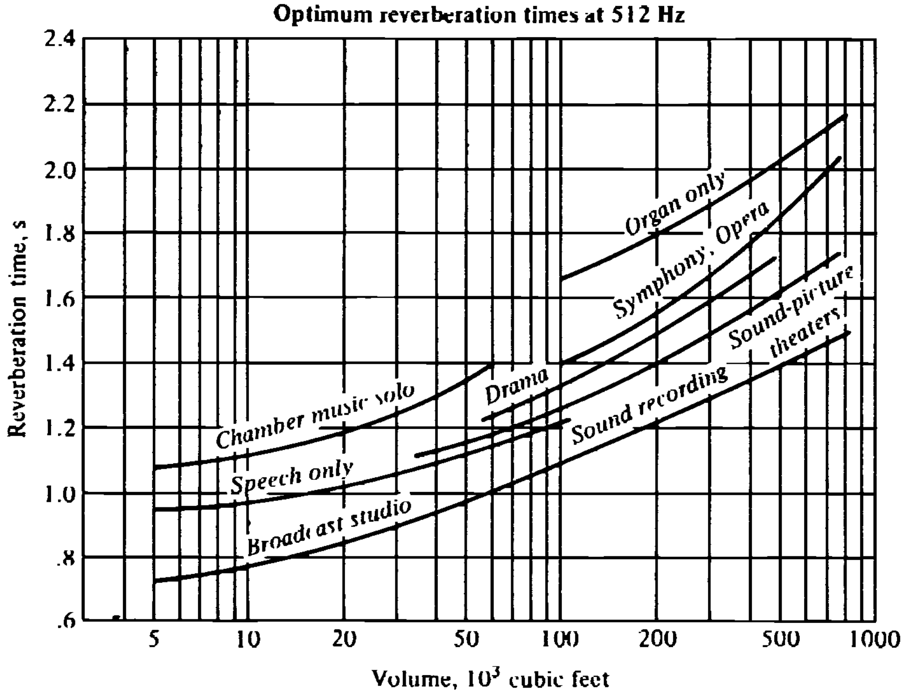
- High reverberation (long T_{60}) is desirable for music (concert halls 1.8 – 2.0 seconds)
- Low reverberation (short T_{60}) is desirable for speech intelligibility (such as in a classroom, 0.4 - 0.6 seconds)

The reverberation time at 512 or 1000 Hz is typically used as a single number to quantify the acoustic properties of a space. Recommended values for various applications are shown in Figure 9 and Table 2. An equation for calculating the "Optimum" Reverberation Time (according to Stephens and Bate 1950) is

$$T_{60} = K[\ 0.0118\ V^{1/3} + 0.1070] \quad \text{Equation 8}$$

V = volume in meters

K = 4 for speech, 5 for orchestras, 6 for choirs example V = 1000 m^3 for speech, T_{60} = .9 sec



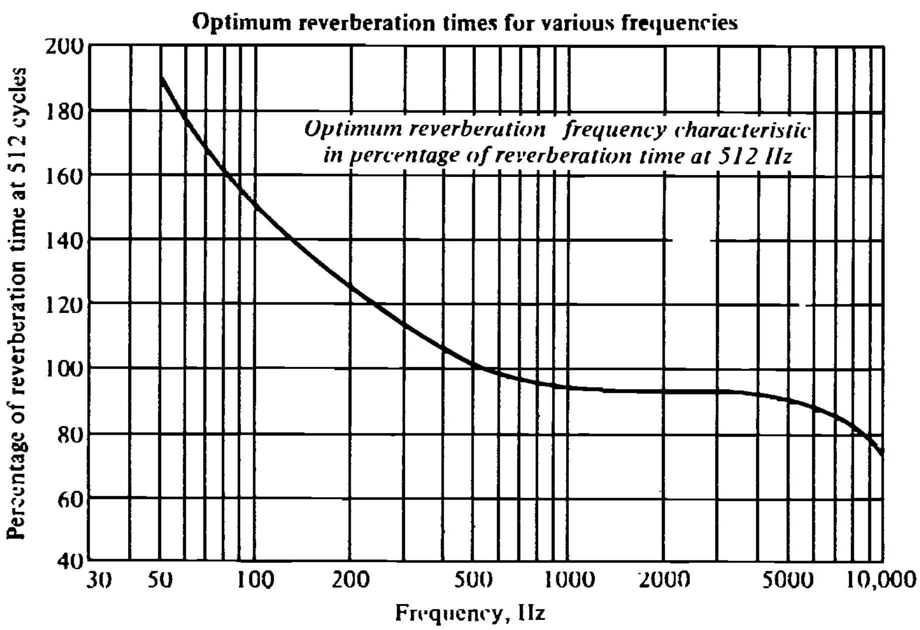


Figure 10. Recommended reverberation times for various uses
(reference Lord, Gatley and Evenson)

Table 2. Suitable reverberation times (seconds) for various rooms typically found in educational facilities. (ref. Classroom Acoustics, Acoustical Society of America, 2000)

Music Rehearsal	0.6 – 1.1
Auditoriums	1.0 – 1.5
Gymnasiums	1.2 - 1.6
Cafeterias	0.8 – 1.2

Classrooms	0.4 – 0.6

8.9 Relating Reverberation Time to Room Dimensions and Materials

T_{60} is, to a first approximation, proportional to the total room absorption **A** and the room volume **V**.

$$T_{60} \propto \frac{V}{A}$$

The simplest relation, from empirical data, called the **Sabine equation** is:

$$T_{60} = .161 \frac{V}{\sum_{i=1}^{n} \alpha_i S_i}$$

for mks units, or

$$T_{60} = .049 \frac{V}{\overline{\alpha} S}$$

for English units (feet) Equation 9

This equation assumes a diffuse field, air at 24° C, and works well if the absorption coefficient of each of the surfaces, $\alpha_i < .20$

For larger absorptions, and a uniform distribution of absorption around the room, the **Eyring equation** can be used (mks units):

$$T_{60} = \frac{.161\ V}{-S \ln(1-\overline{\alpha})}$$

Equation 10

Air absorption is negligible for frequencies < 1000 Hz. However, if the room is very large, and high frequencies are of concern, air absorption cannot be neglected:

$$T_{60} = \frac{.161\ V}{-\overline{\alpha}\, S + 4mV} \quad \text{(mks)} \quad = \frac{.049V}{-\overline{\alpha}\, S + 4mV} \quad \text{(English units)}$$

Equation 11

m = energy attenuation constant for air (see Figure 10).

Table 3. Reverberation time equations for various applications T_{60} = .161 V/A (SI units)

Absorption, A	Application	Comments
$\Sigma S_i \alpha_i$	Live rooms, all values of α_i <.20	Sabine Equation
$-S \ln(1-\alpha)$	α' >.20, Uniform distribution of absorption	Eyring Equation
Σ-$S_i \ln(1-\alpha_i)$	At least one value of α_i >.20, Non-uniform distribution of absorption	Millington-Sette Equation
A + 4mV	Large rooms, air absorption not negligible, m= attenuation constant from Figure 10	

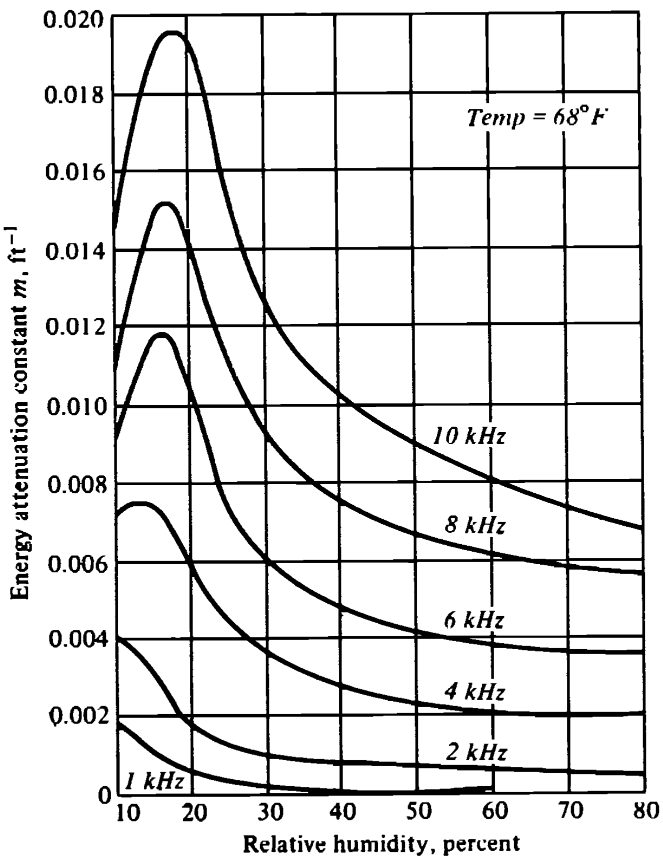


Figure 11. Attenuation for propagation of sound in air

8.10 Steady State Sound Levels In Enclosures

In a direct field, we already know that the intensity varies with distance.

$$I_\theta = \frac{W}{4\pi r^2} Q_\theta \qquad \text{and} \qquad I = \frac{\langle p^2 \rangle}{\rho c}$$

where: Q_θ = directivity factor where: $\langle p^2 \rangle$ = mean square sound pressure

In a reverberant field, the intensity is constant everywhere and is related to pressure by:

$$I_{rev} = \frac{1}{4}\frac{\langle p^2 \rangle}{\rho c} \qquad \text{Equation 12}$$

Note that the intensity in a diffuse (reverberant) field is only ¼ that of a plane wave.

If we assume steady state conditions and a diffuse field, the amount of energy absorbed by the walls must equal the reverberant power supplied. The reverberant power is the sound power of the source minus the sound power absorbed in the first reflection, $W(1-\overline{\alpha_{ST}})$. The absorbed power is $I_{rev}(S\overline{\alpha_{ST}})$.

The reverberant intensity is then:

$$I_{rev} = \frac{W(1-\overline{\alpha_{ST}})}{S\overline{\alpha_{ST}}} = \frac{W}{R} \qquad \text{Equation 13}$$

Where **R** is called the **room constant,** $R = \dfrac{S\overline{\alpha_{ST}}}{1-\overline{\alpha_{ST}}}$ Equation 14

In most cases of low absorption, we typically simplify by assuming:

$$R \approx S\overline{\alpha_{ST}} \quad \text{and} \quad \overline{\alpha_{ST}} \approx \overline{\alpha_{SABINE}}$$

A real room is somewhere between a diffuse and a free field. Therefore the total pressure is the sum of the direct and reverberant fields.

$$\left\langle p^2 \right\rangle = \rho c I_\theta + 4\rho c I_{rev} = W\rho c\left[\frac{Q_\theta}{4\pi r^2} + \frac{4}{R}\right]$$

and in terms of levels:

Direct Field

Reverberant Field

$$L_P = L_W + 10\log_{10}\left[\frac{Q_\theta}{4\pi r^2} + \frac{4}{R}\right] \qquad \text{Equation 15}$$

The quantity Lp – Lw is plotted in Figure 12. In the reverberant field, the sound pressure level is independent of location. Note that in a highly reflective room (low R), the reverberant field is very large, and begins very close to the source.

The change in a room's SPL due to changing its absorption is called the
Noise Reduction, NR:

$$NR = L_{P1} - L_{P2} = 10\log(R_2/R_1) = 10\log\frac{S_2\overline{\alpha_2}}{S_1\overline{\alpha_1}} \qquad \text{Equation 16}$$

In order to get a decrease of 6 dB, the room absorption must be increased by a factor of 4. (that's a lot !)

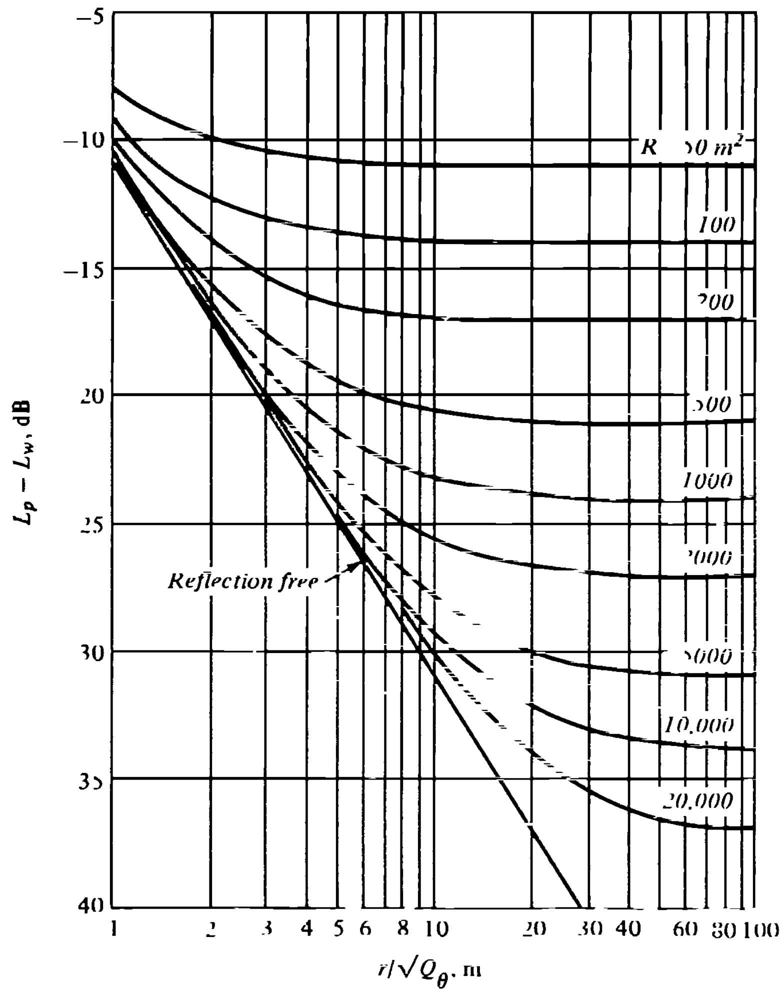


Figure 12. Difference between the sound pressure level and the sound power level in a room as a function of the room constant R_T, the distance from the source r and the directivity factor Q_θ

Other Room Theories:

The preceding relation is based on diffuse field theory. Schultz [ASHRAE Transactions 1983, 91(1), pp 124-153] proposed an empirical formula based on his studies of domestic rooms and closed offices. He found that levels did not ever reach a constant level with distance from the source, as predicted by the diffuse field model. He found that the curves always had a slope of about -3dB/doubling of distance. Notice that there is no term for room absorption!

$$Lp = Lw - 10 \log_{10} r - 5 \log_{10} V - 3 \log_{10} f + 12 \qquad \text{Equation 17}$$

where: r = distance (m)
V = room volume (m^3)
f = frequency (Hz)

8.11 Effect of Mounting

The more area an absorbing material presents to incident sound, the more energy is absorbed. In addition, it is possible to make a material more effective at low frequencies by mounting it with an air space between it and the adjacent wall or ceiling (see Figure 13 and Table 4).

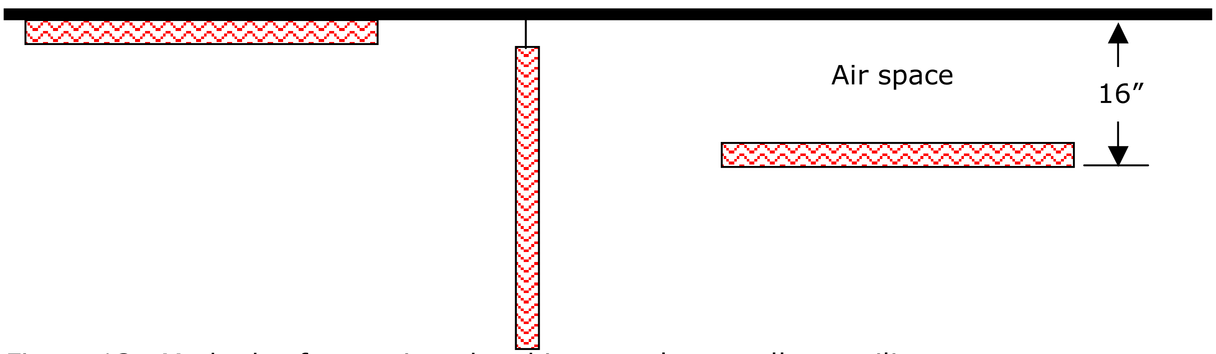


Figure 13. Methods of mounting absorbing panels on walls or ceilings:
a) hard mounted b) hanging baffle c) air space behind panel

Table 4. Effect of mounting on a 24″ x 48″ x 1.5″ thick fiberglass panel on total absorption (absorption in Sabins) (data from NIOSH Compendium of Noise Control materials)

	Frequency - Hz					
Mounting Configuration	**125**	**250**	**500**	**1000**	**2000**	**4000**
Hanging baffle	4.3	6.6	9.8	13.3	13.6	10.8
Hard mounted on rigid wall (#4 mount)	1.5	3.5	6.2	7.4	6.5	6.2
16″ air space (#7 mount)	7.2	6.4	6.0	7.2	6.2	3.6

8.13 Standing Waves

Room modes
Placement of sound sources and absorbing material
Modal density

8.12 Anechoic Rooms

Effectiveness of wedges

8.12 Reverberation Rooms

8.14 Good and Bad Reflections

bad - flutter echo
good – early reflections, reflectors in front of classrooms, orchestra shells

effect of surface roughness on reflection:

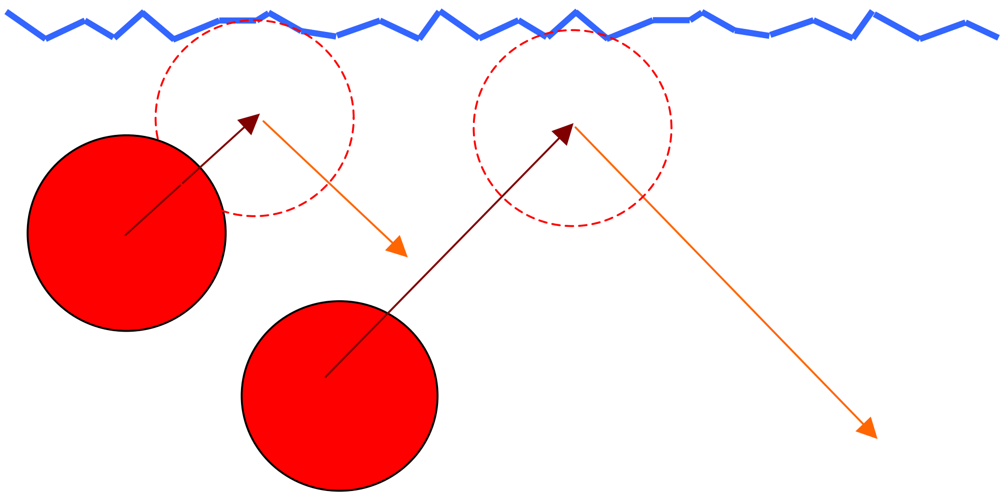


Figure 15. Specular reflection – occurs when the surface roughness length is smaller than the acoustic wavelength (represented by the diameter of the balls)

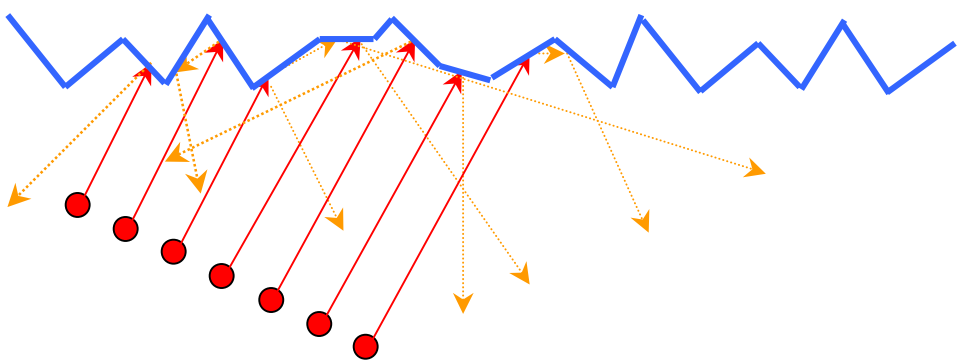


Figure 16. Diffuse reflection – occurs when the surface roughness length is larger than the acoustic wavelength (represented by the diameter of the balls)

8.15 Summary

Adding absorption is only justifiable if the ***reverberant*** field is dominant. Absorption on walls or ceilings will have little or no effect in the direct field, i.e. in the immediate vicinity of a noise source.

Design guidelines:

1. To have the greatest effect on total absorption (and the reverberation time), add absorption to the **least** absorptive areas first.
2. Distribute absorption around the room as much as possible to minimize local effects.
3. Avoid having two parallel walls that are both highly reflective. This can cause a flutter echo.
4. Low frequency absorption (< 250 Hz) is difficult to achieve with porous materials of reasonable thickness. To be effective at low frequency, porous materials must be thick,

   Material thickness $\geq 1/4\ \lambda$ for anechoic ($\alpha \approx 1.0$)
5. Low frequency absorption of porous materials can be increased by mounting them with an airspace behind them.
6. Design the room with non-parallel walls wherever possible to break up standing waves and flutter echo.
7. Absorption or a diffusing element on the back wall of a room (the wall directly opposite to the sound source or speaking person) is highly desirable
8. Mount absorbing panels so as to maximize the area exposed to incident sound

8.16 References

1) Compendium of Materials for Noise Control, NIOSH, 1975, HEW Publication No. 75-165.
2) Sonic and Vibration Environments for Ground Facilities – A Design Manual, NASA , NAS8-11217.
3) Classroom Acoustics, Acoustical Society of America, Architectural acoustics technical committee, August 2000.

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To better understand the concept of acoustical absorption, let us consider the basic tube method for measuring the normal incidence absorption coefficient. The method outlined follows closely the American Society of Testing and Materials (ASTM) Standard C384 [1].

In the tube method, a sample of the material is placed at the end of the tube, as illustrated in Fig. 6.1. Discrete frequency sound waves generated by the loudspeaker propagate down the tube, impinge upon the sample, and are reflected. A standing wave interference pattern results due to the superposition of the incident and reflected wave. The following parameters are then measured with the movable microphone or probe:

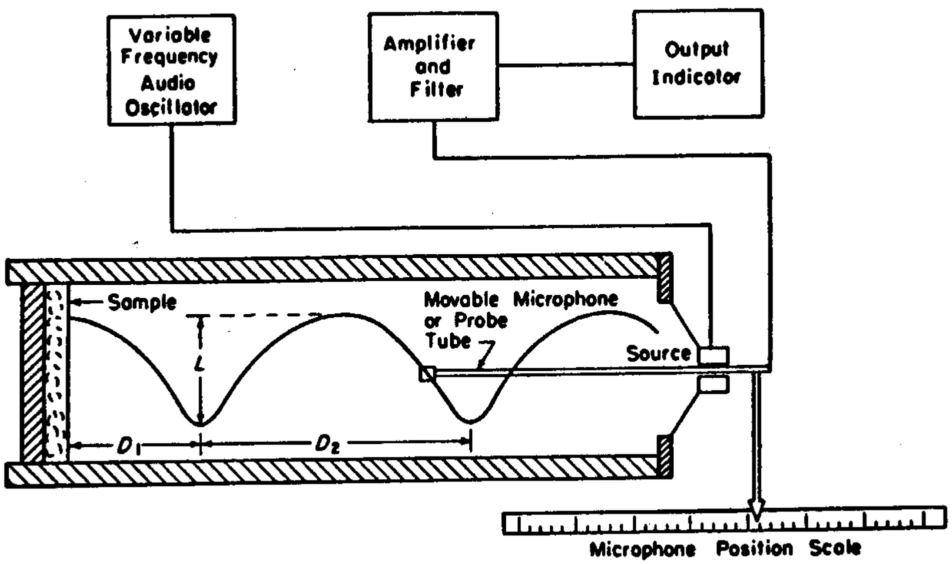

Figure 6.1 Acoustic impedance tube apparatus. (Reprinted with permission from the *Annual Book of ASTM Standards*, Copyright American Society of Testing and Materials, Philadelphia.

L = difference in decibels between the maximum and minimum sound pressure levels in the standing wave pattern in the tube

D_1 = distance from the face of the specimen to the nearest minimum in standing wave pattern, measured in any convenient units

D_2 = distance from the first to the second minimum in standing wave pattern, measured in the same unit as D_1

Now it can be shown [1–3] that the normal incidence sound absorption coefficient (α_n) is given by

$$\alpha_n = 1 - \left(\frac{z/\rho c - 1}{z/\rho c + 1}\right)^2 \quad \text{[unitless]} \tag{6.1}$$

where

z = specific normal acoustic impedance = r + jx (rayls)

r = specific normal acoustic resistance

$j = \sqrt{-1}$

x = specific normal acoustic reactance

ρc = characteristic acoustic impedance of free air (z, r, and x are customarily expressed in terms of their ratio to ρc)

Now Eq. (6.1) can be rewritten in terms of L [4,5], the difference between the maximum and minimum sound levels of the standing wave measured in the tube:

$$\alpha_n = 1 - \left(\frac{\log_{10}^{-1}(L/20) - 1}{\log_{10}^{-1}(L/20) + 1}\right)^2 \tag{6.2}$$

Consider an example.

Example

The measured difference between adjacent maximum and minimum levels in a standing wave tube was 8 dB at 1000 Hz. What is the normal incidence absorption coefficient for the sample at 1000 Hz?

Solution

From Eq. (6.2), with the measured sound level difference L = 8 dB, we get

$$\alpha_n = 1 - \left(\frac{\log_{10}^{-1}(8/20) - 1}{\log_{10}^{-1}(8/20) + 1}\right)^2$$

$$= 0.815$$

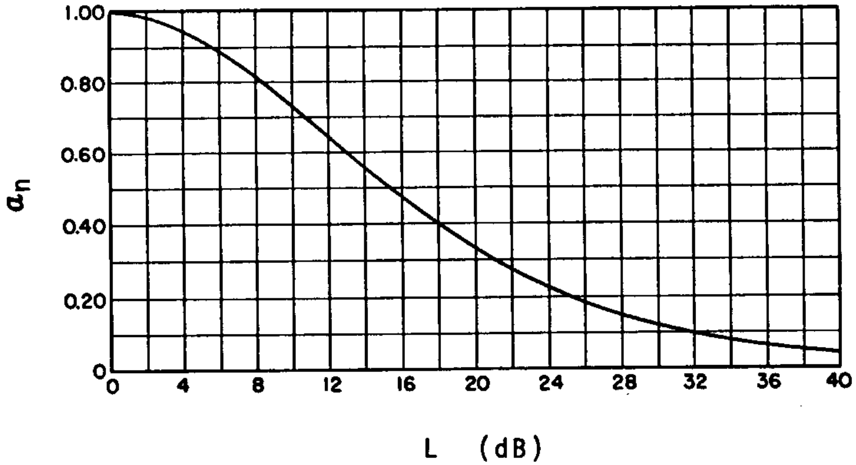

Figure 6.2 Chart showing the relation of the normal incidence absorption coefficient α_n to the difference in decibels L between the measured maximum and minimum sound levels.

Hence, the normal incidence absorption coefficient is 0.815, or, on a percentage basis, about 82% of the incident energy was absorbed by the sample. Equation (6.2) is presented graphically in Fig. 6.2, which simplifies calculations and provides sufficient accuracy for most noise control applications.

Although this method yields directly the normal incidence absorption coefficient, unfortunately, in most practical situations, the noise is not normally incident. Therefore, to account for a wide range of incidence angles, a more applicable coefficient commonly called the statistical absorption coefficient α_{stat} can be determined when the resistive and reactive components of the impedance are known. These impedance components follow also from measurements determined by the *tube* method, which, as a matter of interest, is commonly called the impedance tube.

To determine the acoustic impedance z = r + jx from tube measurements, it is again necessary to determine L, the standing wave ratio in decibels; D_1, the distance from the face of the specimen to the first minimum (referring to Fig. 6.1); and D_2, the distance between two successive minimums. The measured values are then substituted into the following equation [6] to obtain the specific acoustic impedance ratio:

$$\frac{Z}{\rho c} = \frac{r}{\rho c} + \frac{jx}{\rho c} = \coth(A + jB) \qquad \text{[unitless]} \qquad (6.3)$$

where

$$A = \coth^{-1}[\log_{10}^{-1}(L/20)] \quad \text{(unitless)}$$

$$B = \pi(1/2 - D_1/D_2) \quad \text{(unitless)}$$

Computational charts of Eq. (6.3) are shown in Figs. 6.3 and 6.4, from which $r/\rho c$ and $x/\rho c$ may be taken directly from the measured values of L and D_1/D_2. Consider an example.

Example

In an impedance tube the measured parameters at 500 Hz were L = 8, D_1 = 5 in., and D_2 = 11 in. What are the values of the resistive and reactive components of the impedance?

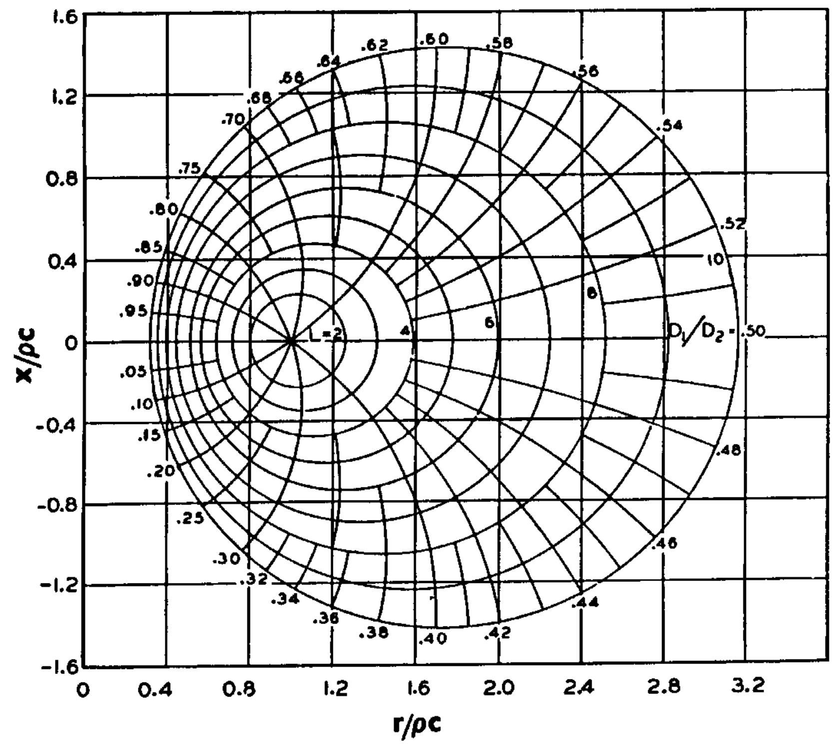

Figure 6.3 Relationship of specific acoustic impedance ratios and measured parameters L and D_1/D_2, L = 0 to 10. (Reprinted with permission from the *Annual Book of ASTM Standards*, copyright American Society of Testing and Materials, Philadelphia.)

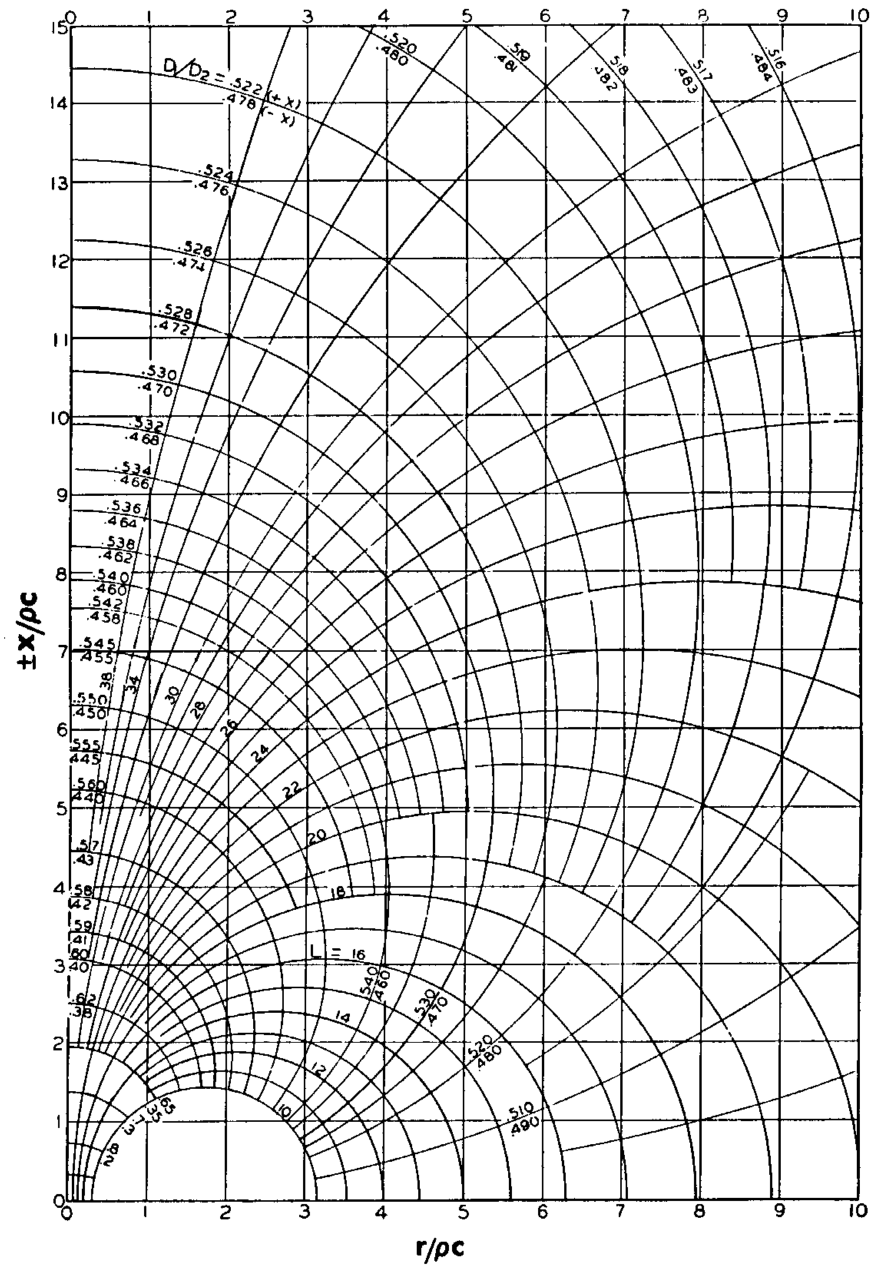

Figure 6.4 Relationship of specific acoustic impedance ratios and measured parameters L and D_1/D_2, L = 10 to 40. (Reprinted with permission from the *Annual Book of ASTM Standards*, copyright American Society of Testing and Materials, Philadelphia.)

Solution

$$\frac{D_1}{D_2} = \frac{5}{11} = 0.455$$

From Fig. 6.3, with L = 8 and $D_1/D_2 = 0.455$, the resistive component is $r/\rho c = 2.3$, and the reactive component is $x/\rho c = -0.7$ (approximately).

We now have the elements to calculate the statistical absorption coefficient, but a few more definitions are required. The ratio given in Eq. (6.3) is the specific acoustic impedance ratio,

$$\xi = \frac{Z}{\rho c}$$

and for convenience of calculation, it is desirable to define also the reciprocal of the impedance ratio η, which is called the specific acoustic admittance ratio:

$$\frac{1}{\xi} = \eta = \mu + j\kappa \qquad \text{[unitless]} \qquad (6.4)$$

where

μ = specific acoustic conductance ratio

κ = specific acoustic susceptance ratio

In terms of these parameters, it is possible to compute the difference in intensity of the incident and reflected waves and obtain the absorption coefficient, which is the fractional loss of sound intensity, from the following [6]:

$$\alpha(\theta) = \frac{4\mu \cos\theta}{\kappa^2 + (\mu + \cos\theta)^2} \qquad \text{[unitless]} \qquad (6.5)$$

Finally, statistically averaging over all incident angles θ, the statistical absorption coefficient is obtained:

$$\alpha_{stat} = 8\mu\left[1 - \mu \ln\left(1 + \frac{2\mu + 1}{|\eta|^2}\right) + \frac{\mu^2 - \kappa^2}{\kappa}\tan^{-1}\left(\frac{\kappa}{|\eta|^2 + \mu}\right)\right]$$

$$\text{[unitless]} \qquad (6.6)$$

Equation (6.6) has been computed for a wide range of absorption coefficients and is illustrated graphically in Fig. 6.5 [7]. The statistical absorption coefficient is given in terms of the specific resistance ratio $r/\rho c$ and specific reactance ratio $x/\rho c$, which are obtained directly from the impedance tube measurements. Consider an example.

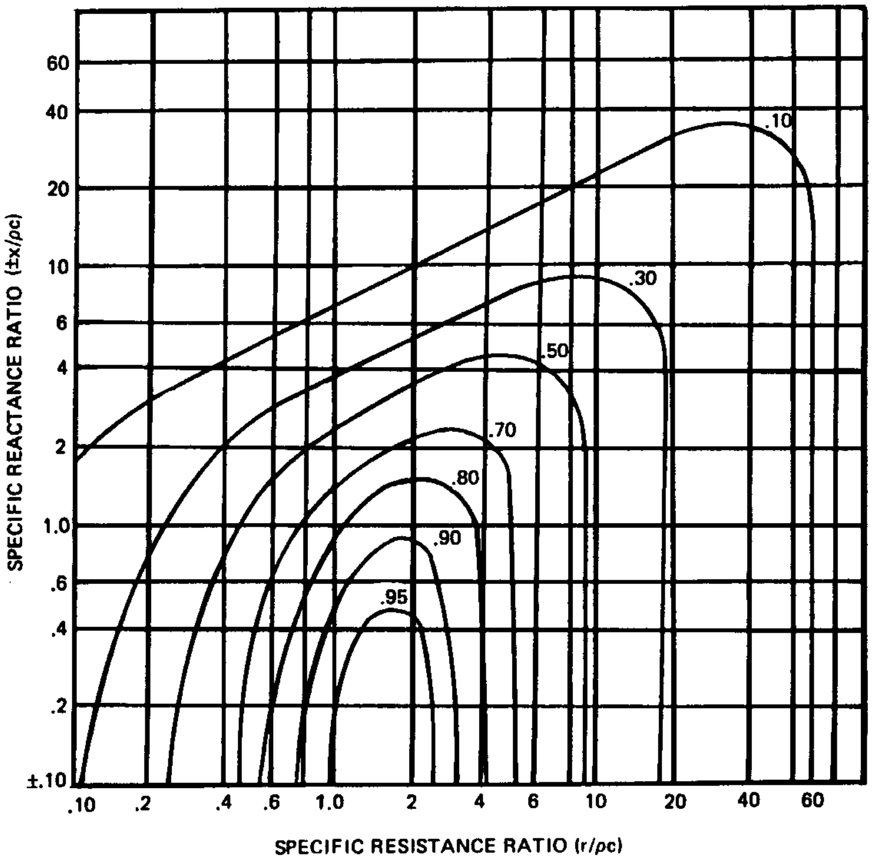

Figure 6.5 The statistical absorption coefficient in terms of the specific acoustic resistance and reactance ratios. (From Ref. 7.)

Example

From impedance tube measurements, the specific reactive and resistive ratios of a sample at 1000 Hz were found to be −2.0 and 4.0, respectively. What is the statistical absorption coefficient at 1000 Hz?

Solution

From Fig. 6.5, for $x/\rho c = -2.0$ and $r/\rho c = 4.0$, the statistical absorption coefficient α_{stat} is 0.70 (approximately).

The justification for the extent of this discussion can be seen by noting that for effective absorption, say values larger than 0.90, the following conditions must be met, referring again to Fig. 6.5:

1. The specific resistance ratio must be in the range $0.7 < r/\rho c < 3$.
2. The specific reactance ratio must be in the range $-1 < x/\rho c < 1$.

These ranges are rather narrow and limit drastically the number and types of materials which are effective absorbers.

It should be emphasized that the specific reactance ratio is naturally low for many fiberous or porous materials; thus condition 2 is easily met. However, condition 1 is satisfied in fibrous and porous materials only by careful control of the density, porosity, and thickness. For this reason, many *soft* and *fuzzy* materials used in packing crates and applied as a quick "fix" in noise reduction programs are disappointingly poor absorbers. For design purposes, the value usually selected to assure good absorption is

$$\frac{r}{\rho c} = 1.5 \qquad \text{(approximately)} \tag{6.7}$$

Therefore, to assure effective absorption, from Eq. (6.7) the specific acoustic resistance r of fibrous or porous materials must be

$$r = 1.5\rho c$$

and for air, given $\rho c = 415$ mks rayls,

$$r = 1.5 \times 415$$
$$= 622 \text{ mks rayls}$$

In summary, for effective sound absorption, the acoustic impedance of the material and medium must be nearly equal or, as commonly expressed, *matched*.

For fibrous and porous materials, the real or resistive component of the acoustic impedance is usually determined experimentally. Here the flow resistance r of the material is calculated from measurements of the flow velocity and pressure drop across the sample [8]:

$$r = \frac{SP}{U} \qquad \text{[mks rayls]} \tag{6.8}$$

where

P = air pressure difference across the test specimen (Pa)
U = volume velocity of the airflow through the specimen (m^3/s)
S = area of the specimen (m^2)

More often for homogenous materials, the resistivity r_0, which is the resistance per unit thickness, is the preferred parameter. The resistivity is then just a natural extension of Eq. (6.8) and is given by

$$r_0 = \frac{SP}{TU} \qquad \text{(mks rayls/m)} \tag{6.9}$$

where T is the thickness of the material (m). In this way, the total resistance of a piece of absorbing material can be determined simply from its dimensions.

REF. ENGINEERING NOISE CONTROL
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ABSORPTION COEFFICIENTS

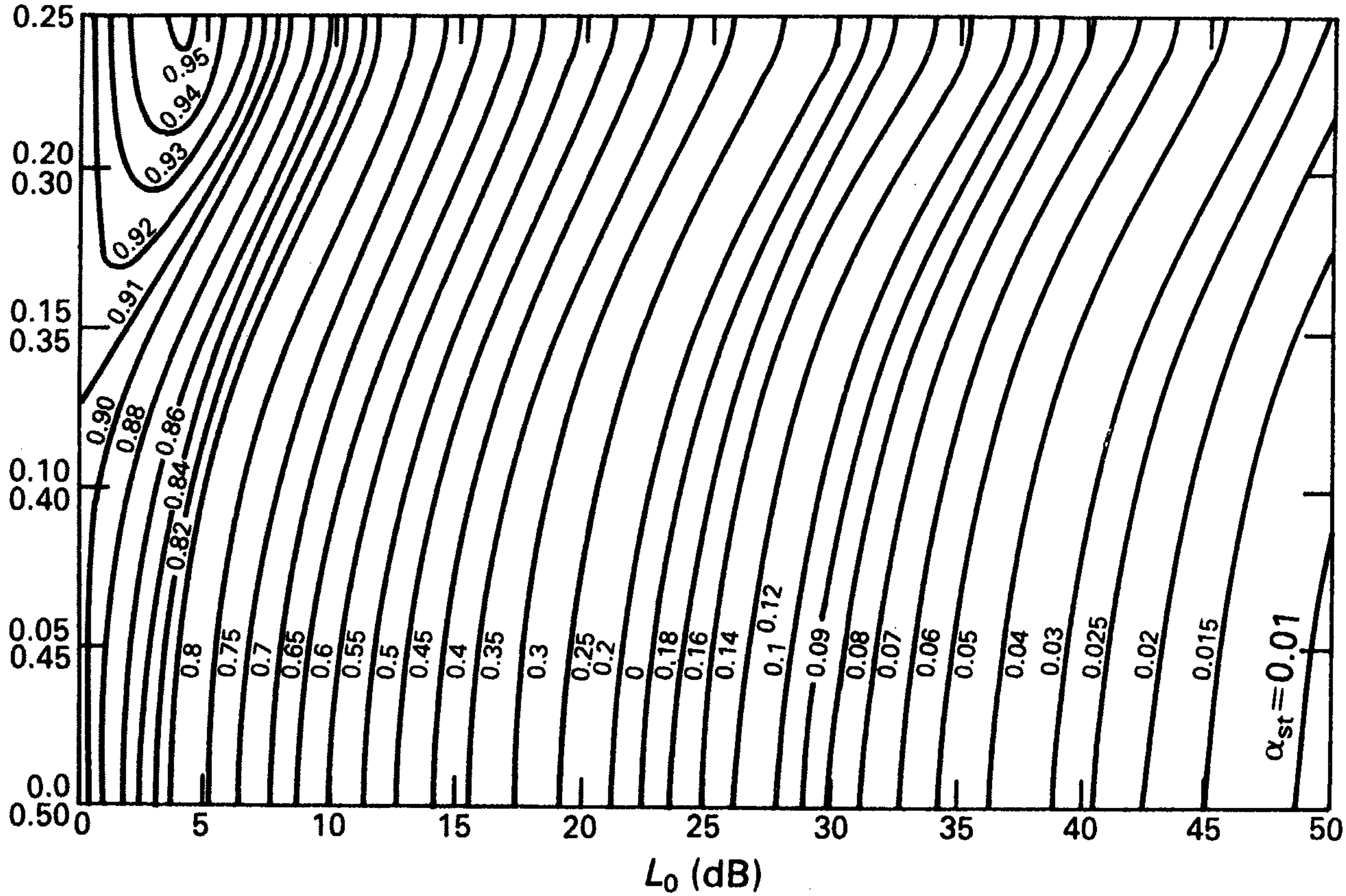

Figure A4.2 A chart for determining the statistical absorption coefficient α_{stat} from measurements in an impedance tube of the standing wave ratio, L_0, and position D_1/λ of the first minimum sound pressure level. α_{stat} is shown parametrically in the chart.

where S' is the total area of all surfaces in the room including the area of the material under test. Equation 7.43 is written with the implicit assumption that the surface area S of the test material is large enough to measurably affect the reverberation time, but not so large as to seriously affect the diffusivity of the sound field which is basic to the measurement procedure. The standards recommend that S should be between 10 and 12 m^2 with a length-to-breadth ratio between 0.7 and 1.0.

Statistical absorption coefficients may be estimated from impedance tube measurements, as discussed in Appendix 4.

A list of absorption coefficients selected from the literature is included in Table 7.1 for various materials. The method by which these values were determined is unknown: thus they have not been labeled as either statistical or Sabine coefficients and, for most purposes, may be used as either. The approximate nature of the available data makes it desirable to use manufacturers' data or to take measurements.

A smaller list of Sabine absorption coefficients, determined using reverberant room measurements, is included in Table 7.2.

Table 7.1 Absorption coefficients for some common internal finishes.

Material	Thickness, including any air space (mm)	Frequency (Hz)							
		63	125	250	500	1,000	2,000	4,000	8,000
Normal wall or ceiling finishes									
brickwork	—	0.05	0.05	0.04	0.02	0.04	0.05	0.05	0.05
breeze or cinder block	—	0.10	0.20	0.45	0.60	0.40	0.45	0.40	0.40
concrete	—	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03
up to 4 mm thick glass pane about 1 m square	4	0.25	0.35	0.25	0.20	0.10	0.05	0.05	0.05
6 mm plate glass about 1 m square	6	0.08	0.15	0.06	0.04	0.03	0.02	0.02	0.02
polished marble or glazed tile or glass with solid backing	—	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
plaster or solid wall	12	0.04	0.04	0.05	0.06	0.08	0.04	0.06	0.05
water (e.g., swimming pool)	—	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
boarded roof; underside of pitched slate or tile roof	—		0.15	0.10	0.10	0.10	0.10	0.10	0.10
Wall or ceiling treatments									
curtains hung in folds against solid wall or spaced away from wall	—	0.05	0.05	0.15	0.35	0.40	0.50	0.50	0.40

continued

Table 7.1 (*continued*).

Material	Thickness, including any air space (mm)	Frequency (Hz)							
		63	125	250	500	1,000	2,000	4,000	8,000
curtains hung straight and close to wall	—		0.05		0.25		0.30	0.40	
acoustic plaster (typical values)	12	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.35
glass or rockwool blanket, typical values for medium density material	25	0.05	0.10	0.35	0.60	0.70	0.75	0.80	0.75
25 mm glass or rockwool blanket faced with 3% open area perforated steel	25		0.10	0.30	0.65	0.85	0.50	0.15	
25 mm glass or rockwool blanket faced with 10% open area	25		0.10	0.25	0.50	0.75	0.75	0.55	
expanded polyurethane foam (open cell)	25	0.10	0.15	0.30	0.60	0.75	0.85	0.90	0.90
rigid polyurethane foam			0.20	0.40	0.65	0.55	0.70	0.70	
9 mm plasterboard on battens at 0.5 m centers, 18 mm air space filled with glasswool	27	0.25	0.30	0.30	0.20	0.15	0.05	0.05	0.05
5 mm plywood on battens at 1 m centers, 50 mm air space filled with glasswool	55	0.30	0.40	0.35	0.20	0.15	0.05	0.05	0.05
12 mm plywood on battens at 1 m centers, 59 mm air space filled with glasswool	71	0.25	0.30	0.20	0.15	0.10	0.15	0.10	0.05
3 mm hardboard with roofing felt stuck to back over 50 mm air space	53	0.50	0.90	0.45	0.25	0.15	0.10	0.10	0.05
suspended plaster or plasterboard ceiling (large air space)	—	0.20	0.20	0.15	0.10	0.05	0.05	0.05	0.05
fiberboard on solid backing	12	0.05	0.05	0.10	0.15	0.25	0.30	0.30	0.25
fiberboard (normal soft on solid backing)	13		0.05		0.15		0.30	0.30	
fiberboard (normal soft on solid backing), painted	13		0.05		0.10		0.15	0.15	
plywood mounted solidly			0.05	0.05	0.05	0.05	0.05	0.05	

continued

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Table 7.1 (*continued*).

Material	Thickness, including any air space (mm)	Frequency (Hz) 63	125	250	500	1,000	2,000	4,000	8,000
(unplastered) solidly mounted wood-wool slabs, 80 mm thick			0.20		0.80		0.80	0.80	
(unplastered) solidly mounted wood-wool slabs 25 mm thick			0.15		0.60		0.60	0.70	
6.5 mm hardboard with 19% perforation, backed by 25 mm of 74 kg m^{-2} glassfiber, followed by a 25 mm air gap	56.5			0.40	0.75	0.92	0.82		
Floor coverings									
composition flooring or hard floor tiles	—	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
haircord carpet on felt underlay	6	0.05	0.05	0.05	0.10	0.20	0.45	0.65	0.65
medium pile carpet on sponge rubber underlay	10	0.05	0.05	0.10	0.30	0.50	0.65	0.70	0.65
thick pile carpet on sponge rubber underlay	15	0.05	0.15	0.25	0.50	0.60	0.70	0.70	0.65
rubber floor tiles, cork slabs, wood blocks	6	0.05	0.05	0.05	0.10	0.10	0.05	0.05	0.05
medium pile carpet on solid concrete floor			0.10		0.30		0.50	0.60	
medium pile carpet on joist or board and batten floor			0.20		0.30		0.50	0.60	
Proprietary acoustic tiles and boards (Note that performance varies according to individual construction and method of fixing. Always obtain exact figures from manufacturer. The figures shown indicate the likely range of performance.)									
fixed direct on wall or ceiling or with small air space:									
minimum	12–75	0.05	0.10	0.25	0.50	0.60	0.60	0.45	0.45
maximum	12–75	0.15	0.20	0.60	0.80	0.85	0.80	0.75	0.75
in the form of suspended ceiling:									
minimum	—	0.15	0.30	0.40	0.50	0.65	0.75	0.70	0.65
maximum	—	0.30	0.50	0.60	0.90	0.90	0.85	0.80	0.75

Table 7.2 Sabine absorption coefficients of some common acoustic materials.

Material	Thickness (mm)	Frequency (Hz) 63	125	250	500	1,000	2,000	4,000	8,000
open cell polyurethane foam	12		0.05	0.25	0.43	0.78	0.9	0.95	
	18		0.10	0.32	0.60	0.90	0.95	0.98	
	25		0.15	0.46	0.70	0.92	0.98	0.98	
as above, but faced with perforated vinyl	12			0.08	0.23	0.62	0.98	0.68	
	25			0.18	0.70	0.98	0.92	0.83	
	50			0.50	0.98	0.92	0.75	0.90	
as above, but faced with a mylar film	12		0.08	0.13	0.68	0.82	0.40	0.42	
	25		0.18	0.32	0.78	0.93	0.80	0.52	
16 kg m^{-3} glassfiber insulation (7% binder)	25		0.14	0.56	0.62	0.74	0.86	0.98	
	50		0.23	0.78	1.08	1.07	0.99	1.0	
	75		0.40	1.05	1.21	1.14	1.04	1.0	
24 kg m^{-3} glassfiber insulation (7% binder)	12		0.1	0.42	0.37	0.53	0.68	0.78	
	25		0.17	0.54	0.63	0.8	0.88	0.95	
	50		0.26	0.80	1.12	1.06	1.04	1.05	
	75		0.49	1.12	1.25	1.21	1.10	1.05	
32 kg m^{-3} glassfiber insulation (7% binder)	12		0.1	0.41	0.36	0.54	0.72	0.83	
	25		0.16	0.53	0.65	0.85	0.95	1.0	
	50		0.29	0.82	1.13	1.08	1.07	1.05	
48 kg m^{-3} glassfiber insulation (7% binder)	12		0.12	0.36	0.29	0.54	0.79	0.88	
	25		0.14	0.45	0.64	0.95	0.98	1.02	
34 kg m^{-3} black-coated glassfiber	25		0.26	0.55	0.56	0.74	0.87	0.94	
	50		0.38	0.73	0.94	0.99	0.99	0.99	
Room contents (figures shown are total $S\bar{\alpha}$ in m^2 units)									
audience, per person, in fully upholstered seat	—	0.15	0.10	0.40	0.45	0.45	0.50	0.45	0.40
audience, per person, in wood or padded seat	—	0.10	0.15	0.25	0.40	0.40	0.45	0.40	0.35
unoccupied seat, fully upholstered	—	0.05	0.10	0.20	0.30	0.30	0.30	0.35	0.30
unoccupied seat, wood or padded	—	0.02	0.03	0.05	0.05	0.10	0.15	0.10	0.10