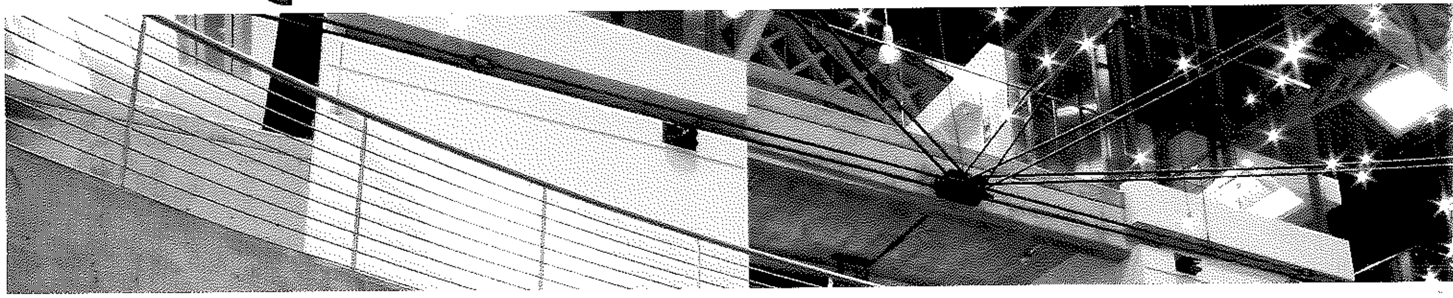
MECHANICAL AND ELECTRICAL EQUIPMENT

ELEVENTH EDITION



FOR BUILDINGS

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CHAPTER 19

Building Noise Control

ACOUSTICS

NOISE REDUCTION

NOISE CONTROL IN BUILDINGS INVOLVES three key concepts:

1. Reduction of noise generation at the source by proper selection and installation of equipment
2. Reduction of noise transmission from point to point (along the transmission path) by proper selection of construction materials and appropriate construction techniques
3. Reduction of noise at the receiver through acoustical treatment of the relevant spaces to meet the noise criteria developed in Chapter 17

Speech privacy is achieved by manipulation of all of the foregoing plus the use of masking noise where necessary.

Noise reduction is essentially the science of converting acoustical energy into another, less disturbing form of energy—heat. Since the amounts of energy involved are minute—130 dB corresponds to 1/1000 of a watt, or 0.003 Btu/h—the heat produced is completely negligible. This energy conversion is accomplished by absorption of sound energy by the room contents and wall coverings and also by the structure itself. The former controls noise levels *within* a space and the latter noise transmission between spaces. The reasons for this will become clear as our discussion proceeds.

ABSORPTION

19.1 THE ROLE OF ABSORPTION

Absorptive noise control treatment of a room will affect the reverberant noise level *within* that room but will have a minimal effect on the noise level in adjoining spaces. Refer to Fig. 19.1 for a graphic presentation of this fundamental fact. The best that can be accomplished with acoustic room treatment is elimination of the reverberant field, that is, making the intensity at the room boundaries what it would have been in free space, as in Fig. 19.1*d*. (Even this is extremely difficult; the actual field at the wall would be above 72 dB, except in a completely anechoic chamber.) Adding further wall (or other) acoustic absorbent (as in Fig. 19.1*e*) does nothing in the room itself and has a minimal effect on the overall transmission loss, since the transmission loss in the acoustic material itself is very low, as can be seen in Fig. 18.1.

The subject of acoustic energy absorption and absorptive materials, and their effect on room acoustics (including noise reduction) is treated extensively in Sections 18.1 through 18.10 for porous absorptive materials. Two other types of absorptive material are in use, although much less commonly: panel resonators and cavity resonators.

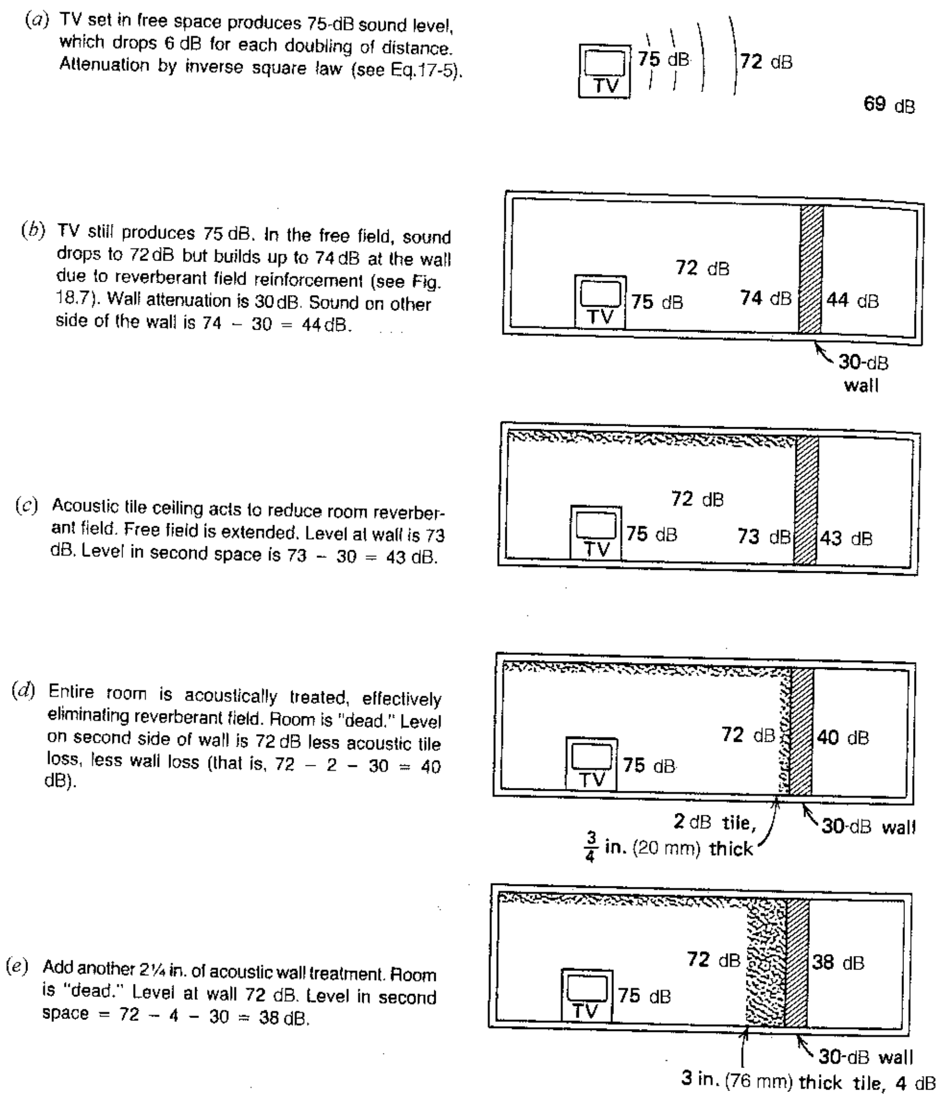


Fig. 19.1 *Graphic description of the effect of porous absorptive material on sound fields and sound pressure level (SPL) in adjoining spaces.*

19.2 PANEL AND CAVITY RESONATORS

Panel resonators are built with a membrane such as thin plywood or linoleum in front of a sealed air space generally containing absorbent material. The panel is set in motion by the alternating pressure of the impinging sound wave. The sound energy is converted into heat through internal viscous damping. Panel resonators are used where efficient low-frequency absorption is required and middle- and high-frequency absorption is unwanted or provided by another treatment (Fig. 19.2). Panel resonators are often used in recording studios.

A *volume* or *cavity resonator* (Helmholtz resonator) is an air cavity within a massive enclosure connected to the surroundings by a narrow neck opening. The impinging sound causes the air in the neck to vibrate, and the air mass behind causes the entire construction to resonate at a particular frequency. At that frequency absorption approaches unity, but drops fairly sharply above and below this frequency (see Fig. 19.2). Adjusting the neck opening and cavity dimensions allows a unit to be tuned to resonate at different frequencies. This makes it extremely useful when a major single frequency is present, as with 120-Hz transformer

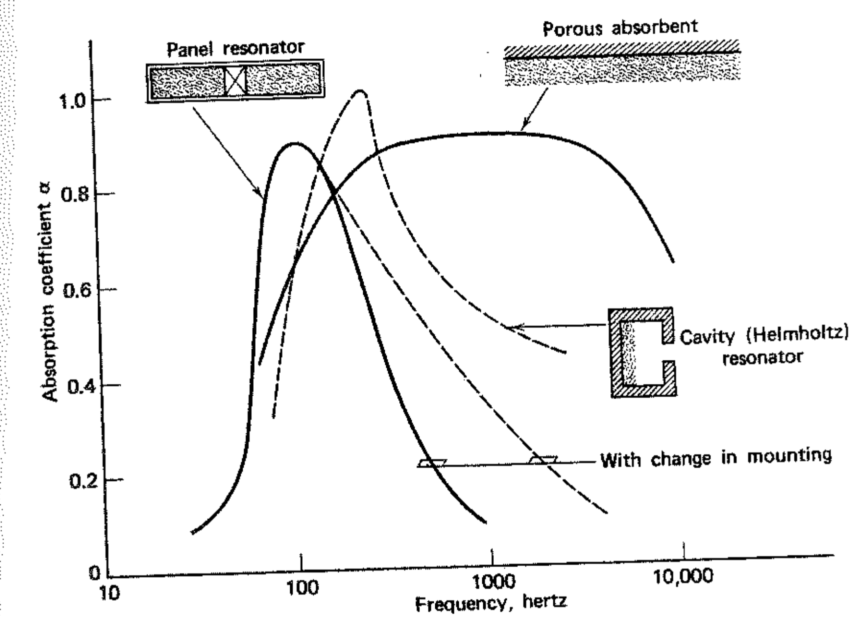
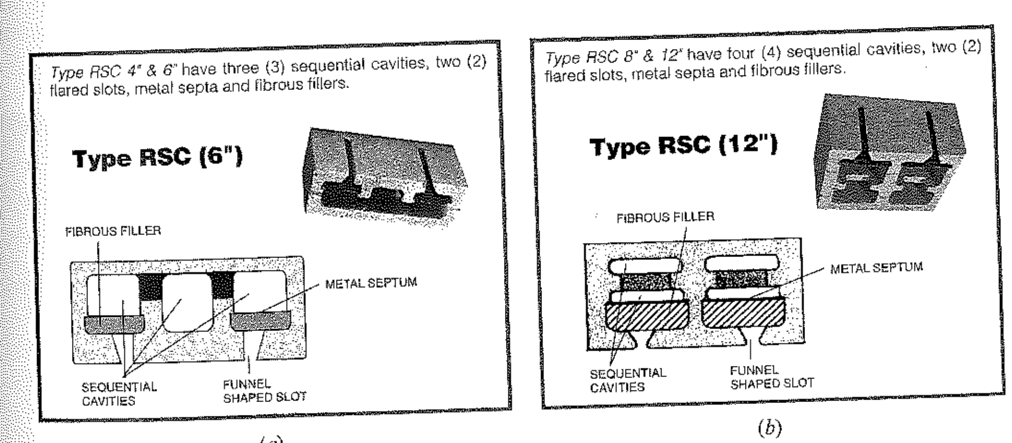


Fig. 19.2 *Typical absorption curves for the three major types of sound absorbers. The absorption characteristic of each type can be changed by varying the design, as discussed in the text.*



Sound Absorption Coefficients — Type RSC

Size	Type	Surface	Exposed Slots/ Cavities	FREQUENCY – Hertz 125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	NRC
6"	RSC	PAINTED	2/3	.48	.70	.93	1.14	1.05	.97	.91	.84	.75	.76	.77	.70	.67	.68	.56	.51	.59	.85
8"	RSC	PAINTED	2/4	.48	.85	1.17	.99	.90	.88	.98	.79	.62	.58	.60	.61	.70	.69	.70	.64	.51	.80
12"	RSC	PAINTED	2/4	.57	*	*	.76	*	*	1.09	*	*	.94	*	*	.54	*	*	.59	*	.85

(c)

Fig. 19.3 *Details of a Helmholtz resonator design using concrete blocks, with tuned block cavities as the resonating chambers. (a) A 6-in. (150-mm) block with three sequential cavities tuned with a metal divider (septum). (b) A 12-in. (305-mm) block with four cavities and added absorptive filler. (c) Sound absorption coefficients. (Courtesy of The Proudfoot Co., Inc.)*

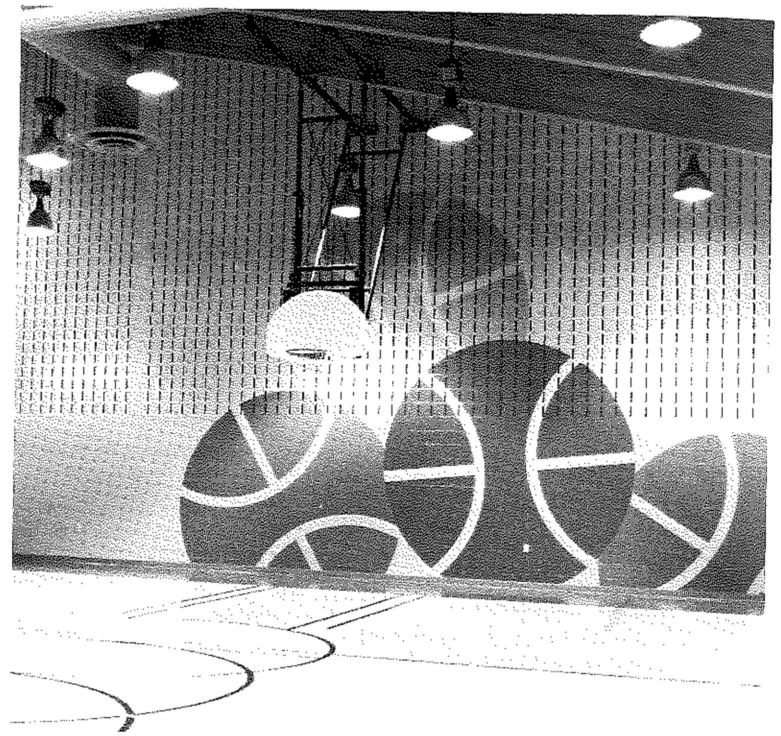


Fig. 19.4 Application of concrete block resonators in a school gymnasium. (Courtesy of The Proudfoot Co., Inc.)

hum. Concrete blocks can be used as resonators by tuning their cavities. Their absorption characteristic over the entire frequency band is improved by adding absorptive material in the cavities. Fibrous filler can be used in the block to increase high-frequency absorption. The blocks also serve as standard concrete construction blocks. See Fig. 19.3 for typical block details and Fig. 19.4 for a common application.

19.3 ACOUSTICALLY TRANSPARENT SURFACES

The soft, porous material of which acoustic absorbents are constructed may be covered with perforated metal or other materials to provide physical protection and act as stiffeners. These coverings are generally acoustically transparent except at higher frequencies. The frequency at which a noticeable reduction in absorption occurs for a perforated metal cover with circular holes can be estimated as

$$f = \frac{40p}{d} \qquad (19.1)$$

where

f = frequency, Hz

p = percentage of open area

d = diameter of holes, in.

Thus, for ¼-in. holes and 60% open area, which is a typical commercial material,

$$f = \frac{40(60)}{0.25} = 9600 \text{ Hz}$$

which is very high and generally not of major concern. It is always preferable, given a fixed percentage of open area, to use covers with small holes rather than large ones since, as seen from the formula, this raises the frequency at which absorption drops. It is also desirable to stagger the holes, as this improves absorption. An open-weave fabric is almost completely transparent to sound and is often used as a decorative cover on absorbent wall coverings.

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19.4 ABSORPTION RECOMMENDATIONS

To summarize, absorption techniques are useful and effective:

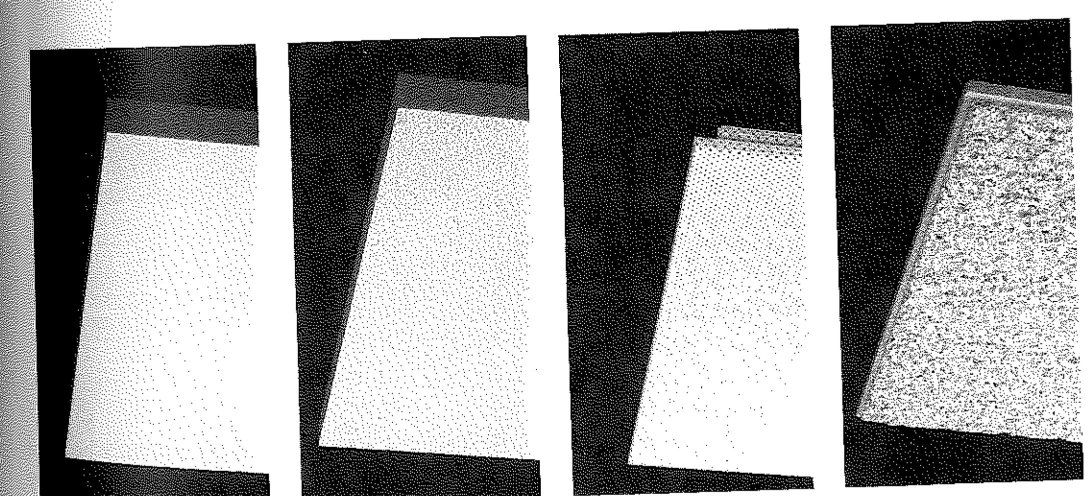
1. To change room reverberation characteristics.
2. In spaces with distributed noise sources such as offices, schools, restaurants, and machine shops.
3. In spaces with hard surfaces and little absorptive content.
4. Where listeners are in the reverberant field. (No amount of absorptive material can reduce intensity levels in the free field.)

Concentrated noise sources are better handled by individual equipment enclosures than by room treatment, since enclosures reduce the amount of sound emitted into a room, which room surface treatment cannot do. In addition to ceiling tiles and wall panels, acoustic absorbent material can be applied in the form of a sprayed-on finish (acoustic plaster), suspended unit absorbers, carpets, draperies, and the like.

19.5 CHARACTERISTICS OF ABSORPTIVE MATERIALS

1. *Acoustic tile* is available in size multiples of 12 in. (nominal 305 mm), from 12 in. × 12 in. (305 × 305 mm) up to 48 in. × 96 in. (1.2 × 2.4 m), in a huge variety of patterns and finishes, including units with fire ratings. Installation methods include lay-in, nailing to furring strips, and gluing. Tile materials are generally mineral fiber or faced fiberglass, with noise reduction coefficient (NRC) ratings in the range of 0.45 to 0.75 for mineral fiber tiles and up to 0.95 for fiberglass. The latter, which are frequently used in open-office applications, have Articulation Class (AC) ratings of 170 to 210 (see Section 19.20d). Tiles for use in high-humidity areas should be certified by the manufacturer for that application (see Fig. 19.5).

2. *Perforated metal-faced units* are usually installed in a lay-in suspension ceiling, although



(a) (b) (c) (d)

Fig. 19.5 Four of the many types of acoustic ceiling tiles available are illustrated. (a) and (b) are 2 ft × 4 ft × 1½ in. (600 × 1200 × 36 mm) fiberglass ceiling tiles with an acoustically transparent plastic humidity shield facing and a foil back for good sound dispersion in the plenum of open-plan offices. (a) Tile has 1.0 NRC, 200 AC, 0.89 light reflectance, and a thermal R value of 4.0. (b) Tile has similar acoustic and thermal characteristics, but due to its coarser surface, its light reflectance is 0.85. Both tiles are applicable to open-plan offices and are usable with indirect lighting systems. (c) Perforated metal cassette panels are used in lobbies, corridors, entries, outdoor canopies and soffits, and areas with high humidity. They are usable in HVAC systems for air returns and, when supplied with an acoustic infill (mineral fiber or fiberglass), have good acoustic properties. (d) General-purpose, coarse-textured mineral fiber ceiling tile is rated 0.70 NRC, 25 CAC (Ceiling Attenuation Class), and 0.73 light reflectance. It can be used acoustically in offices, libraries, restaurants, and public spaces. (Photos courtesy of Armstrong World Industries.)

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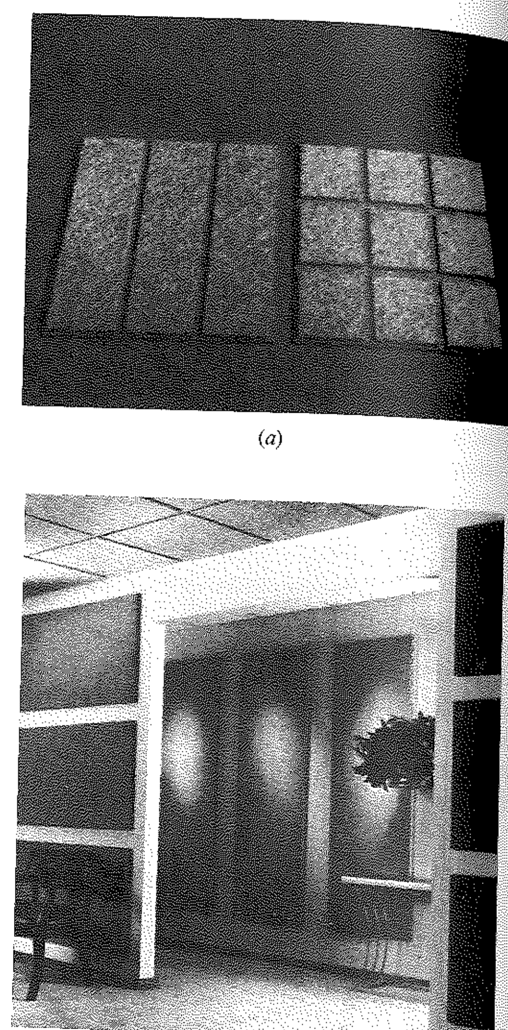
nailing to furring strips is possible. Units range in size from 12 in. × 24 in. (305 × 610 mm) to 24 in. × 96 in. (0.6 × 2.4 m)—and larger on special order. The fill material is either wrapped mineral wool or fiberglass, with NRC ratings somewhat lower than those of acoustic tile of the same material. The metal finish is generally baked enamel in a range of colors. The units are applicable to all spaces and have the advantages of easy cleaning, high luminous reflectivity, and incombustibility. With the acoustic backing removed, a perforated unit can be used for air return (Fig. 19.5).

3. *Acoustic panels* (boards) are made of treated wood fibers, bonded with an inorganic cement binder, in sizes ranging from 12 in. × 24 in. (305 × 610 mm) to 24 in. × 120 in. (0.6 × 3.0 m), with thicknesses from 1 to 3 in. (25 to 75 mm) and a smooth or "shredded" finish. Panels are used in ceiling suspension systems, or nailed or glued when applied to walls and structural ceilings. Their principal advantage is their high structural strength, which makes them applicable to installations requiring acoustic treatment combined with strength and abuse-resistance. A second advantage is their excellent flame-spread rating. Typical applications include full-span corridor ceilings, long-span direct-attached ceiling finish, wall panels in school gyms and corridors, and the like. NRC ratings range from 0.40 to 0.70. Acoustic panels are usually resistant to humidity, but usage in high-humidity spaces should be confirmed with the product manufacturer. This is particularly true for panels with "reveal" edges (Fig. 19.6).

4. *Acoustic plaster*, a material comprising a plaster-type base into which is introduced fibrous or light aggregate, is useful for application to curved and other nonlinear surfaces, in thicknesses of up to 1.5 in. (38 mm). Its advantages are ease of application and a high fire rating; its disadvantages are its inability to resist even mild abuse and its inapplicability to humid atmospheres. The noise absorption characteristics of acoustic plaster vary widely with composition, thickness, and application technique, and are generally below those of acoustic tile and panels.

5. *Sound blocks, baffles,* and *hanging panels* are simply masses of absorptive acoustic material that achieve absorption coefficients in excess of 1.0 by exposing more than a single absorptive surface to the impinging sound. In all cases, because of their prominent appearance, necessitated by their shape, they obtrude into the space and frequently become a major architectural element. This is especially true of hanging baffles (Fig. 19.7).

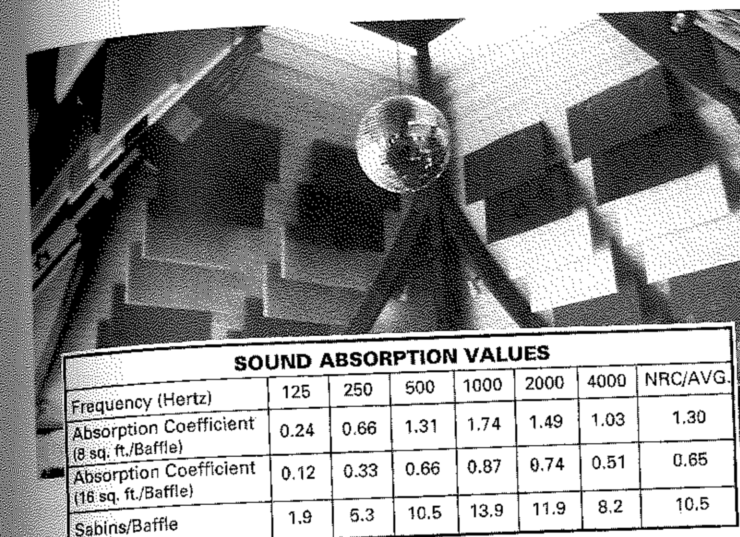
6. *Wall panels* consist of a wood or metal backing on which is mounted a mineral fiber or fiberglass substrate and a fabric covering. NRC coefficients vary from 0.5 for direct-mounted 1-in. mineral fiber substrate to as high as 0.85 for strip-mounted 1½-in. (38 mm) fiberglass substrate panels. Wall panels are available in widths ranging from 18 to 48 in. (457 to 1220 mm) and lengths of up to 120 in. (3 m). Fabric coverings generally carry a fire-spread rating. These panels are frequently used in offices, conference rooms, auditoriums, theaters, teleconferencing centers, and educational facilities (see Fig. 19.8).



(a)

(b)

Fig. 19.6 *Acoustic panel material made of pressed organic fiber with an inorganic binder can be used as ceiling tile (a) or wall panels (b). The latter has cloth covering as an outer finish. (Photos courtesy of Tectum.)*



SOUND ABSORPTION VALUES

Frequency (Hertz)	125	250	500	1000	2000	4000	NRC/AVG.
Absorption Coefficient (8 sq. ft./Baffle)	0.24	0.66	1.31	1.74	1.49	1.03	1.30
Absorption Coefficient (16 sq. ft./Baffle)	0.12	0.33	0.66	0.87	0.74	0.51	0.65
Sabins/Baffle	1.9	5.3	10.5	13.9	11.9	8.2	10.5

Fig. 19.7 *Application of hanging acoustic baffles to reduce reverberation in the high pyramid-shaped ceiling of a restaurant. The baffles are 1½-in.-thick (38-mm) fiberglass with a tough fire-rated cover. Sound absorption values are given in the accompanying table. (Courtesy of The Proudfoot Co., Inc.)*

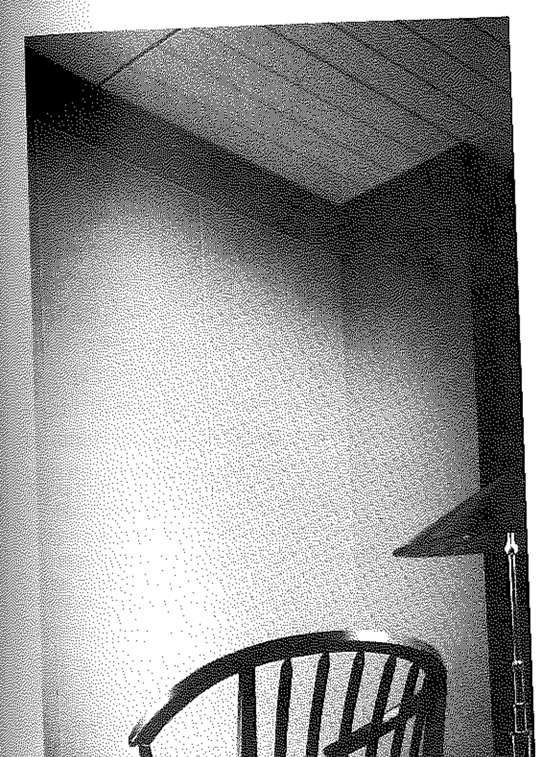
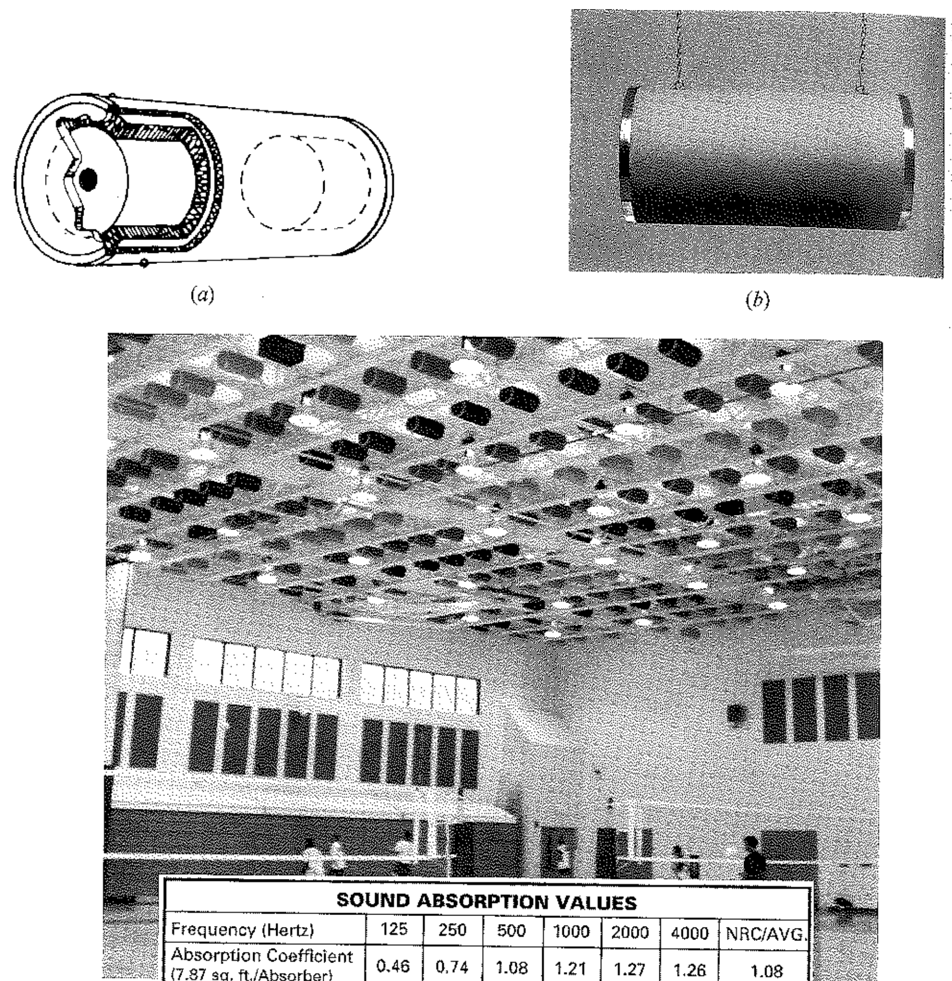


Fig. 19.8 *Acoustic wall panel consists of a rigid backing covered with either mineral fiber or fiberglass and finished with any of a wide selection of fabrics. NRC averages 0.6 for mineral fiber substrate and 0.8 for fiberglass for contact mounting (A mounting) and 0.7/0.9 when the panels are mounted on 2-cm (nominal ¾-in.) furring strips (D-20 mounting). The latter mounting is particularly effective in increasing absorption below 500 Hz. (Photo courtesy of Armstrong World Industries.)*

7. *Resonator sound absorbers* are available in a wide variety of sizes and shapes. Although some designs are available off the shelf, most are tailored to the specific acoustic needs of a project, using one of several standard designs. One fairly common type is shown in Fig. 19.9. In general, resonators are large and must therefore be integrated into the architectural design of a space. Exterior shapes can be altered, and the units can be installed less obtrusively to fulfill this architectural requirement.

8. *Carpeting and drapery* are used to cover large acoustically reflective surfaces in a space. Carpeting can be selected in almost any degree of density, looping, and depth, plus an additional depth of padding, to produce a high degree of absorption in middle and high frequencies (see Table 18.1). In general, absorption is proportional to pile height and density and increases when the carpet is installed on a thick, fibrous pad. Where drapery is not feasible and wall panels are impractical, carpeting can be installed on walls. In such instances, installation on furring strips with an enclosed air space behind will increase absorption over the entire acoustic spectrum and especially at low frequencies (where direct-contact installation exhibits poor absorption).



(a) (b)

SOUND ABSORPTION VALUES							
Frequency (Hertz)	125	250	500	1000	2000	4000	NRC/AVG.
Absorption Coefficient (7.87 sq. ft./Absorber)	0.46	0.74	1.08	1.21	1.27	1.26	1.08
Sabins/Absorber	3.65	5.84	8.48	9.51	9.98	9.90	8.45

(c)

Fig. 19.9 *(a) Resonator/absorber unit consists of a molded fiberglass cylinder, of 12-in. (305-mm) diameter and 24-in. (610-mm) length, containing a metal resonator at each end for low-frequency absorption and a fill of acoustic fiberglass for full-spectrum absorption. (b) The unit, which weighs about 6 lb (2.7 kg), is suspended on thin wires or chains that are essentially invisible when the unit is mounted 10 ft (3 m) above the finished floor (AFF) or higher. (c) A typical application in a school gymnasium. Because of their large size, the units constitute a major architectural element. By color selection and hanging patterns, they can be effectively used as such. The absorption characteristics of these units are listed in the table as a function of frequency. (Courtesy of The Proudfoot Co., Inc.)*

Draperies are essentially acoustically transparent and provide appreciable absorption only in the middle and upper frequencies with heavy, dense, fuzzy fabrics, particularly when draped with a high degree of fold. As with carpeting, absorption increases over the entire spectrum when a heavy folded drapery forms an air space between itself and the wall. Approximate absorption figures are given in Table 18.1.

SOUND INSULATION

19.6 AIRBORNE AND STRUCTURE-BORNE SOUND

In contrast to the preceding material, which was concerned with in-room sound reduction by absorption, the following sections will discuss

the characteristics of sound *transmission* between enclosed spaces. A distinction is often made between airborne and structure-borne sound, although in reality they differ only in the origin of the sounds. Airborne sound originates in a space with any sound-producing source, and although it changes to structure-borne sound when the sound wave strikes the room boundaries, it is still referred to as airborne because it originated in the air. *Structure-borne sound* is generally understood as energy delivered by a vibrating or impacting source directly contacting the structure. Hence, a child crying in an adjoining apartment is contributing airborne sound; the same child bouncing a ball on the floor is creating structure-borne sound, in this case by impact. Pumps that were installed without proper damping mounts create structure-borne sound by vibration.

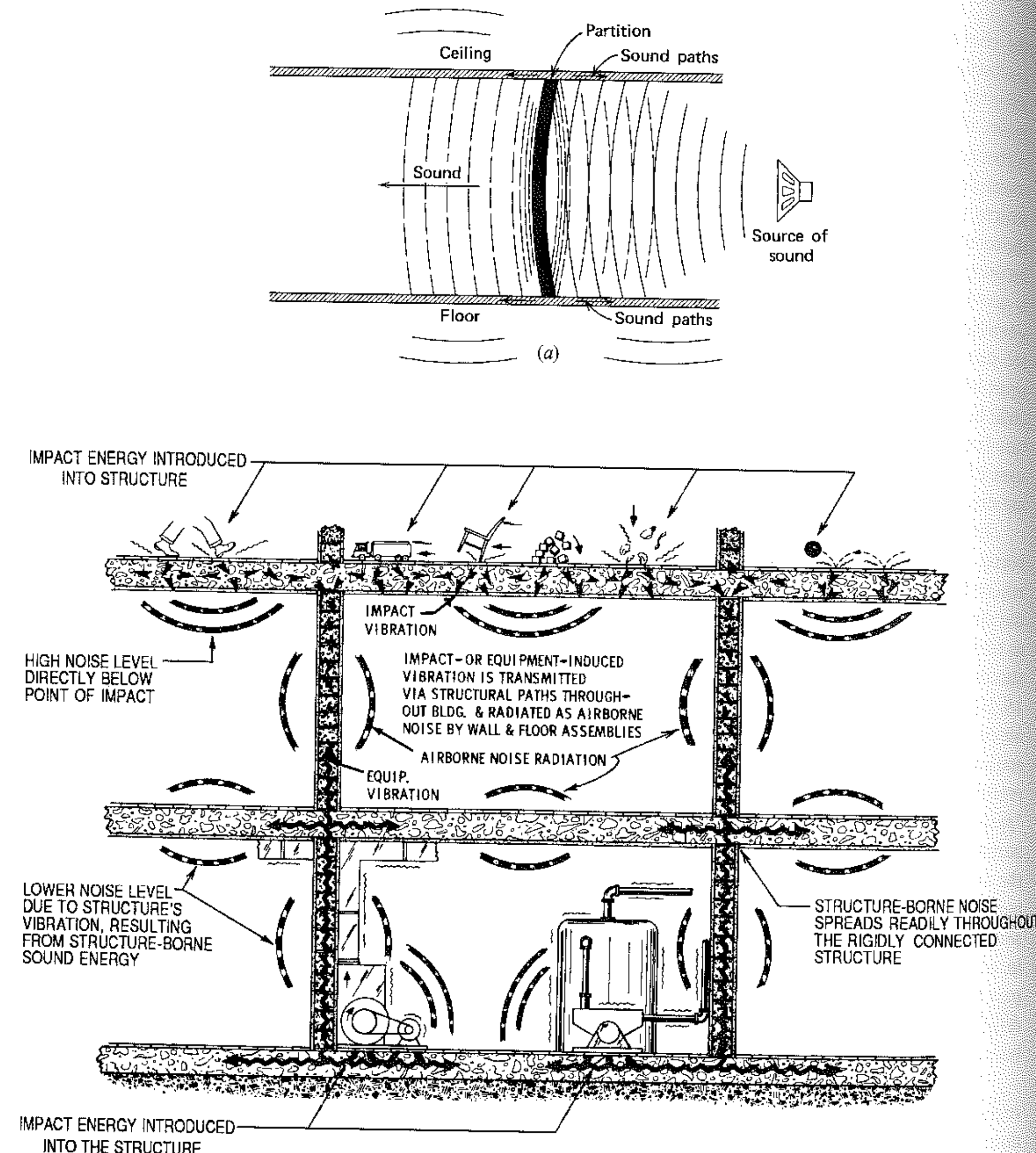
In reality, all sound transmission is both airborne and structure-borne since, once having entered the structure, the sound travels along the structure and causes the structure to vibrate, in turn generating airborne sound. Figure 19.10 should assist in understanding this action. In Fig. 19.10*a*, the sound is airborne, originating in the air on one side of the partition. The incidence of sound energy causes the partition to vibrate, generating sound on the other side. Sound does not "pass through" unless an air path exists. If the partition is airtight, then the sound energy causes the structure to become a secondary source. The partition vibrates primarily in the direction of the sound, that is, in the vertical plane. It also vibrates in other modes, causing some sound energy to pass into the floor and ceiling, depending upon the details of attachment. This energy becomes structure-borne sound.

In Fig. 19.10*b*, the process is similar but reversed. Energy is introduced into the structure directly (and efficiently) by mechanical contact, that is, by vibration and impact. Sound travels along the structure, as shown, and, by causing the structure to vibrate, creates *airborne sound*. In a structure with rigid wall-to-floor connections, these sounds are clearly heard throughout the building. It is a common misconception that in a (relatively) massive concrete structure with masonry walls, such as a multistory residential building, light impacts such as footfalls will not be transmitted. On the contrary, the rigidity of the structure, and in particular the rigid, airtight connections between partitions, floors, and ceilings, provide an excellent path for structure-borne sound. Only impact absorption by heavy carpeting will attenuate the sound of footsteps, and resilient floor-wall connections will attenuate structure-borne sound.

Airborne sound (originating in the air) is generally much less disturbing than structure-borne sound, since its initial energy is very small and it attenuates rapidly at boundaries. Structure-borne sound generally has a much higher initial energy level and attenuates slowly as it travels through a structure, thereby causing disturbance over large sections of a building. This disturbance is magnified by the "sounding board effect."

We are all familiar with the fact that a tuning fork must be held up to the ear to be heard directly, but if its handle is placed on a table the sound is amplified. This action is not really amplification but an increase in the efficiency of energy transfer. In general, the efficiency of a radiator is proportional to the ratio of its surface dimensions to the sound wavelength. A tuning fork vibrating at concert A (440 Hz) with a wavelength of 2½ ft (0.75 m) cannot efficiently couple its energy into the air. It is simply too small. By placing the instrument on a table whose dimensions are approximately one wavelength, we permit it to transfer its energy efficiently, hence the amplification. The same effect can be extremely troublesome in structure-borne sound. A vibrating pump itself makes little sound. However, it transfers a large amount of energy into the structure, which will appear as audible sound at each partition, floor, and wall that is rigidly coupled to the structure. Soft (damping) connections prevent energy transfer, thereby greatly attenuating the transmission of sound energy into connecting efficient radiating surfaces—hence the desirability of such flexible connections.

Airborne sound changes direction easily (diffracts), with low frequencies being most flexible in this regard. Structure-borne sound travels much more rapidly than airborne sound (see Table 17.1) and with attenuation as low as 1 dB per kilometer (about 0.5 dB per mile). A sound traveling along a massive structure will radiate outward from the structure only minimally (although enough to be very annoying) because the large mass minimizes vibration in that direction. Thus, in Fig. 19.10*b*, noise from impact on the floor above will be louder (for equal impact energy) than noise from



(b)

Fig. 19.10 *(a) Airborne sound is so called because it originates in air; its energy level is low. Here the loudspeaker is the source of acoustic energy, which is converted to a vibration of the partition (shown greatly exaggerated), which in turn becomes a secondary source of airborne sound for the adjoining space. A small amount of energy is reradiated by the ceiling and floor of both spaces directly, and indirectly via the rigid partition-to-floor and partition-to-ceiling connections. (b) Structure-borne sound originates from mechanical contact between the structure and vibrating or impacting sources. As such, its energy level is usually much higher than that of airborne sound. This energy is transmitted with little attenuation throughout the structure via the rigid partition-to-floor and partition-to-ceiling connections. The entire structure is then set into vibration as shown, converting the (large) structure-borne sound energy to noise throughout the building.*

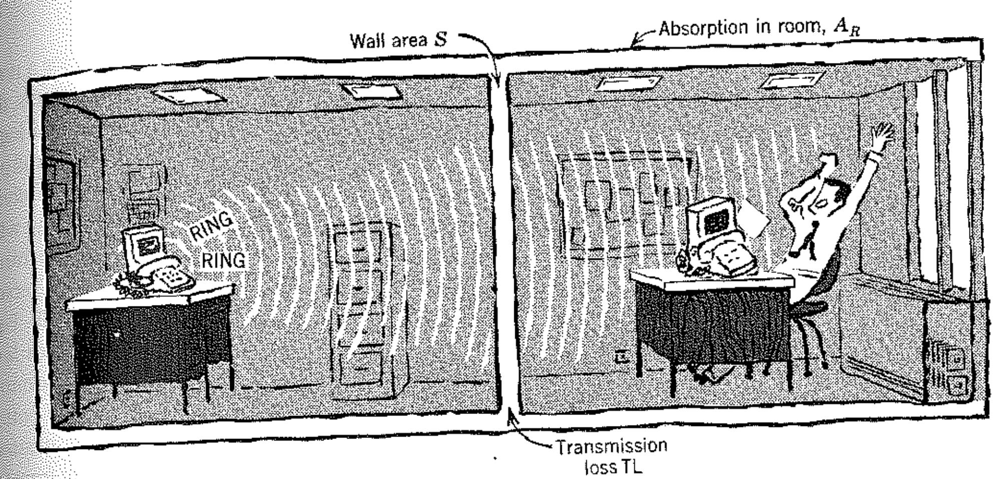


Fig. 19.11 *A simple case of airborne sound transmission between adjacent rooms through a common barrier. With a sound source in one room, the transmitted sound level is dependent not only on the transmission loss of the barrier but also on the area of the barrier and the receiving-room absorption. The background noise level in the receiving room determines whether the transmitted sound will be noticed.*

machines below, because the former generates sound directly downward, while the latter introduces energy into the entire network of parallel paths.

The sections immediately following deal with airborne sound and the means for controlling it (Fig. 19.11). Impact noise (a form of structure-borne sound) is covered in Sections 19.22 to 19.34.

AIRBORNE SOUND

19.7 TRANSMISSION LOSS AND NOISE REDUCTION

The transmission loss (*TL*) of a barrier is the ratio, expressed in decibels, of the acoustic energy reradiated by the barrier to the acoustic energy incident on it. This number is a figure of merit for the sound-isolating quality of the wall itself and is obtained from controlled laboratory tests. (In Europe, transmission loss is referred to as *sound reduction index*, *R*.) However, the number that is of greater importance to the building designer is the actual noise reduction (*NR*) between two spaces separated by a barrier, that is, the action of the barrier in context. This noise reduction is defined as the difference between the sound intensity levels in the two rooms, that is,

$$NR = IL_{\text{room 1}} - IL_{\text{room 2}} \tag{19.2}$$

and is related to the TL of the barrier by the expression

$$NR = TL - 10 \log \frac{S}{A_R} \tag{19.3}$$

where

NR = noise reduction, dB

TL = barrier transmission loss, dB

S = area of the barrier, ft² (m²)

A_R = total absorption of the *receiving* room, sabins, ft² (m²)

We see, therefore, that noise reduction and transmission loss are not equal but are related by the size of the dividing barrier, *S*, and the absorption characteristic of the receiving room, A_R. A moment's thought will confirm the logic of this relation. When sound energy impinges on the barrier, the barrier in turn becomes the sound source, radiating into the receiving room. Therefore, the amount of sound energy transferred is proportional to the (log of) area *S* of the common barrier between the two spaces.

The sound level in the receiving room is related to its own reverberance (absorption characteristic,

A_R), as we have seen repeatedly. Thus, if the receiving room is a reverberant, live space, A_R is low and *NR* is less than *TL*. Conversely, if the receiving room is dead, A_R is large and *NR* can be greater than *TL*, depending upon the ratio of the barrier wall size to the room area (see Fig. 19.11). In lieu of precise calculations, the following generalizations can be used:

1. For a live receiving room,

$$NR = TL - 1 \text{ dB}$$

2. For a medium receiving room,

$$NR = TL + 4 \text{ dB}$$

3. For a dead receiving room,

$$NR = TL + 7 \text{ dB}$$

The extreme case of "deadness" of a receiving room is one with no walls, that is, sound transmission from inside to the exterior. In such cases, *NR* exceeds *TL* by 10 to 15 dB, depending upon the size of the exterior opening and the point outside where *IL* is measured. To acquire facility with sound-insulation techniques, the designer must become familiar with the relationship of transmission loss to the barrier's physical characteristics, its mass, rigidity, material of construction, and method of construction and attachment. These considerations are the subject of the following sections.

Note: The reader is cautioned to be careful when encountering the term *noise reduction* (NR), since a similar and completely unrelated term—*noise reduction coefficient* (NRC)—also exists. The latter is very poorly named.

19.8 BARRIER MASS

Sound transmission between spaces requires that a barrier be set into vibration by the incident sound energy. Although this was stated in the preceding sections, we repeat it here to emphasize the fundamental importance of this simple statement. (We are assuming a barrier that is impervious to air—i.e., a solid barrier. Otherwise, the moving air molecules bearing the sound will simply pass through with minimal transmission loss.) The impinging sound energy acts as a force on the wall. Since $F = MA$, the larger the mass, the less it will vibrate. When other factors (particularly angle of incidence) are taken into account, the resultant acoustical relationship is known as the *mass law*. It states that for a nonporous, homogeneous structure of low stiffness, the sound transmission loss is proportional to the logarithm of the surface mass (the weight of the wall per unit of surface area) and to the frequency of vibration. Thus, doubling the mass (or frequency) will, theoretically, cause an increase of 6 dB in the transmission loss; stated otherwise, the slope of *TL* versus the frequency times mass (*fM*) curve is 6 dB. Figure 19.12 is a graphic representation of mass law operation. With sound incident at 9°, maximum energy is imparted to the barrier and the entire mass resists, resulting in maximum transmission loss. In practice, however, sound is incident from 0° to 80° (called *field* or *random incidence*), reducing the mass effect but keeping the slope at 6 dB per octave. Due to nonhomogeneity, porousness, and stiffness, actual field results indicate transmission losses closer to 4 dB per octave, as shown by the lower curve in Fig. 19.12.

19.9 STIFFNESS AND RESONANCE

The *stiffness* of a barrier is a function of its material composition and the rigidity of its mounting. The former depends upon its internal cohesiveness—that is, its modulus of elasticity—and the latter depends upon its boundary restraints—whether the barrier is tightly or loosely held. A homogeneous material of high Young's modulus (such as steel) has great cohesiveness between its molecules. As soon as one molecule is set in motion by incident sound energy, the motion is passed to the next molecule, and so on, making the material an excellent sound conductor. Homogeneous materials with a low modulus of elasticity have high internal damping (the motion of molecules is not transmitted well), and they are good sound insulators. Composite materials such as concrete and organic materials such as wood do not conform to these general rules.

Rigidity of mounting can be likened to a drumhead—the tighter it is stretched, the better it resounds. Rigidity (stiffness) in a panel barrier resists damping and assists vibration, making it a good transmitter and, conversely, a poor noise transmission insulator. As a result, a material such as lead, which has a high mass and a low modulus of elasticity and resists rigid mounting, is an excellent sound attenuator.

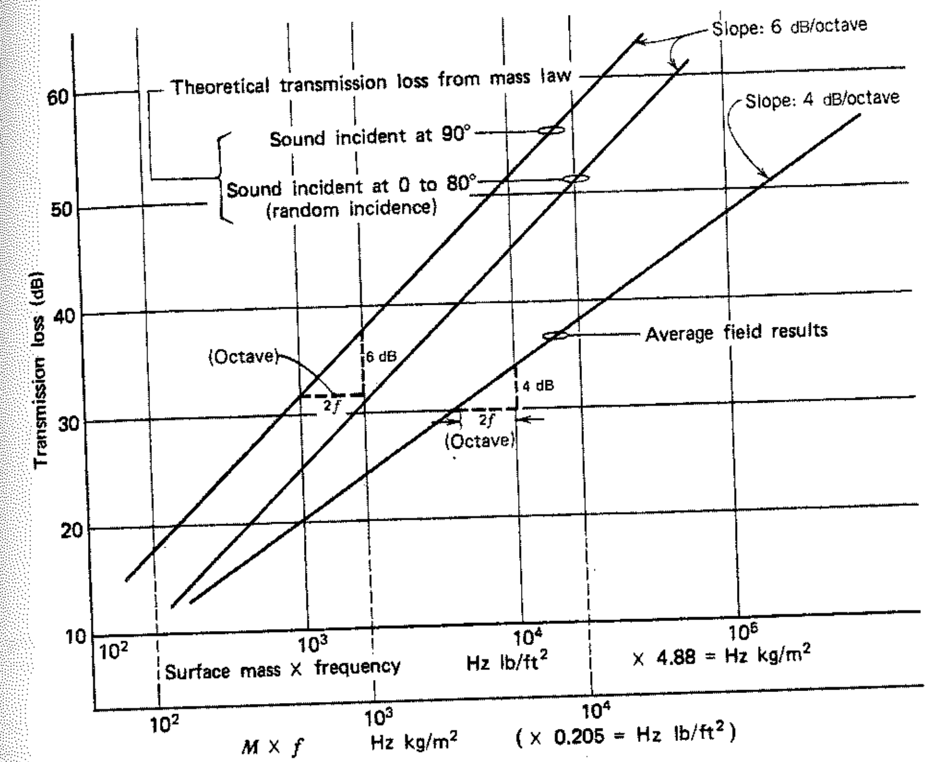


Fig. 19.12 Graphic representation of mass law action in attenuation of transmitted sound. Perpendicular (90°) sound incidence results in maximum transmission loss. Field or random incidence (0° to 80°) is approximately 6 dB lower but maintains the 6-dB-per-octave slope. Field results are lower due to flanking and stiffness effects, and the slope of the curve averages only 4 dB per octave (frequency doubling).

The effects of stiffness and mass both vary with frequency, unfortunately in opposite directions. Stiffness acts to reduce transmission loss as frequency increases, while, as we have seen, mass acts to increase it; the combined effect is shown in Fig. 19.13. Therefore, stiffness is most effective at low frequencies and mass at high frequencies. At very low frequencies the mass and stiffness effects negate each other, giving the resonance dips shown. Beyond approximately 200 Hz, most common wall construction enters the mass law range and continues with it until the critical frequency. Deviations from a smooth 4 to 6 dB per octave slope are due to the nonhomogeneous nature of most wall constructions. At the *critical frequency* the phase of incident sound waves corresponds to or coincides with the phase of vibration (shear wave) of the barrier in such a way as to pass a large portion of the incident energy. See the insert in Fig. 19.13, which shows this effect as the coincidence dip. This effect is most pronounced in thin, homogeneous partitions and light, stiff ones.

Critical frequency, f_c, as a function of panel thickness for common materials, is plotted in Fig. 19.14. To avoid a coincidence dip in the audible range, partitions can be either very heavy and/or very stiff (which greatly decreases the critical frequency) or heavy and limp (resilient—which greatly increases the critical frequency). In practical terms, cost effectiveness is heavily in favor of the latter alternative. Thus, for instance, the transmission loss of a wood partition can be improved by grooving it to increase its flexibility, thereby increasing the critical frequency. The dramatic improvement in transmission loss, resonances, and coincidence dip achieved by the use of resilient mounting of a simple masonry partition is shown in Fig. 19.15. Both walls have the same weight—approximately 21 lb/ft² (102 kg/m²). The solid wall *A* has better attenuation below 200 Hz in the stiffness-controlled range. Above that frequency the resilient-mounted partition is 10 dB better, which means that the transmitted noise is only one-half as loud. The sound transmission class (STC) (which

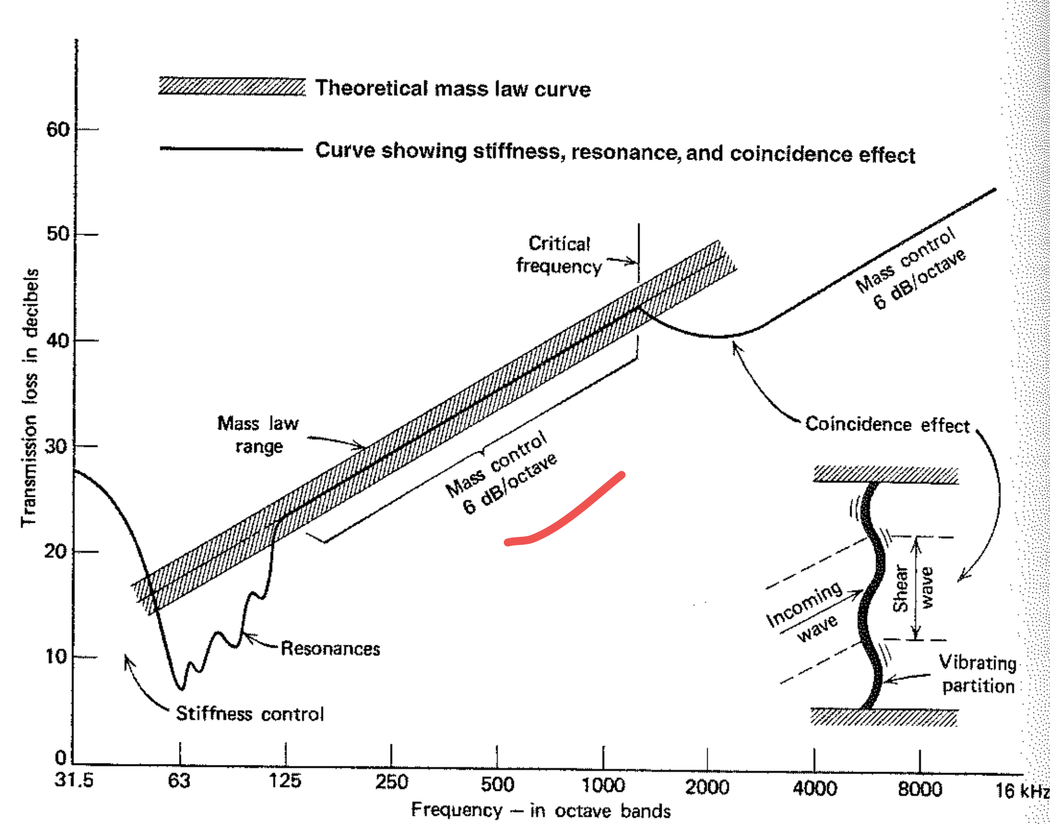


Fig. 19.13 Partition transmission loss as a function of frequency showing the effects of stiffness, resonance, and coincidence. At frequencies below resonance, control is almost purely a stiffness function; at frequencies above critical, control is almost purely a surface mass function.

is a figure of merit for partition sound transmission, as explained in Section 19.11) of wall *A* is 40; that of wall *B* is 51. Both show a coincidence dip at approximately 250 Hz (see Fig. 19.14), but that of *B* is shallow, whereas that of *A* is deep and wide. Furthermore, wall *B* is consistently better than mass law attenuation would predict, wall *A* consistently worse (due to stiffness).

19.10 COMPOUND BARRIERS (CAVITY WALLS)

Since the maximum theoretical increase in transmission loss with an increase of mass is 6 dB per doubling of mass, it is apparent that this method of transmission loss improvement rapidly reaches the limits of practicality. Indeed, as we have seen, the transmission loss of actual single homogeneous walls fall below the mass law curve. This is because mass increase brings with it stiffness increase, which acts to *reduce* transmission loss. If, however, a barrier is constructed of two separate layers without rigid interconnection, its performance exceeds the calculated transmission loss based on mass alone. Note that even the nonrigid wire ties of wall *B* in Fig. 19.16 lower the STC by five points. At low frequencies, where stiffness controls the transmission loss (see Fig. 19.13), the cavity in wall C (Fig. 19.16) acts as a rigid connection between the layers, adding stiffness and increasing transmission loss. At higher frequencies, in the mass law range, the air in the cavity acts as a damping coupling to reduce stiffness. The net result is an improvement in performance throughout the frequency range.

Transmission loss for the entire cavity wall increases with the width of the air space at the rate of approximately 5 dB per doubling. Performance can be improved still further by filling the void with porous, sound-absorbent material. This acts to further decrease the stiffness of the compound structure *and* to absorb sound energy that reflects back and forth between the two inside surfaces. The performance of

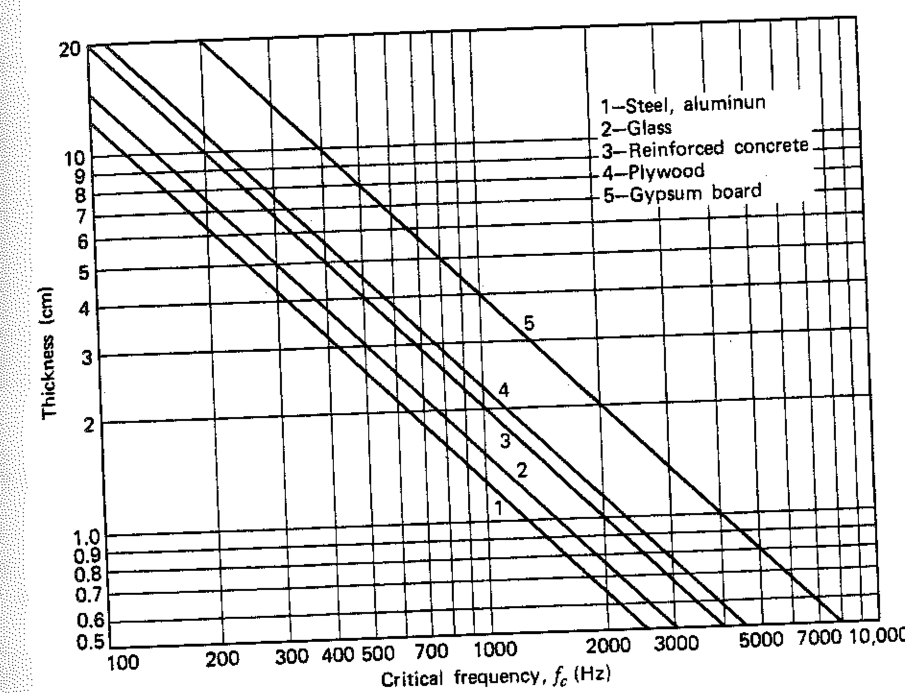


Fig. 19.14 Critical frequency as a function of thickness for several common materials. (Reprinted with permission from E. B. Magrab. 1975. Environmental Noise Control. Wiley. New York.)

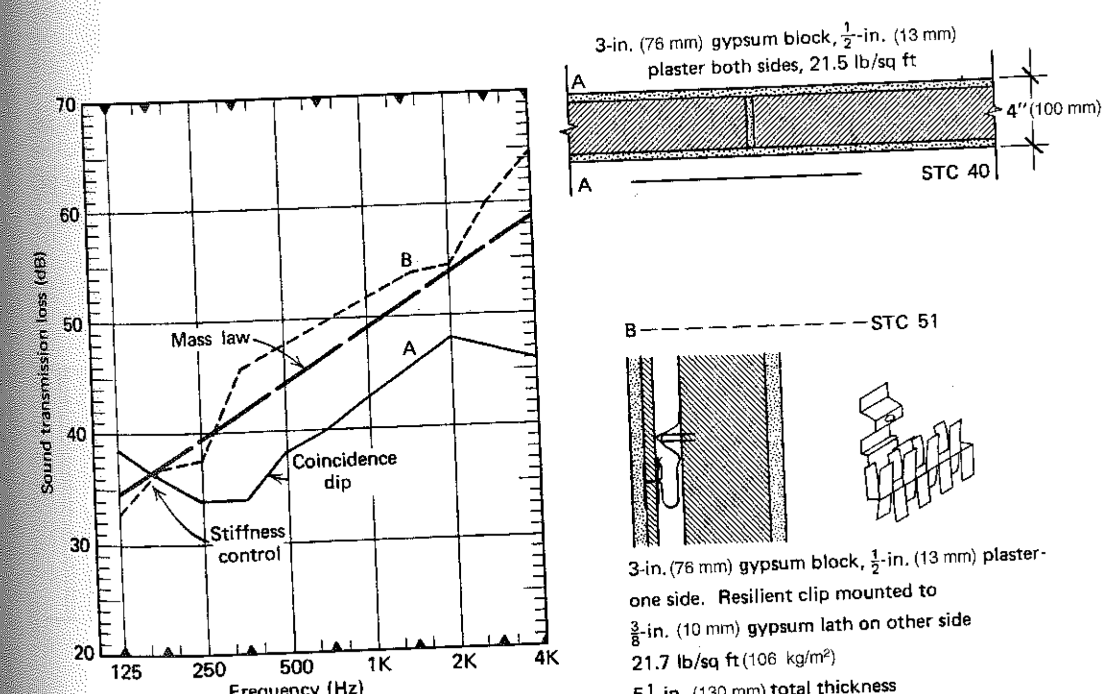


Fig. 19.15 Transmission loss characteristics of two equal-weight partitions with similar boundary constraints. The solid partition A performs worse than the mass law, due to stiffness. The resilient-mounted wall B performs better than the mass law and much better than wall A, except at the lowest frequencies. (Data extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968.)

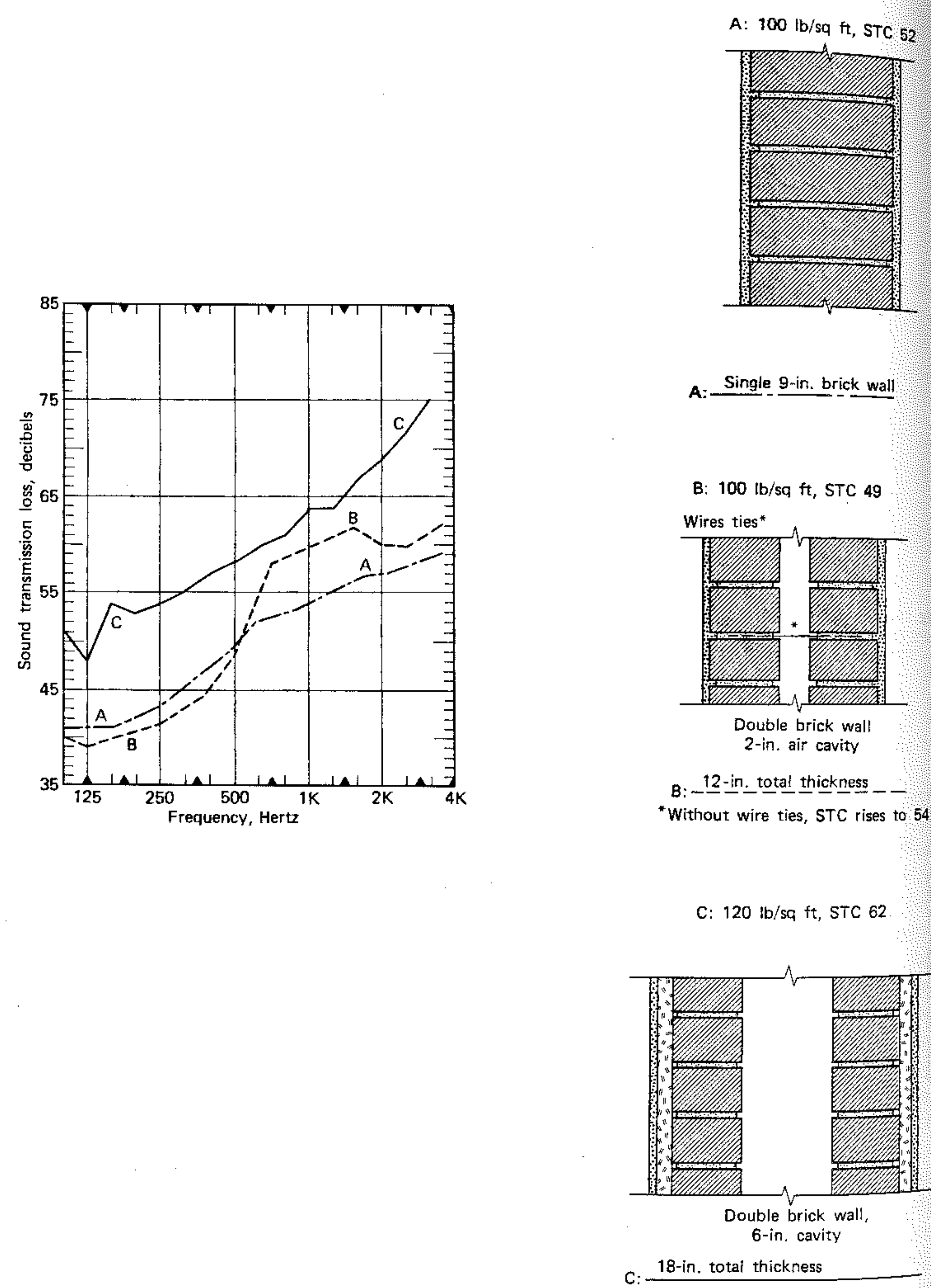


Fig. 19.16 Transmission loss curves showing the effect of air space on heavy wall construction. All three walls are approximately the same mass. The 2-in. (50-mm) air space of wall B is not significant until the higher frequencies, whereas the large 6-in. (200-mm) air space of wall C is effective throughout the frequency spectrum. (Data extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968.)

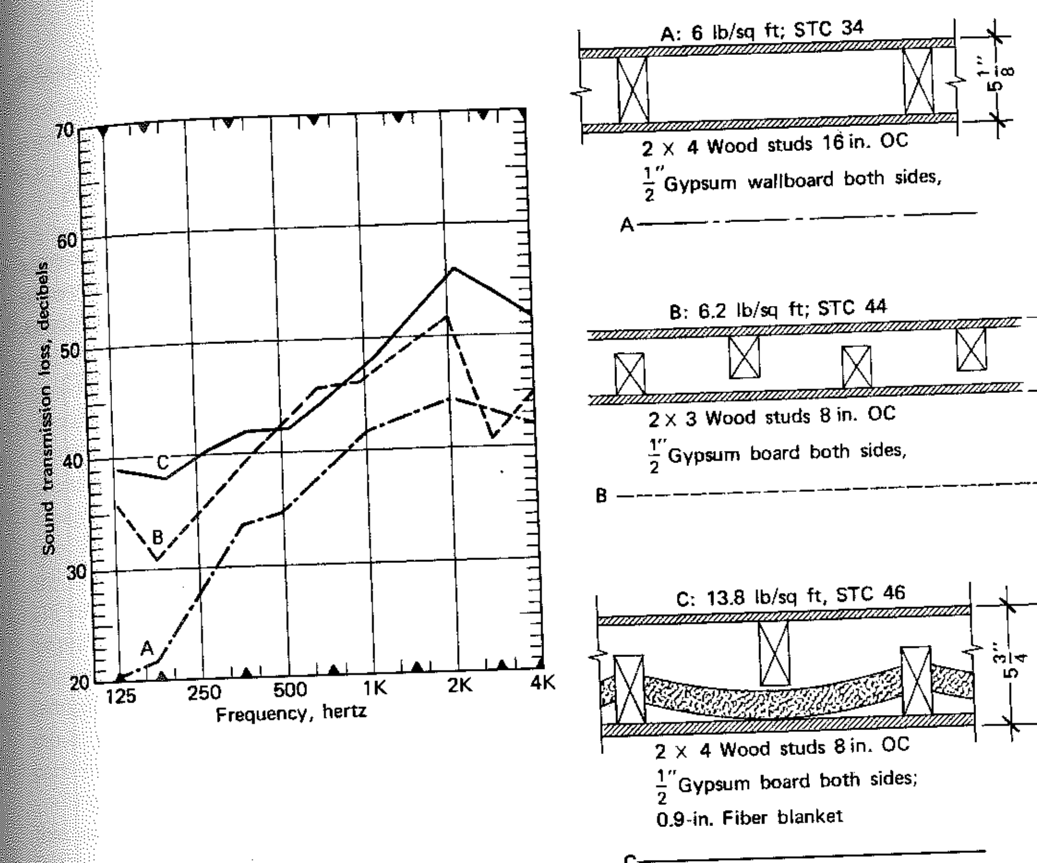


Fig. 19.17 Transmission loss curves illustrating the effect on lightweight walls of stiffness reduction and addition of absorptive material in the cavity. Curve A is a standard stud wall typically found in frame construction. Curve B shows the advantage of staggered studs over the entire frequency range. The dip at 3 kHz is a coincidence dip for a single leaf. Addition of absorptive material (Curve C) improves the attenuation characteristic at both ends of the spectrum and is particularly useful for its low-frequency improvement. (Data extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968.)

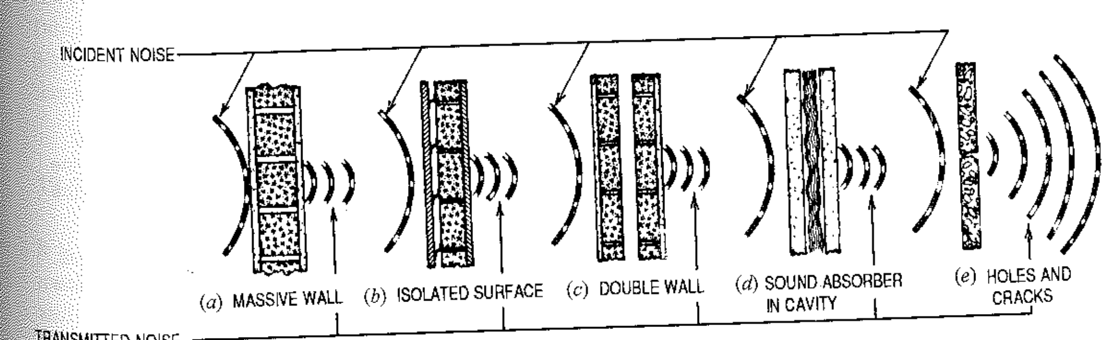
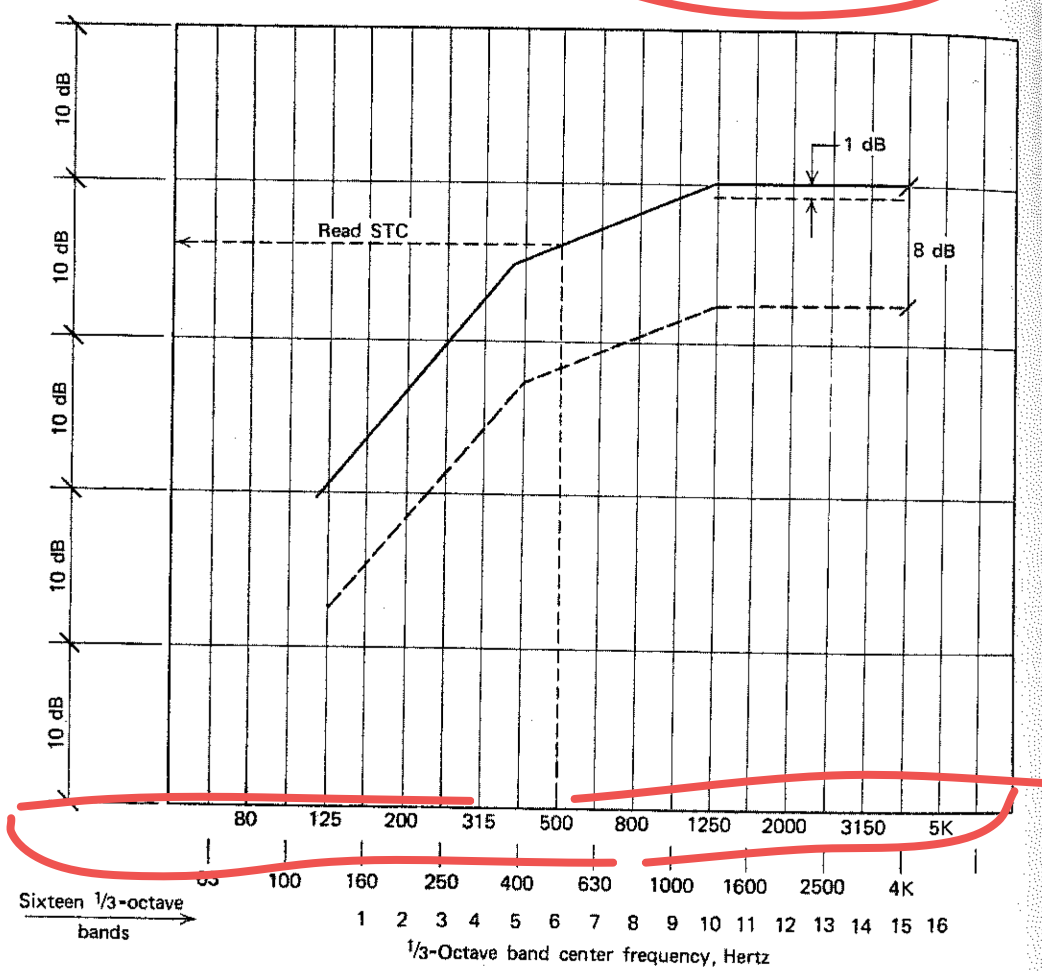


Fig. 19.18 The various techniques used to increase the transmission loss of a partition are shown in (a–d). In contrast, even a very small air path through the partition (e) can effectively destroy its effectiveness as a sound barrier. (Data extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968.)

cavity walls is reduced by any rigid interconnections between leaves. Thus, a common stud wall with frequent rigid interconnections acts little better than a single homogeneous wall. However, a stud wall with staggered studs exhibits greatly improved performance over a single-material wall or a common stud wall. These effects are illustrated in Figs. 19.16 and 19.17 (see also Appendix K). The effects of mass (Section 19.8), stiffness (Section 19.9), and compound barriers with and without filler are shown qualitatively and graphically in Fig. 19.18.

19.11 SOUND TRANSMISSION CLASS

Various attempts at using a single-number average transmission loss to describe a barrier's characteristics have been made, with only limited success.



The STC is determined by comparison with a transparent overlay of this graph on which the STC contour is drawn. The STC contour is shifted vertically, relative to the test curve, until some of the measured *TL* values for the test specimen fall below those of the STC contour (the solid line) and the following conditions are fulfilled:

1. The sum of the deficiencies (i.e., the deviations below the contour) shall not be greater than 32 dB.
2. The maximum deficiency at a single test point shall not exceed 8 dB [the broken (dashed) line beneath the STC contour].

When the contour is adjusted to the highest value (in integral dB) that meets the above requirements, the sound transmission class for the specimen is the *TL* value corresponding to the intersection of the contour and the 500-Hz ordinate.

Fig. 19.19 *Overlay from which sound transmission class (STC) is determined graphically.*

Indeed, such averages can be misleading, since they ignore both deficiencies and proficiencies at particular frequencies. Their use, therefore, in all but rough work is to be discouraged.

To avoid the shortcomings of averages and yet to benefit from the indisputable convenience of single-number ratings, a system of standard contours was developed in the United States called *sound transmission class* (STC) contours. (A similar system, conforming to ISO 717-1, 1996, is used in Europe, involving a weighted sound reduction index R_W. In practice, the STC number for a particular barrier construction is derived by comparing actual test results measured in a series of sixteen ⅓-octave bands to the standard STC contours according to a fixed procedure. The technique is illustrated in Fig. 19.19. Figure 19.20 shows two transmission loss curves and STC ratings of each. Because STC fails to give credit for performance *above* the established requirements, octave-band transmission loss data, rather than STC ratings, should be used in all critical areas such as music rooms or mechanical rooms where certain particular frequencies may be dominant.

Figure 19.21 gives three standard STC contours that are of interest because they are used by the Federal Housing Administration (FHA) to specify grades of construction. The criteria for their application are found in Section 19.33. An appreciation of the degree of speech sound insulation provided by walls with different STC ratings is given in Section 19.17 (see Table 19.5). Since the subjective reaction on the quiet side depends upon the background sound level, the table gives this reaction for two NC curve levels. To assist the designer, extensive sound transmission testing has been performed on most types of standard wall and partition construction and the results published. Tables 19.1 and 19.2 and Appendix K give descriptions of constructions with typical details, transmission loss data, STC ratings, and other pertinent data.

19.12 COMPOSITE WALLS AND LEAKS

It is frequently necessary to determine the transmission loss of a composite wall—that is, a wall with a window, door, louver opening, and the like. It should be appreciated that the two elements are "in parallel," to borrow an electrical concept, and the behavior is similar to that situation. That is, the overall performance will be strongly affected by the

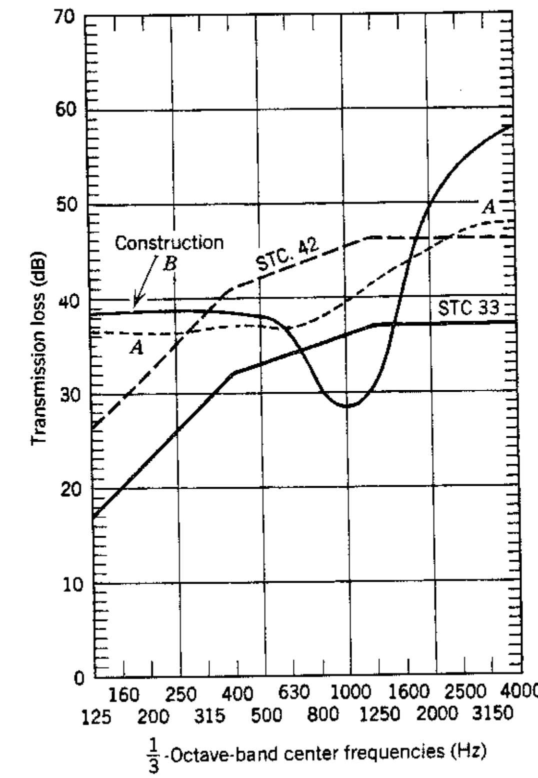


Fig. 19.20 *Curves A and B are two different construction types with the same average transmission loss. However, application of the STC curve criteria (given in Fig. 19.19) yields an STC of only 33 for construction B because of its deep center dip compared to STC of 42 for construction A. (From E. B. Magrab 1975.* Environmental Noise Control. *Wiley. New York.)*

poorer of the two, with some tempering of the degradation when the poorer barrier is much smaller in area than the other barrier element. Figure 19.22 enables us to analyze situations of this type.

Since an opening in a wall is effectively a second material of $TL = 0$, the curves in Fig. 19.22 can be replotted for this situation as in Fig. 19.23. Note that the curves very rapidly flatten out; thus, any wall with a 1% open area will have a *maximum* transmission loss of 20 dB, which is all but useless as a sound barrier. For this reason, it is imperative that all openings be completely sealed, particularly those around doors and windows. A hairline crack degrades a wall 6 dB, a keyhole degrades a door 3 dB, and so on. Special considerations for doors and windows are discussed in the next section. Care must also be taken with such common acoustic leaks as back-to-back electric outlets, pipes passing through walls, and medicine cabinets—in fact any break in the integrity of a partition. All such openings must be caulked to

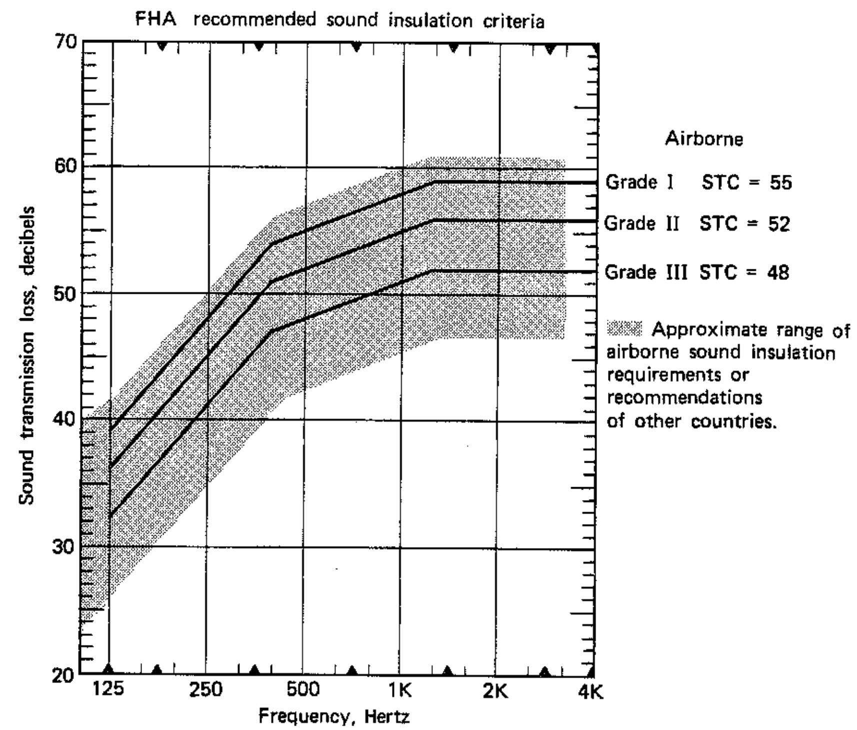


Fig. 19.21 Sound insulation criteria recommended by the FHA. (From A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *1968.)*

TABLE 19.1 Improvements in STC Rating of Stud[a] Partitions[b]

Description	STC[c]
Basic partition: single wood studs, 16 in. (406 mm) on centers, ½-in. (13-mm) gypsum board on both sides, air cavity	35
Add to basic partition	
Double gypsum board, one side	+2
Double gypsum board, both sides	+4
Single-thickness absorbent material in air cavity	+3
Double-thickness insulation	+6
Resilient channel supports for gypsum board	+5
Staggered studs	+9
Double studs	+13

[a]For application to metal stud partitions, use adders as in note *b*, but begin with STC = 40 for a 3⅝-in. (92-mm) basic partition.

[b]When using two improvements, add an additional +2; for three improvements, add +3.

Example: Improvements to 35 STC basic partition:

Staggered wood studs	+9
Double gypsum board, one side	+2
Single-thickness insulation	+3
Adder (3 improvements)	+3
Total	+17
Total STC	35 + 17 = 52

[c]The STC figures are conservative. Other sources list the same constructions with 1 to 5 points higher STC.

TABLE 19.2 STC Ratings of Masonry Walls

Description	STC[a]
4-in. (102-mm) lightweight[b] hollow block	36
4 in. (102-mm) dense hollow block	38
6-in. (152-mm) lightweight hollow block	41
6-in. (152-mm) dense hollow block	43
8-in. (203-mm) lightweight hollow block	46
8-in. (203-mm) dense hollow block	48
12-in. (305-mm) lightweight hollow block	51
12-in. (305-mm) dense hollow block	53
4-in. (102-mm) brick	41
6-in. (152-mm) brick	45
8-in. (203-mm) brick	49
12-in. (305-mm) brick	54
6-in. (152-mm) solid concrete	47
8-in. (203-mm) solid concrete	50
10-in. (254-mm) solid concrete	53
12-in. (305-mm) solid concrete	56

[a]See note c, Table 19.1.

[b]All ratings of lightweight block assume sealing with paint. Note that this reduces absorption.

Modifications

Add sand to cores of hollow blocks	+3
Add plaster to one side	+2
Add plaster to both sides	+4
Add furring strips, lath and plaster:	
One side	+6
Two sides	+10
Add plaster via resilient mounting:	
One side	+10
Two sides	+15

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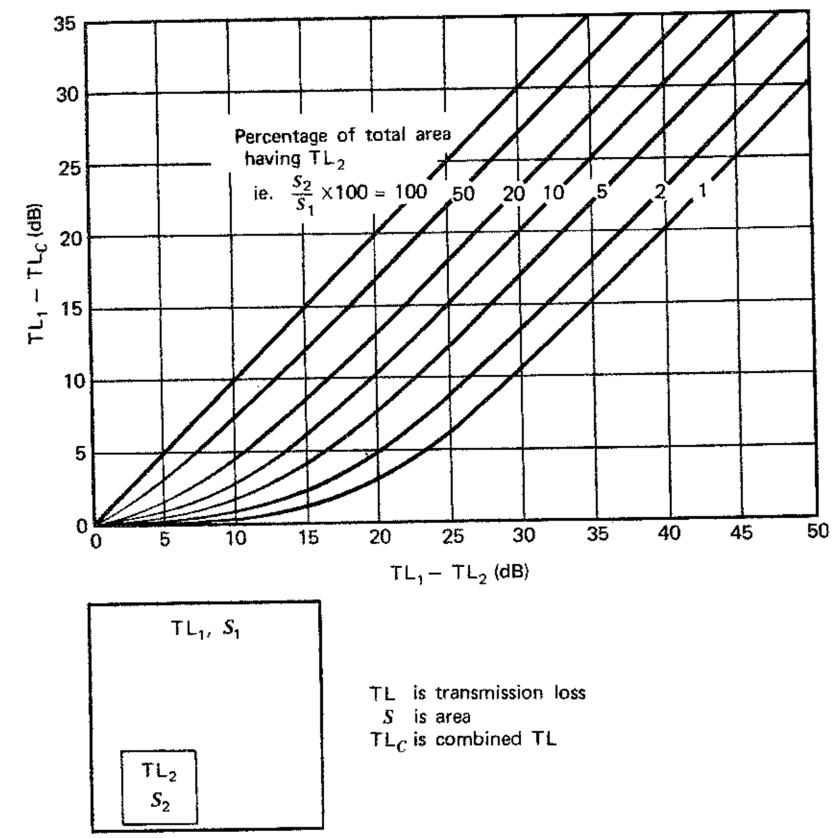

Fig. 19.22 Transmission loss of a two-element composite barrier as a function of the relative transmission loss of the components. (From E. B. Magrab. 1975. Environmental Noise Control. *Wiley. New York.)*

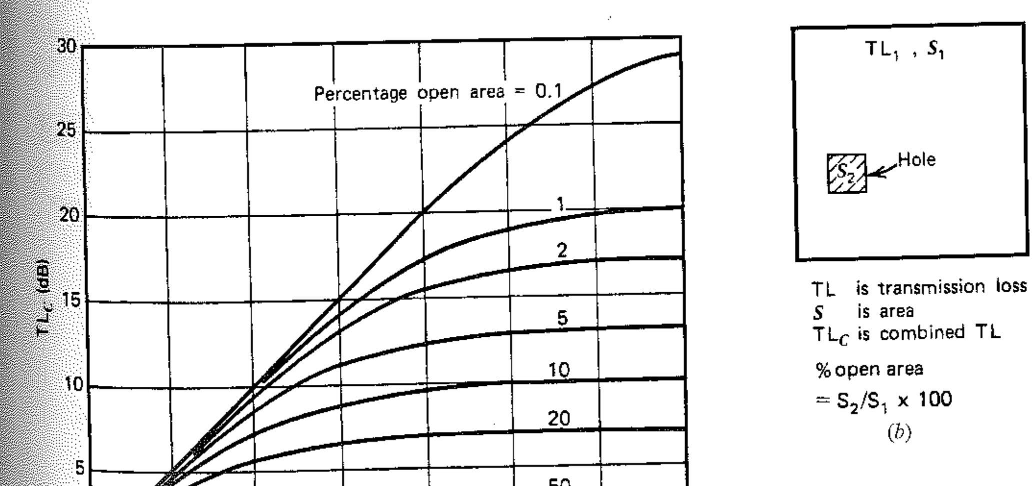

Fig. 19.23 Effect of a hole of a given size (as a percentage of the total area) on a partition with a given transmission loss. (From E. B. Magrab. 1975. Environmental Noise Control. *Wiley. New York.)*

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make an airtight joint if any appreciable degree of sound insulation is to be maintained.

Examples 19.1 and 19.2 show how barriers of high transmission loss are degraded by standard openings. To maintain the integrity of a barrier, special care must be taken in the design of windows and doors, as explained in Section 19.13.

EXAMPLE 19.1 Given a 9-ft × 18-ft (2.7 × 5.5-m) wall with a transmission loss of 52 dB at 1000 Hz, containing a 3-ft × 7-ft (0.9 × 2.1-m), 6-in. (150-mm) hollow core door of 22 dB transmission loss at that frequency, find the overall transmission loss of the composite wall.

SOLUTION

Refer to Fig. 19.22.

$$TL_1 - TL_2 = 30 \text{ dB}$$

$$\frac{S_2}{S_1} = \frac{3 \times 7.5}{9 \times 18} \times 100 = 13.9\%$$

From the curves in Fig. 19.22:

$$TL_1 - TL_c = 21.5$$

$$TL_c = 52 - 21.5 = 30.5 \text{ dB}$$

That is, a door with an area of only 14% of the entire wall reduces the transmission loss of the structure from 52 to 30.5 dB—that is, from excellent to very poor. ■

EXAMPLE 19.2 An exterior brick/frame wall having a transmission loss of 54 dB at 1000 Hz, measuring 8 ft × 16 ft (2.4 × 4.9 m), is pierced by two wood-frame windows, each of area 3 ft × 4 ft (0.9 × 1.2 m), with single ⅛-in. (3-mm) glass, with a transmission loss of 34 dB at 1000 Hz. Find the combined transmission loss.

SOLUTION

$$TL_1 - TL_2 = 54 - 34 = 20 \text{ dB}$$

$$\frac{S_2}{S_1} = \frac{2 \times 3 \times 4}{8 \times 16} \times 100 = 18.8\%$$

From Fig. 19.22:

$$TL_1 - TL_c = 12.5 \text{ dB}$$

$$TL_c = 54 - 12.5 = 41.5$$

Again, the result is a reduction from an excellent wall to a poor one. ■

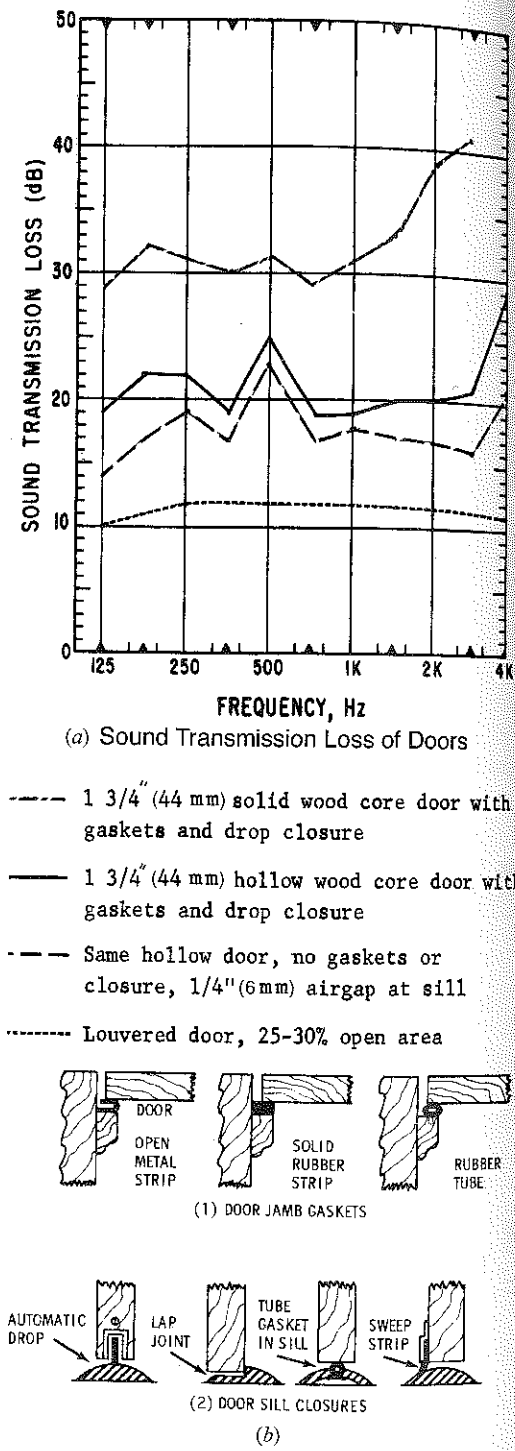

Fig. 19.24 (a) Chart of typical transmission loss values for representative door constructions as a function of frequency. (b) Method for gasketing a door edge enclosure (1) and sealing the gap between the bottom of the door and the door saddle (2). (Chart and drawings extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *1968.)*

19.13 DOORS AND WINDOWS

As can be appreciated from the preceding section, doors and windows can in large measure determine the overall transmission loss of a wall. Since in almost every instance doors and windows have a lower acoustic transmission loss than the wall in which they are mounted, particular care must be taken not to degrade performance further with air leaks.

(a) Doors

Figure 19.24 gives nominal transmission loss data for the most common types of doors as a function of frequency. Average transmission loss values for doors, that is, the arithmetic average of the octave band transmission losses in the range of 150 Hz to 3000 Hz, are not useful for two reasons:

- The very important low-frequency attenuation data are absent.
- Sharp peaks and valleys in the curves (see, for instance, the 6-dB peaks at 500 Hz in Fig. 19.24*a*) are unrecognized. As a result, a particularly troublesome frequency may not be sufficiently attenuated. In the absence of a complete frequency analysis, the STC rating of a door is a better indication than an average transmission loss figure. Typical STC values are given in Table 19.3.

Conclusions that can be drawn from inspection of Fig. 19.24*a* are:

1. Louvered doors (and doors undercut to permit air movement) are useless as sound barriers.
2. The most important step in soundproofing doors is complete sealing around the opening. A door in the closed position should exert pressure on gaskets, making the joints airtight (see Fig. 19.24*b*).

TABLE 19.3 Typical STC Values for Doors

Door Construction	STC
Louvered door	15
Any door, 2-in. (51-mm) undercut	17
1½-in. (38-mm) hollow core door, no gasketing	22
1½-in. (38-mm) hollow core door, gaskets and drop closure	25
1¾-in. (45-mm) solid wood door, no gasketing	30
1¾-in. (45-mm) solid wood door, gaskets and drop closure	35
Two hollow core doors, gasketed all around, with sound lock	45
Two solid core doors, gasketed all around, with sound lock	55
Special commercial construction, with lead lining and full sealing	45–65

When a single door does not provide sufficient attenuation and specially constructed high-attenuation commercial acoustic doors are not practical, a simple and very effective technique is the construction of a sound lock consisting of two doors, preferably with sufficient space between them to permit full door swing (see Fig. 19.25). All surfaces in the sound lock should be covered completely by absorbent material and the floor carpeted. Such an arrangement will increase attenuation across the board by at least 10 dB and by as much as 20 dB at some frequencies, depending upon the shape of the sound lock and the type, amount, and mounting of absorptive material in the sound lock. The two doors of the sound lock must be gasketed, as explained in the preceding discussion.

Another important consideration with respect to sound intrusion via doors is the location of a door relative to sources of unwanted sound. This is particularly important in multiple-resident buildings of all types, including private homes, apartment

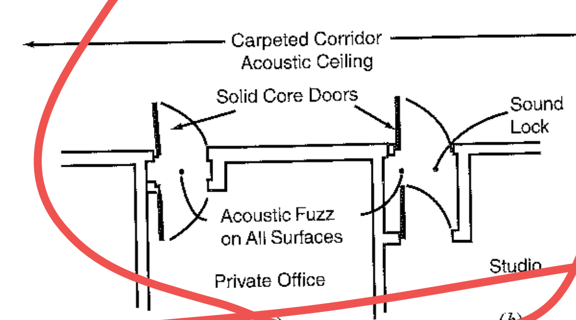

Fig. 19.25 A two-door sound lock should increase the transmission loss of a door assembly by a minimum of 10 dB for the small lock (a) and 15 dB for the larger one (b), depending upon the type, thickness, and mounting technique of the absorptive material in the lock. The solid core doors must be sealed by one of the techniques shown in Fig. 19.24b.

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houses, dormitories, hotels, and rooming houses. The same principle applies to commercial spaces where numerous private spaces such as offices open onto a common lobby or foyer. Figure 19.26 shows the effect of improvements in door placement.

(b) Windows

Windows are critically important to block exterior noise, and all the more so, since exterior wall construction is generally of high STC, making the window the deciding factor in the composite exterior wall transmission loss. Sound leaks through cracks in closures of operable windows will normally establish a window's rating, regardless of the type of glazing. Fortunately, the attention now given to the sealing of windows for thermal purposes has had a salutary effect on their acoustic properties. As with doors, the importance of proper gasketing and sealing cannot be overemphasized. Double glazing is effective only when the two panes are separated by a wide air gap (Fig. 19.27). A narrow air gap acts as a stiff spring between the panes and transmits sound energy almost unattenuated. The result is approximately that of a single pane of double weight. Note that here too, as with absorptive material, the requirements of acoustic and thermal insulation are opposed. A small sealed air space between panes is desirable for thermal insulation, because a large space allows convection currents to transfer heat. For acoustical purposes, a small sealed space is not very useful, as explained previously, whereas a large space traps acoustic energy and is an effective noise barrier, as is clearly seen in Fig. 19.28.

In addition to a window's sound transmission characteristic when closed, it is important to consider the transmission loss when open because of ventilation and passive cooling requirements. The sound attenuation between the center of a room with a clear-through open window and a point some distance outside is 5 to 15 dB. This drops to about 5 dB as the receiver-observer approaches the open window. By making the path from inside to outside indirect, the open window attenuation can be increased to as much as 25 dB, but with considerable reduction of airflow and hence ventilation capacity. Several possible arrangements with approximate mid-frequency transmission loss figures are given in Fig. 19.29. This principle can be applied advantageously when exterior noise reduction is important but

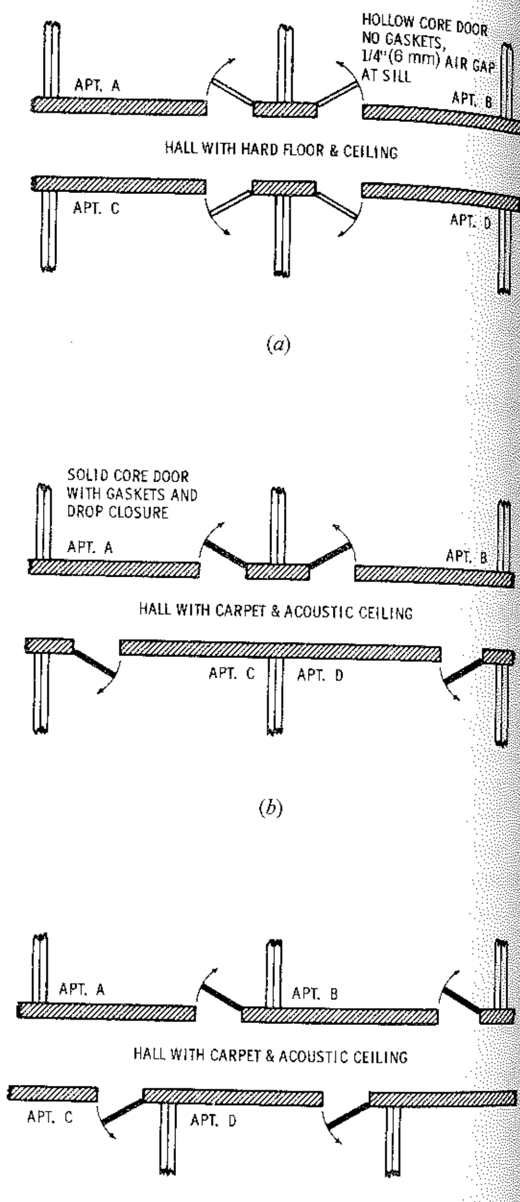
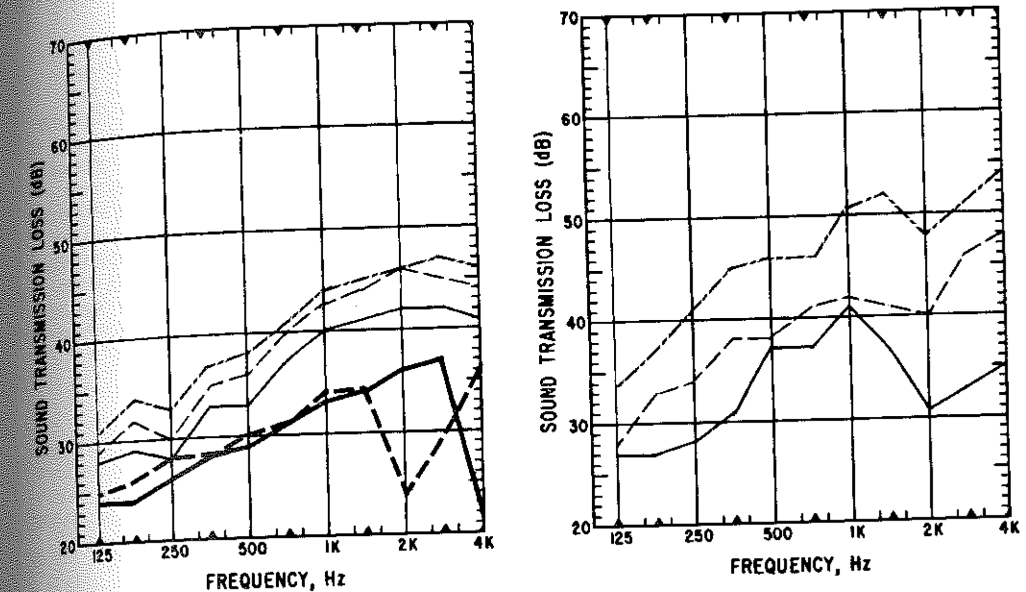


Fig. 19.26 Proper arrangement of doors to rooms on a common corridor can diminish noise transfer in the area. (a) Poor arrangement because any noise emanating from one of the rooms or from the corridor has a very short and unattenuated path into the remaining rooms. (b) Better arrangement than plan (a) because noise from any source must travel a minimum of a room width along an absorbent corridor to reach any other room. Noise to the remaining rooms is further attenuated. The weak point of this plan is a noise short circuit via adjacent doors for Apt. A and Apt. B. Plan (c) is best because there are no short circuits for sound travel. Although the A–C and B–D paths are slightly shorter than in plan (b), the difference would not be noticeable. (Extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968.)



1/8-in. (3 mm) plate glass
1/4-in. (6 mm) plate glass
0.45-in. (11 mm), 3 ply, laminated glass panel
0.62-in. (46 mm), 4 ply, laminated glass panel
0.80-in. (20 mm), 5 ply, laminated glass panel

(a)

Aluminum framed windows with glass panes isolated with neoprene gaskets
two 1/4-in. (6 mm) glass panes, 1/2-in. (13 mm) air space.
1/4-in. (6 mm) and 3/16-in. (20 mm) glass panes, 2 1/2-in. (64 mm) air space.
1/4-in. (6 mm) and 7/32-in. (20 mm) glass panes, 3 3/4-in. (95 mm) air space.

(b)

Fig. 19.27 (a) Sound transmission loss frequency spectrum shows the effect of thickening glass. The ¼-in. (6-mm) plate shows a very sharp (10-dB) coincidence dip at 2 kHz, making it less effective than ⅛-in. (3-mm) plate between 1500 Hz and 2500 Hz. Further thickening with laminated glass eliminates the coincidence drop but reaches a practical limit at about ½-in. (13-mm) thickness. (b) Note that two ¼-in. (6-mm) panes with a ½-in. (13-mm) air space act as a stiff, thick pane and exhibit the sharp coincidence drop at 2 kHz. Larger sealed inter-pane air spaces markedly improve the acoustic insulation performance.

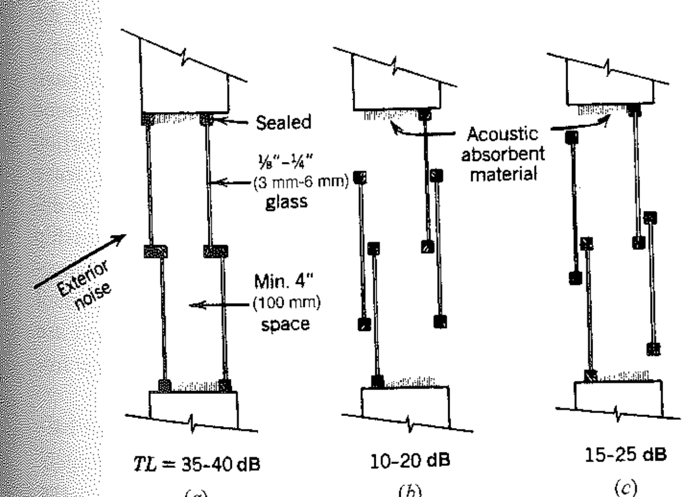


Fig. 19.28 The degree of attenuation of external noise can be regulated with acoustic sealant and absorbent materials when using pairs of double-hung (or horizontally sliding) windows. Ventilation airflow varies inversely with transmission loss.

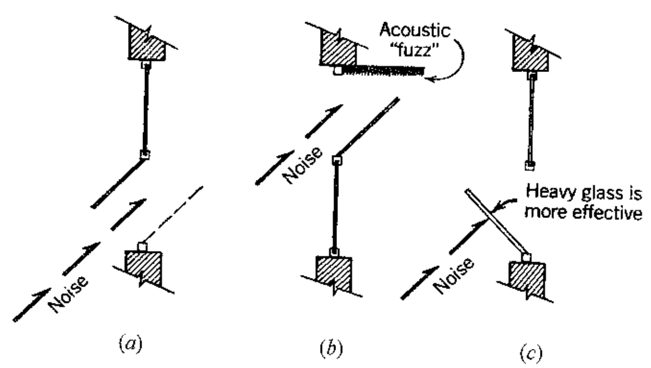


Fig. 19.29 Alternative arrangements of the same basic "hopper" window design can yield results differing by as much as 10 dB. Design (a) is entirely open, and the noise path is unobstructed deep into the room. Design (b) is about 5 dB better than (a) at frequencies above 1 kHz because of higher absorption and less diffraction. Lower frequencies diffract readily around the window leaf and are less affected by absorptive material. Design (c) can be 10 dB better than (a), particularly at high frequencies, because it interposes a rigid barrier into the noise path. In this arrangement, the glass thickness is important.

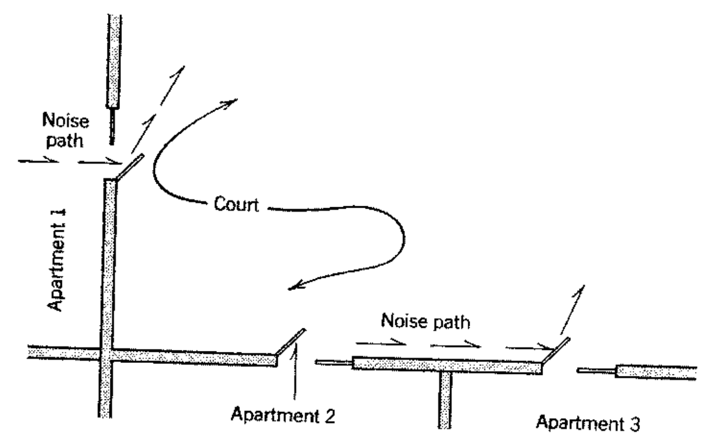


Fig. 19.30 Noise transfer between contiguous corner spaces, as in Apartments 1 and 2, can be particularly severe if windows are improperly designed. Swinging windows, as shown, are preferable to double-hung or hopper windows because they reflect sound away from the adjacent space. Similarly, adjacent spaces on the same wall, such as Apartments 2 and 3, can benefit from this type of swinging arrangement, which is preferable to sliding or double-hung designs.

sealed windows are undesirable. Window-opening style and placement can also have an effect on the amount of exterior noise admitted, as shown in Figs. 19.29 and 19.30. Typical STC ratings of common window constructions are given in Table 19.4.

TABLE 19.4 Typical STC Values for Windows

Window Construction	STC
Operable wood sash, ⅛-in. (3.2-mm) glass, unsealed	23
Operable wood sash, ¼-in. (6.4-mm) glass, unsealed	25
Operable wood sash, ¼-in. (6.4-mm) glass, gasketed	30
Operable wood sash, laminated glass, unsealed	28
Operable wood sash, double-glazed, ⅛-in. (3.2-mm) panes; ⅜-in. (9.5-mm) air space, gasketed	29
Fixed sash, double ⅛-in. (3.2-mm) panes, 3-in. (76-mm) air space, gasketed	44
Fixed sash, double ⅛-in. (3.2-mm) panes, 4-in. (102-mm) air space, gasketed	48

19.14 DIFFRACTION: BARRIERS

The physical process by which sound passes around obstructions and through very small openings is called *diffraction*. Simply stated, diffraction is a process whereby any point on a sound wave establishes a new wave when passing an obstacle. Thus, although much of a sound wave is blocked by a small opening, the portion that does get through establishes a new wave front (see Fig. 19.18*e*). The *amplitude* of the diffracted wave is determined by the relationship between the size of the opening and the wavelengths of the signal components. For a small hole, short wavelengths (high frequencies) are attenuated less than long wavelengths (low frequencies). See Fig. 19.31.

When sound encounters a finite-length barrier, it diffracts around and over it, approximately as shown in Fig. 19.32. The attenuation of the diffracted sound depends upon the frequency, type of source, and dimensions of the barrier. For a *point source*, with only a single *practical* path around the obstruction (barrier), the noise reduction in

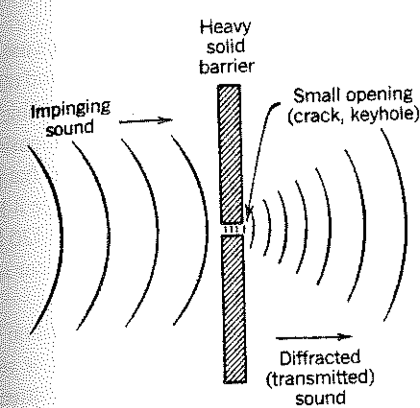


Fig. 19.31 Sound passes through small openings by diffraction. The intensity of the transmitted sound is proportional both to its frequency and to the size of the opening. It is always less than the intensity of the impinging sound.

decibels can be calculated from Maekawa's empirical equation (in I-P units):

$$NR = 20 \log \left[\frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} \right] + 5 \text{ dB} \qquad (19.4)$$

where

$N = (f/565)\,(A + B - d)$

NR = noise reduction, dB

f = frequency, Hz

$A + B$ = shortest path length around the barrier, ft (over or around)

d = straight-line distance, source-to-receiver, ft

tanh = hyperbolic tangent

Note that this equation:

1. Is applicable only to exterior barriers where sound passing over the barrier is partially diffracted and partially attenuated by distance. In an interior situation, sound passing over a partial height barrier (see Fig. 19.40) strikes the ceiling and is reflected down, increasing the received

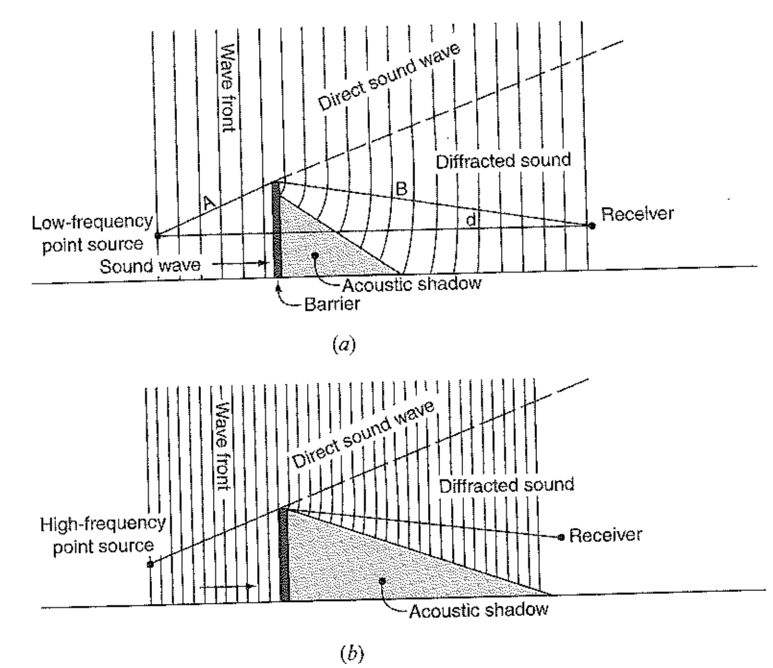


Fig. 19.32 Comparison of the effect of a barrier on sources of different frequencies. The low-frequency sound (a) diffracts more readily over the barrier than the high-frequency sound (b) because of its longer wavelength. Thus, the lower the frequency, the smaller the acoustic shadow and the lower the barrier attenuation. The shadow is not as sharply defined as shown; it represents increasing attenuation closer to the barrier

sound and effectively reducing barrier attenuation. Maximum exterior barrier attenuation is 24 dB as compared to about 15 dB for a partial-height interior partition.

2. Assumes that the barrier is very long (or very high), so that only one sound path exists. In practice, a barrier whose length (height) is at least four times the distance between the source and the wall is sufficient if *the barrier is close to the source.* If the barrier is close to the receiver, it must be longer (higher) still.

3. Assumes a point source. Line sources (such as traffic) show 20 to 25% less attenuation for the same barrier.

The equation will, however, give reliable, usable results when the dimensions of the source are small with respect to the barrier, as is the case for speech; individual motors, fans, engines, and other mechanical devices; and individual motor vehicles. The chart in Fig. 3.22 relates barrier dimensions and position to traffic noise reduction. Note that frequency is not a variable on the chart, since it has been plotted for an average attenuation at 220 Hz, which is the center frequency for random car and truck traffic.

It should be apparent that the best location for a barrier is either very close to the source or very close to the receiver. The worst position for attenuation is halfway between them. All effective barriers are assumed to be opaque and to have a minimum surface density of 5 lb/ft^2 (~25 kg/m^2). The inherent transmission loss of the barrier need not be very high; a massively thick barrier has only marginally higher attenuation than one with the aforementioned minimum surface weight. Absorptive material placed on the source side of a barrier will reduce the noise reflected back toward the source but will not effectively increase the barrier's attenuation with respect to the receiver. Although the maximum theoretical noise reduction of an *exterior* barrier is about 24 dB, in practice it rarely exceeds 20 dB. Figure 19.33 is a nomograph based upon Equation 19.4.

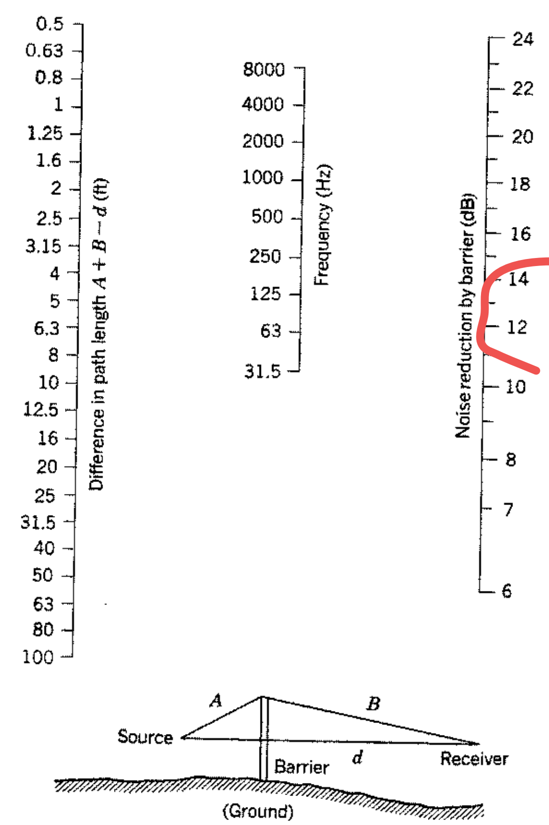
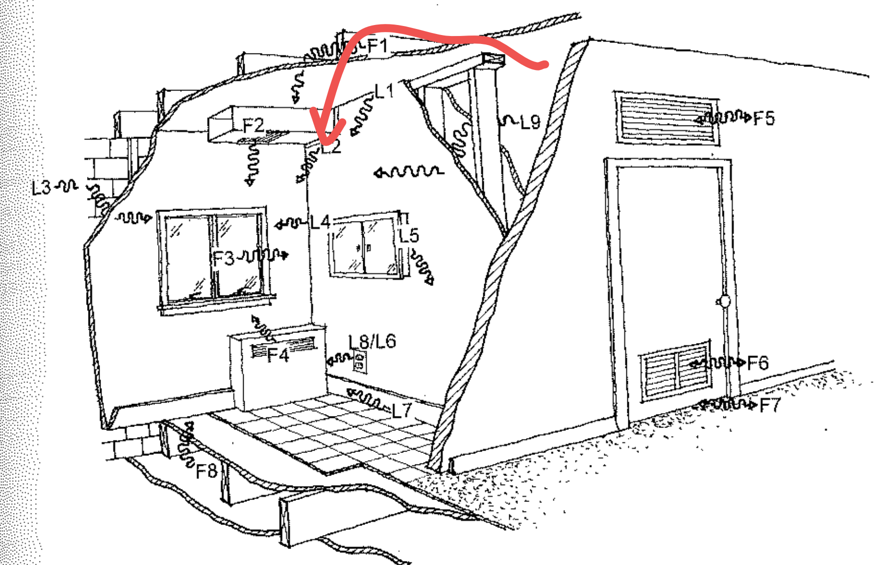


Fig. 19.33 This nomograph for estimating the noise reduction afforded by a barrier is based on Equation 19.4 and assumes a point (small) source and only a single path around the barrier. The dimensions A, B, and d are taken from the insert sketch. Dimensions A plus B represent the shortest path around the barrier—which may be over or around it. (Reprinted with permission from B. Fader. 1981. Industrial Noise Control. Wiley. New York.)

19.15 FLANKING

Just as sound will pass through the acoustically weakest part of a composite wall, it will also find parallel or flanking paths, that is, an acoustic short circuit. Proper design of window locations to avoid flanking paths has already been shown in Fig. 19.30. The same situation obtains with respect to doors, as shown in Fig. 19.26, and any other openings between spaces. Thus, in Fig. 19.34, a high-STC wall between the two spaces is in large measure defeated by flanking paths F5, F6, and F7. In other spaces the most common flanking path is via the plenum, as in Fig. 19.34 (path F1) and in Figs. 19.35*b* and 19.35*d*. Ductwork (with registers or grilles in various rooms) acts as an excellent intercom system unless it is completely lined with sound-absorptive material (see Section 19.27). Even then, low-frequency sound is only minimally attenuated, and special measures must be employed if good transmission loss is required. This subject is discussed further in Sections 19.25 to 19.27.



FLANKING NOISE PATHS

F1 OPEN PLENUMS OVER WALLS, FALSE CEILINGS
F2 UNBAFFLED DUCT RUNS
F3 OUTDOOR PATH, WINDOW TO WINDOW
F4 CONTINUOUS UNBAFFLED INDUCTOR UNITS
F5 HALL PATH, OPEN VENTS
F6 HALL PATH, LOUVERED DOORS
F7 HALL PATH, OPENINGS UNDER DOORS
F8 OPEN TROUGHS IN FLOOR-CEILING STRUCTURE

NOISE LEAKS

L1 POOR SEAL AT CEILING EDGES
L2 POOR SEAL AROUND DUCT PENETRATIONS
L3 POOR MORTAR JOINTS, POROUS MASONRY BLK
L4 POOR SEAL AT SIDEWALL, FILLER PANEL, ETC.
L5 BACK-TO-BACK CABINETS, POOR WORKMANSHIP
L6 HOLES, GAPS AT WALL PENETRATION
L7 POOR SEAL AT FLOOR EDGES
L8 BACK-TO-BACK ELECTRICAL OUTLETS

OTHER POINTS TO CONSIDER, RE: LEAKS ARE (A) BATTEN STRIP A/O POST CONNECTIONS OF PREFABRICATED WALLS, (B) UNDER-FLOOR PIPE OR SERVICE CHASES, (C) RECESSED, SPANNING LIGHT FIXTURES, (D) CEILING & FLOOR COVER PLATES OF MOVABLE WALLS, (E) UNSUPPORTED A/O UNBACKED WALL BOARD JOINTS, (F) EDGES & BACKING OF BUILT-IN CABINETS & APPLIANCES, (G) PREFABRICATED, HOLLOW METAL EXTERIOR CURTAIN WALLS.

Fig. 19.34 Flanking transmission of airborne noise. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968. Redrawn by Jonathan Meendering.)

SPEECH PRIVACY

19.16 PRINCIPLES OF SPEECH PRIVACY BETWEEN ENCLOSED SPACES

The subject of speech privacy has always been of paramount importance in office design. Numerous studies have demonstrated that productivity and noise are related inversely when the noise carries information. When noise does not carry information, it can be annoying and therefore counterproductive or it can be useful as a masking sound, depending upon its frequency content, intensity level, and constancy. Referring to Section 19.7, which discusses the noise reduction of an *airtight* barrier between two spaces, we saw that the sound intensity levels in the source room (1) and the receiving room (2) are related by the expression

$$IL_2 = IL_1 - NR$$

where NR is noise reduction, and IL_2 and IL_1 are sound intensity levels in the receiving and source rooms, respectively. If the receiving room is completely quiet and has no sound source other than the

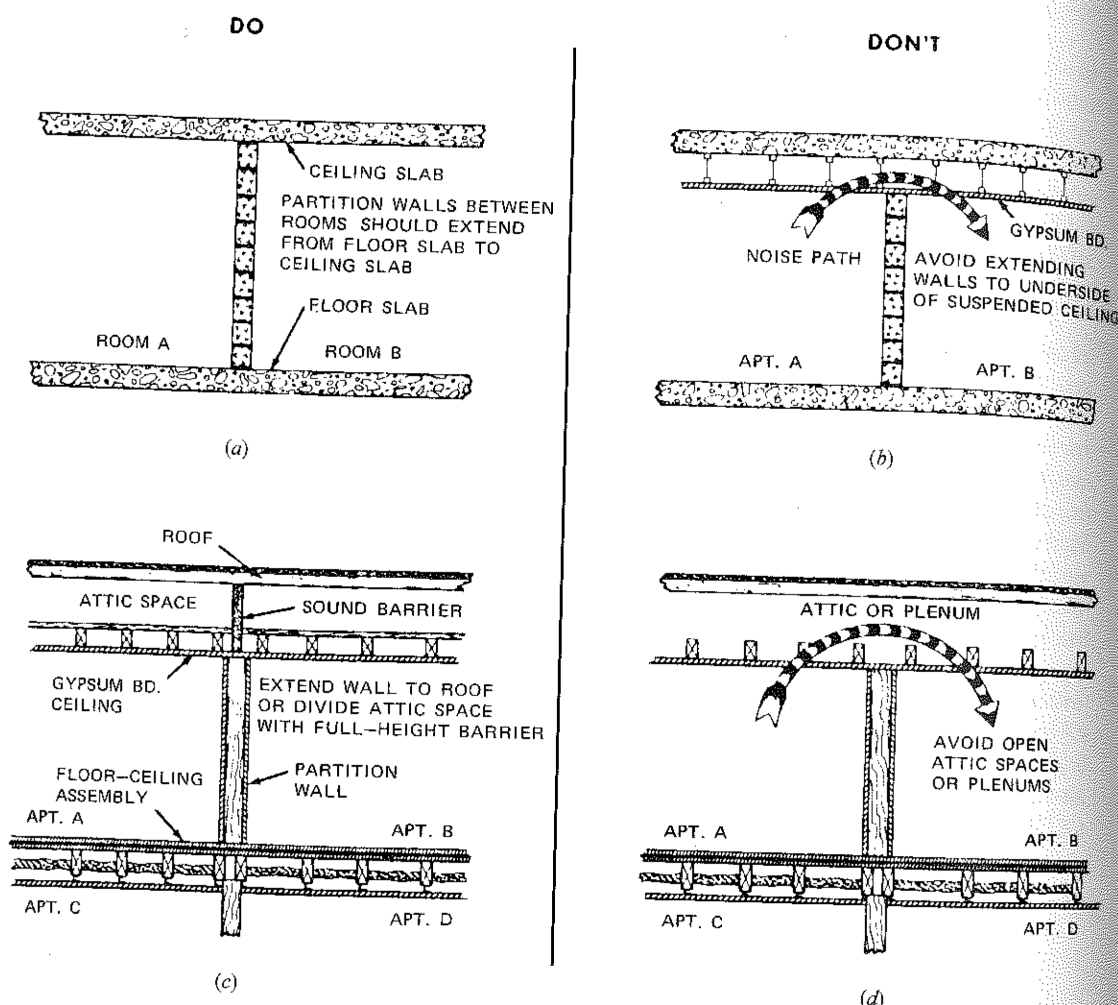


Fig. 19.35 *Construction technique recommendations to avoid flanking paths. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *1968.)*

transmitted sound (essentially IL_2), then that sound will always be a potential source of annoyance to the occupant of the receiving room as long as its intensity level is above the hearing threshold. If, however, there is a *constant* ambient sound level in the receiving room, then, depending upon its characteristics, it may mask the transmitted sound IL_2, even to the extent of making it completely inaudible. In most instances, however, it simply reduces or eliminates annoyance without completely masking the source. What we hear (and therefore what can potentially be a source of disturbance) depends upon our level of attention both to what we are doing and to the intrusive sound. (A remarkable exception is the ability of some, generally young, students to study in the presence of very loud, familiar—and therefore information-bearing—music. Indeed, some claim that they can *only* study that way.)

Tests have shown that a majority of adults will not consider an intruding noise level IL_2 to be annoying if the intensity of a properly designed background sound is either greater than or no more than 2 dB less than IL_2. Thus, a transmitted IL_2 of 40 dBA will not be considered annoying by most people if the level of the background sound is at least 38 dBA. The upper level of usable background masking sound is usually taken to be about 50 dBA. Any higher intensity level will itself become a source of annoyance. Figure 19.36 gives a graphic representation of the relation between transmitted and

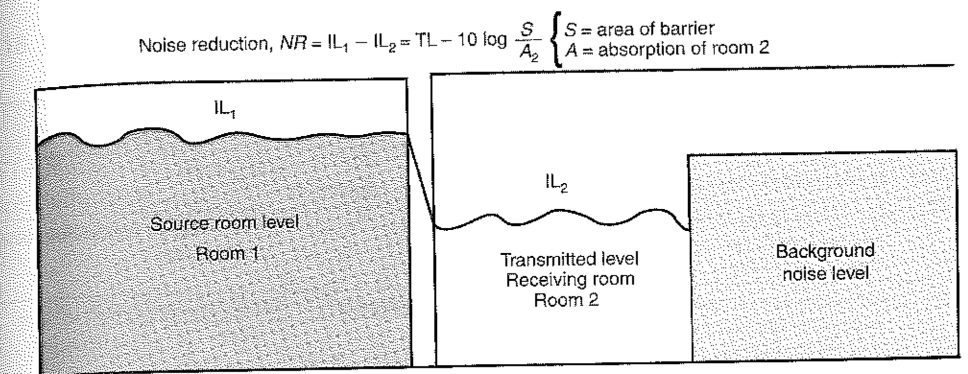


Fig. 19.36 *The background noise level determines whether a transmitted sound will actually be heard. In this case, because the background noise level is considerably higher than the transmitted level from the adjacent room, the transmitted noise will not be noticeable (i.e., it will be masked).*

background sound levels in a receiving room. By way of summarizing the preceding discussion, we can simply state that the degree of *speech privacy* in a space is a function of two factors:

- The degree of sound insulation provided by the barriers between rooms
- The ambient sound level in the receiving room.

19.17 SOUND ISOLATION DESCRIPTORS

Since the degree of intrusiveness of extraneous noise in a space varies, depending as it does upon both transmitted and ambient sound, having a descriptive scale of some sort is appropriate. If we restrict our discussion to speech sounds, since ultimately we are interested in office design, where speech is the primary sound source, then a descriptive scale, as shown in Table 19.5, can be established. With these absolute descriptions in mind, and remembering that the hearing condition in a receiving room can be altered by changing either the barrier characteristics or the background sound level, *or both*, we can express the effectiveness of a construction as a speech sound barrier in terms of its STC for a given ambient sound level. Since the ambient sound (noise) level is frequency dependent, it can be approximated by an NC value. This is particularly useful when the ambient sound level is generated by machinery or by the sound of an air-conditioning system rather than by a shaped signal from an electronic masking sound system.

Table 19.6 shows the hearing conditions in a receiving room with an NC-25 background noise as a function of the barrier STC rating. If the background noise level were raised to NC-30, then each descriptor would roughly increase one level in quality (i.e., poor would become fair, fair would become good, and so forth). Stated otherwise, the *apparent* isolation provided by a barrier may be increased by

TABLE 19.5 Relative Quality of Sound Isolation

Ranking	Descriptor	Hearing Condition[a]
6	Total privacy	Shouting barely audible.
5	Excellent	Normal voice levels not audible. Raised voices barely audible but not intelligible.
4	Very good	Normal voice levels barely audible. Raised voices audible but largely unintelligible.
3	Good	Normal voice levels audible but generally unintelligible. Raised voices partially intelligible.
2	Fair	Normal voice levels audible and intelligible some of the time. Raised voices generally intelligible.
1	Poor	Normal voice audible and intelligible most of the time.
0	None	Normal voice levels always intelligible.

[a]Hearing condition in the presence of ambient noise, if any.

TABLE 19.6 Relation between Barrier STC and Hearing Condition on the Receiving Side, Background Noise Level at NC-25

Barrier STC	Hearing Condition	Descriptor and Ranking[a]	Application
25	Normal speech can be understood quite easily and distinctly through the wall.	Poor/1	Space divider
30	Loud speech can be understood fairly well. Normal speech can be heard but not easily understood.	Fair/2	Room divider where concentration is not essential
35	Loud speech can be heard but is not easily intelligible. Normal speech can be heard only faintly, if at all.	Very Good/4	Suitable for offices next to quiet spaces
42–45	Loud speech can be faintly heard but not understood. Normal speech is inaudible.	Excellent/5	For dividing noisy and quiet areas; party wall between apartments
46–50	Very loud sounds (such as loud singing, brass musical instruments, or a radio at full volume) can be heard only faintly or not at all.	Total Privacy/6	Music room, practice room, sound studio, bedrooms adjacent to noisy areas

[a]See Table 19.5.

raising the background (masking) sound level in the receiving room. Figure 19.37 shows two conditions of adjacent spaces. Although the source room level is uniform and partitions on both sides of the source room are identical, the background sound in the two receiving rooms is different. In *A*, the background is NC-35; in *B*, it is NC-25. The occupant of room *A* is not disturbed by the little heard from the source room. The occupant of room *B* hears clearly. Occupant *A* will probably praise the partition, whereas occupant *B* will complain. Although the levels of reradiated sound are identical in the two receiving rooms, the intruding signal is masked by the background sound in *A*, but it is clearly audible in *B*. Thus, the apparent noise reduction is substantially higher in *A* than in *B*. This clearly demonstrates the effectiveness of masking sound in providing *apparent* sound isolation and speech privacy.

Sound isolation can also be improved by careful planning. Storage and circulation areas can serve as buffers for noise-sensitive areas. Physical separation of noisy areas from quiet ones often eliminates the need for complicated and expensive compound barriers.

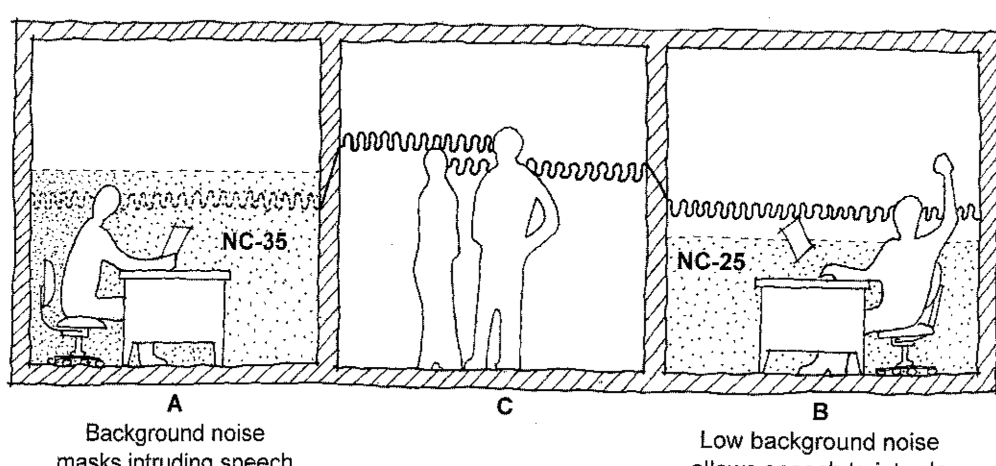


Fig. 19.37 *The occupant in room A with background noise NC-35 (≈ 45 dBA) is unaware of the noise (loud speech from room C) that is so disturbing to occupant B, whose NC-25 (≈ 36 dBA) is insufficient to mask the transmitted noise. (Drawing by Jonathan Meendering.)*

ACOUSTICS

19.18 SPEECH PRIVACY DESIGN FOR ENCLOSED SPACES

The study of speech privacy received considerable emphasis with the advent of open-plan offices (office landscaping), although the same problem prevails with both open and enclosed office designs. Essentially, the problem was to determine the factors affecting speech privacy and to quantify them with a degree of accuracy sufficient for design purposes. It rapidly became evident that although the physical principles are the same, the solutions to speech privacy design problems are radically different for closed spaces and for open-plan offices.

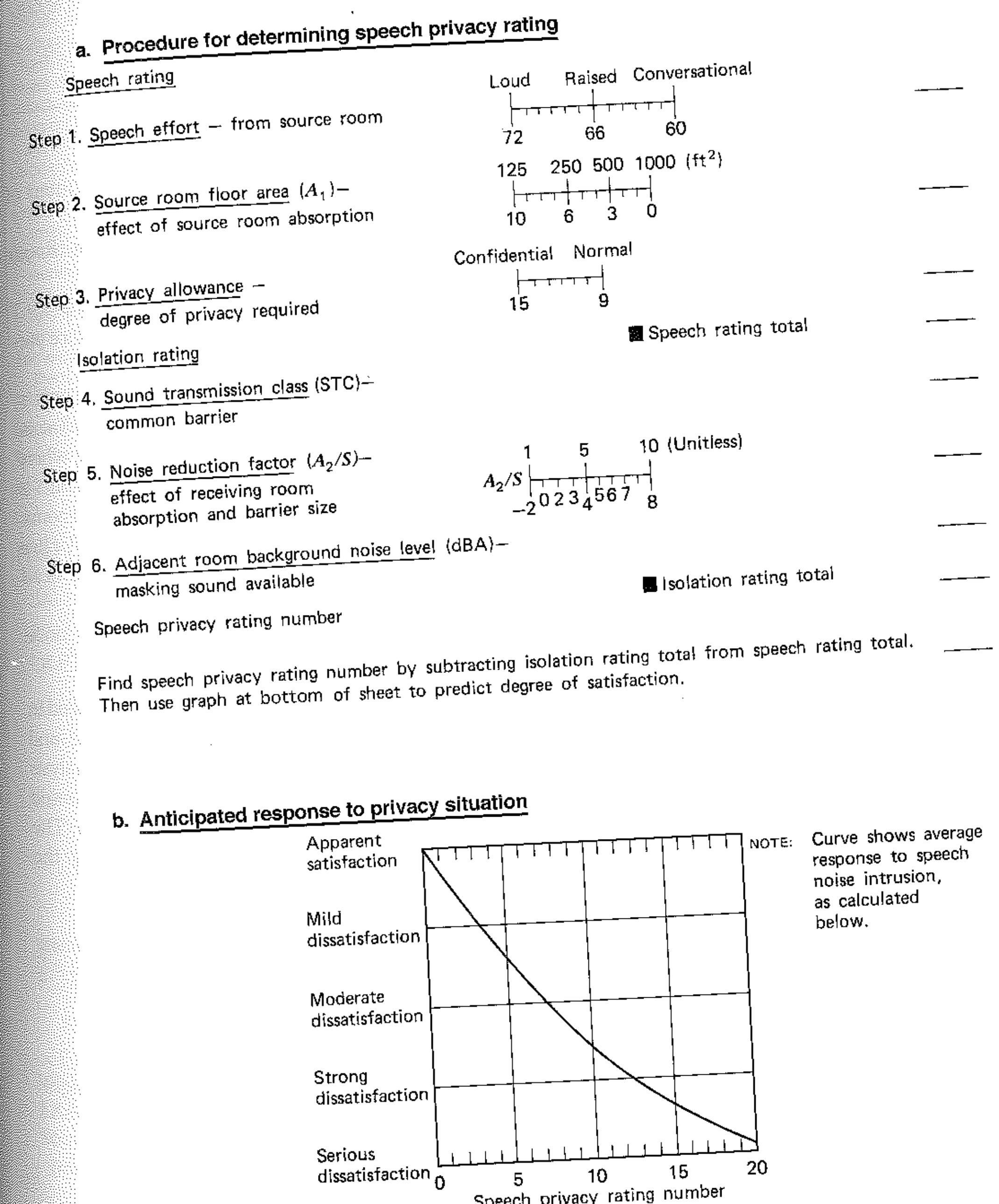


Fig. 19.38 *Speech privacy analysis sheet. (Based on Cavanaugh et al., 1962.)*

ACOUSTICS

In the former, the acoustic character of an airtight barrier between two spaces is the crucial element in the design, because all of the interspace sound transmission is through this barrier. In contrast, sound transmission between adjacent "cubicles" in an open office is primarily the result of *reflected* and *refracted* sound, with the direct component passing through the barrier being of secondary importance. As a result, the acoustic transmission characteristics of the barrier also become secondary in importance.

Studies indicate that six factors are involved in enclosed-space speech privacy, which can be subsumed under two headings (Fig. 19.38):

1. Speech rating of the source room (Room No. 1)
   a. Speech effort—a measure of the loudness of speech.
   b. Source room factor—gives the approximate effect of room absorption on the speech level in the source room. The scale in Fig. 19.38 is drawn for average absorption. For live rooms, raise the factor by 2 points; for dead rooms, lower it by 2 points. Factors $a + b$ give the approximate source-room voice level.
   c. Privacy allowance—what is the measure of privacy required?

The privacy criteria definitions used in this step (Fig. 19.38, Step 3) are:

Normal privacy—such that the receiving-room occupant can understand a small portion of normal voice conversation in the source room by listening intently. This corresponds to "Good" and a ranking of 3 in Table 19.5. It was found that most occupants can work normally with this level of speech intrusion.

Confidential privacy—assumes that only a few words will occasionally be intelligible. This privacy level corresponds to "Excellent" and a ranking of 5 in Table 19.5. The six speech-rating points between Normal Privacy (9 points) and Confidential (15 points) in Fig. 19.38 correspond roughly to a 5-dB difference. If we remember that a sound intensity differential of 3 dB is barely perceptible, 6 dB is clearly noticeable, and 10 dB is a doubling of perceived sound (Table 17.3), we can appreciate that the difference between *normal* and *confidential* privacy is small and calls for accurate design, plus a measure of field adjustment of masking sound.

2. Isolation rating of the receiving room (Room No. 2)
   d. The STC rating of the barrier. Table 19.7 gives some typical STC ratings for office partitions.
   e. The noise reduction factor A_2/S is an indication of receiving-room absorption, that is, the difference between *NR* and *TL*, where A_2 is the area of the receiving room and *S* is the area of the barrier between the rooms. Absorption is assumed to be average. For live rooms, lower this factor 2 points; for dead rooms, raise it 2 points.
   f. For the recommended background noise level in the receiving room, use Table 19.8.

TABLE 19.7 Typical STC Ratings of Interior Partitions

Type of Partition	STC
Demountable partition	STC 20–30
Drywall partition up to acoustical ceiling	STC 30
Drywall partition extending 12 in. (305 mm) above acoustical ceiling tile system into ceiling plenum	STC 35
Drywall partition with cavity insulation, full height to the underside of slab above	STC 40–45
Two-layer drywall partition with insulation, erected full height to underside of slab above	STC 50

An analysis sheet for enclosed spaces is provided in Fig. 19.38 (see also Cavanaugh et al., 1962, and Young, 1965.) The two examples of this analysis that follow should clarify its use. The reader should follow the analysis with Fig. 19.38 in hand. The numbered steps in the examples correspond to the numbers in the figure.

EXAMPLE 19.3. Evaluate the effectiveness of a partition.

Source room:

General clerical office, 40 × 60 × 9 ft (12.2 × 18.3 × 2.7 m), average $\bar{\alpha}$, 16-ft- (4.9-m) long full-height partition, STC 40

Receiving room:

Conference room, 16 × 24 ft (4.9 × 7.3 m), medium-dead room

Background noise level, 40 dBA (NC-30) (from Table 19.8)

TABLE 19.8 Suggested Noise Criteria Ranges for Steady Background Noise

Type of Space (and Acoustical Requirements)	NC Curve	Equivalent[a] dBA
Concert halls, opera houses, and recital halls (for listening to faint musical sounds).	10–20	20–30
Broadcast and recording studios (distant microphone pickup used).	15–20	25–30
Large auditoriums, large drama theatres, and houses of worship (for excellent listening conditions).	20–25	30–35
Broadcast, television, and recording studios (close microphone pickup only).	20–25	30–35
Small auditoriums, small theatres, small churches, music rehearsal rooms, large meeting and conference rooms (for good listening), or executive offices and conference rooms for 50 people (no amplification).	25–30	35–40
Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, and so forth (for sleeping, resting, relaxing).	25–35	35–45
Private or semiprivate offices, small conference rooms, classrooms, libraries, and so forth (for good listening conditions).	30–35	40–45
Living rooms and similar spaces in dwellings (for conversing or listening to radio and TV).	35–45	45–55
Large offices, reception areas, retail shops and stores, cafeterias, restaurants, and so forth (for moderately good listening conditions).	35–50	45–60
Lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas (for fair listening conditions).	40–45	50–55
Light maintenance shops, office and computer equipment rooms, kitchens, and laundries (for moderately fair listening conditions).	45–60	55–70
Shops, garages, power-plant control rooms, and so forth (for just acceptable speech and telephone communication). Levels above PNC-60 are not recommended for any office or communication situation.	—	—
For work spaces where speech or telephone communication is not required, but where there must be no risk of hearing damage.	—	—

Source: Extracted with permission from E. B. Magrab, *Environmental Noise Control*, Wiley, New York, 1975.

[a]For information only. These data are not part of the NC information and do not appear in the source.

Privacy analysis (using I-P units as per Fig. 19.38):

(a) 1. Speech effort: raised — 66
2. Area A_1 > 1000 ft² — 0
3. Privacy—normal — 9

Speech rating a = 75

(b) 4. STC (given) — 40
5. A_2/S — 3
(16 × 24)/(16 × 9) = 2.6, corresponding to 2 on the scale; add 1 for higher than average $\bar{\alpha}$
6. Background noise level — 40

Isolation rating b = 83

Speech privacy rating $a - b = -8$

The partition performance is acceptable. In fact, the STC rating of the partition can be reduced to 32 without affecting speech privacy. ■

EXAMPLE 19.4. Evaluate speech privacy.

Source room:

Drafting room 20 × 30 ft (6.1 × 9.1 m), medium-live

Common wall 12 × 8 ft (3.7 × 2.4 m) high

STC: 26 (half glass, with door)

Receiving room:

Supervisor's office, 12 × 14 × 8 ft (3.7 × 4.3 × 2.4 m), average absorption

Background noise level, 35 dBA

Privacy analysis (using I-P units as per Fig. 19.38):

1. Speech effort—conversation — 60
2. Source room factor:
   For area +2
   For liveness +1 — Total +3
3. Privacy—(almost) confidential — 13

Speech rating a = 76

4. STC (given) — 26
5. A_2/S
   (12 × 14)/(12 × 8) = 1.8, corresponding to a reduction factor of 1.6; gives 2.0 on the scale since the method uses whole numbers only. No adder required for average absorption.
   Therefore, 2 + 0 = 2
6. Background noise level — 35

Isolation rating: b = 63

Speech privacy rating $a - b$ = 13 which indicates strong dissatisfaction

The suggested corrections are to increase the wall STC to 36 by gasketing the door and to increase the background noise level in the receiving room to 40 dBA (NC-30). This would give a speech privacy rating of −2, as follows:

STC of barrier	36
A_2/S	2
Background noise	40
Isolation rating	78

Speech privacy rating = $a - b = 76 - 78 = -2$

This result should be satisfactory according to the chart in Fig. 19.38. ■

19.19 PRINCIPLES OF SPEECH PRIVACY IN OPEN-AREA OFFICES

The huge increase in the service sectors of the world economy has brought with it a corresponding increase in desk jobs, each of which is often equipped with a computer console. This trend has also necessitated increased space density for office workers, made possible by the general elimination of paper storage (files) and the corresponding elimination of the necessity for employees to continually move about. The increased density problem has been largely solved by open-office plans with ever-smaller "cubicles," usually with single occupancy, but recently also with dual occupancy. This situation has obviously aggravated the serious problem of annoyance due to the intrusion of speech sounds from neighboring workers, that is, a lack of *speech privacy*.

Since production is adversely affected by the inability of a worker to concentrate because of annoyance with speech intrusion—an annoyance that usually *increases* over time—the proper design of open office plans can have major economic benefits.

(a) Sound Paths in Open Offices

In contrast to the single, or at most dual, sound paths that exist with full-height enclosures (Fig. 19.39), the sound paths in an open-plan arrangement (including first reflections) are direct, diffracted, ceiling reflected, and laterally reflected (Figs. 19.40 and 19.41). Careful study of these illustrations shows a number of important facts affecting speech privacy in open offices.

1. The angles of reflection of sound waves from the ceiling depend upon the location and height of the source and the ceiling height (Fig. 19.40*a*). Measurements have shown that these angles vary from a minimum of 30° for a standing speaker in the center of a cubicle to a maximum of 60° for a speaker close to, and facing, a partition for ceiling heights of up to 9 ft (2.7 m). Since much of the sound energy reaching an adjacent occupant does so after reflecting off the ceiling at these angles (30°–60°), a ceiling material with high absorption at these angles of incidence is required for speech privacy. This effectively negates the use of the noise reduction coefficient (NRC) as a useful factor to describe a ceiling material's absorption characteristic in an open-office design, since the NRC averages absorption at all angles. All major ceiling material manufacturers have tested, and will supply, accurate angular absorption data for their products. A single-number descriptor that relates to this characteristic, called the *Articulation Class*, is discussed in detail in Section 19.20.

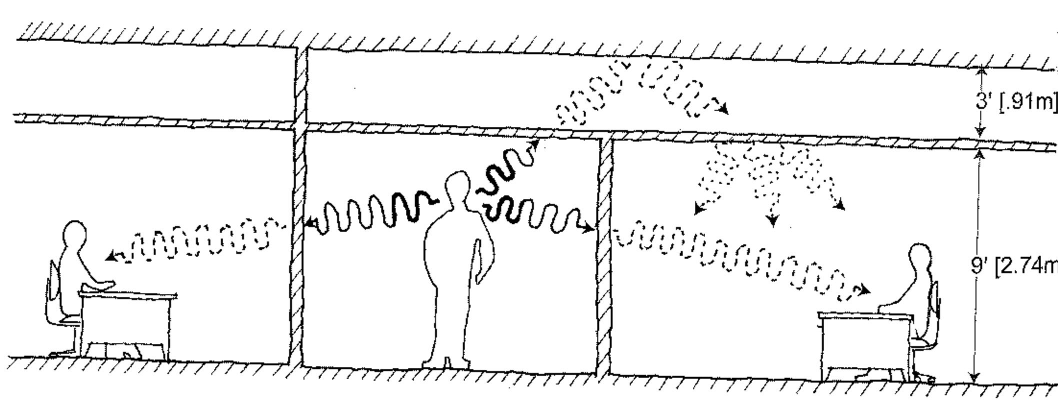
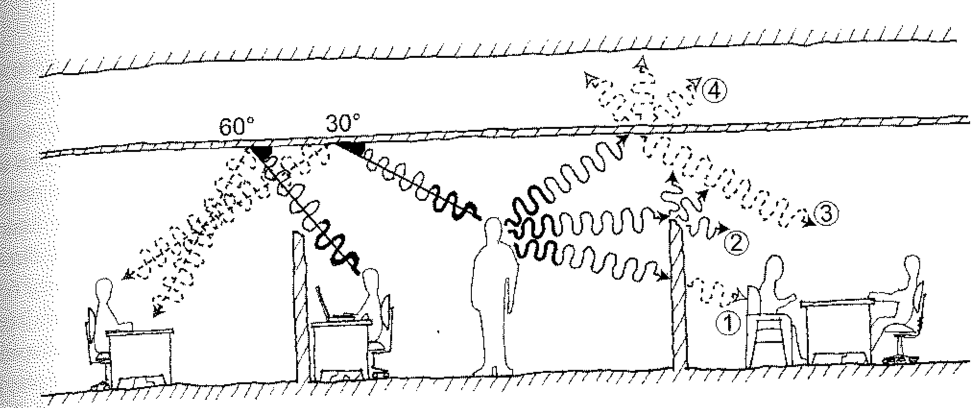


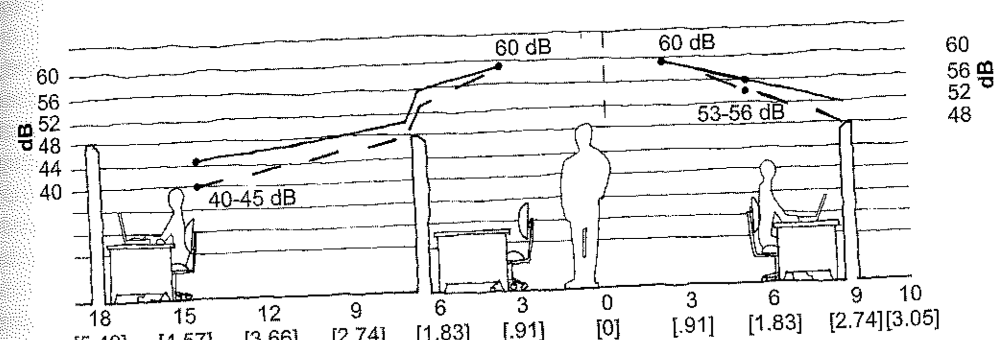
Fig. 19.39 *Sound paths between enclosed spaces are determined by the type of barrier separating them. In the case of a full-height barrier reaching to the underside of the ceiling slab, the only sound path is through the barrier, and its STC determines the sound pressure (noise) level in the receiving room. In the case of a ceiling-height partition with an overhead plenum, most of the sound energy will travel the upper, less attenuating path. Factors affecting the level of received sound are the ceiling's CAC rating (Ceiling Attenuation Class, indicative of its transmission characteristic) and the acoustic characteristics of the plenum, including all of its contents. In all cases, sound within a reasonably absorptive space attenuates with increasing distance. (Drawing by Jonathan Meendering.)*



Principal Sound Paths

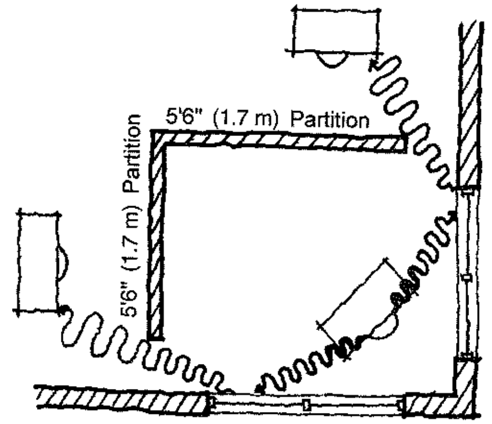
① Direct path through 5'-6"- [1.68m]-high partition
② Diffracted path over partition
③ Reflected path over partition
④ Sound absorbed and diffused

(*a*)



(*b*)

Fig. 19.40 *(a) The principal sound paths between occupancies in an open office plan are (1) direct, (2) diffracted, (3) ceiling reflected, and (4) reflected from the slab above the plenum. Only paths (2) and (3) are problematic from the speech privacy viewpoint, requiring masking sound. Note that the angle of incidence of the sound wave at the ceiling varies from 30° for a standing speaker to 60° for a seated speaker, requiring a ceiling material of high absorption between these angles. Large VDT screens (17–19 in. [432–482 mm]), in common use, create another path of strongly reflected sound. (b) Sound is attenuated by distance, dropping 4–6 dB for each doubling of the distance from the source (6 dB in the open; 4 dB in enclosed spaces due to interreflections). Average SPL of conversational speech is 60 dBA at 3 ft (0.9 m) from a speaker. Attenuation of a diffracted signal at a partial-height partition is 4–8 dB. Note that the diffracted sound (without a contribution from ceiling-reflected sound) drops to 40–45 dB in the adjacent cubicle. In a two-person open office, the received signal from a standing speaker is at least 53–56 dBA (i.e., perfectly intelligible, even in the presence of maximum [50 dB] masking noise). (Drawings by Jonathan Meendering.)*



PLAN

Fig. 19.41 Confidentiality in offices on exterior building walls is difficult to maintain because of the lack of attenuation of sound reflected from windows. The problem is compounded by the custom of placing management personnel in such offices.

2. Since absorption at the ceiling increases with the angle of incidence of a sound wave, it is always desirable for speech privacy to have maximum ceiling height. Most authorities recommend a *minimum* ceiling height of 9 ft (2.7 m).

3. Absorption efficiency of ceiling tiles varies inversely with the STC, which is to be expected, since sound transmission depends upon mass and absorption at air pockets. Light fiberglass ceiling tiles will typically have an absorption coefficient α of 0.95 at voice frequencies, with a *Ceiling Attenuation Class* (CAC) of 22 to 24 compared to more massive mineral fiber tiles with a maximum α of 0.8 to 0.85 but an STC of 34 to 36. Since we are interested in maximum absorption at the ceiling, the tile of choice is always that with the highest α at voice frequencies. The fact that more energy will pass through a tile of lower CAC (STC) does not affect the acoustic result, since most of the sound energy enters the plenum above the ceiling through openings in the far-from-airtight suspension system, and is then largely absorbed and dissipated by the spray fireproofing, sound-absorbing material, ductwork, and structural members typically found in a plenum.

4. Since sound will always find the path of least resistance to travel, very little sound energy will pass through partitions between cubicles; the paths over the partition by diffraction and reflection are much less resistant. That being so, the STC of these partitions need not be high. Where the source is close to the partition, as is the case with a seated speaker facing a partition and delivering sound energy directly at the partition at a height of approximately 44 to 48 in. (1.1 to 1.2 m) from a distance of about 3 ft (0.9 m), the STC of the partition should be 25 to 26. For speakers at greater distances and heights, an STC of 20 to 22 is usually sufficient.

An exception to this general rule *may* occur when a large (17 to 19 in. [430 to 480 mm]) computer console is interposed between a seated speaker and an absorbent partition. Large visual display terminals (VDTs) are becoming increasingly common. Their smooth, highly reflective glass surface creates a strong sound path to the rear of the speaker and decreases the sound energy absorbed by the partition behind the VDT. The variables, however, are so numerous that conservative design will use the higher STC rating. (Contrast these values with those required of a full-height, fixed-partition construction typical of enclosed spaces, as listed in Table 19.7.)

The absorption coefficient α of a partial-height partition at voice frequencies should be a minimum of 0.8 and preferably 0.85 to 0.95. Some manufacturers have assigned an Articulation Class rating to their partition products, although that descriptor is usually reserved for ceiling tiles, as explained in point 3. The recommended ratings for partitions range from 180 to 220.

5. Partitions must be tall enough to block direct line-of-sight voice transmission, since such a path is unattenuated except by distance. The median mouth height of a standing American male is 63 in. (1.6 m). This is the basis of the widely accepted recommendation that partitions between adjoining cubicles should not be lower than 65 in. (1.7 m) and preferably 66 to 72 in. (1.7 to 1.8 m). Since a 72-in.-high (1.8 m) partition blocks vision for all but the tallest people, giving a subjective closed-in sensation to the occupant of a (small) cubicle, this height is normally used only between departments, with intradepartment partitions being 63 to 66 in. (1.6 to 1.7 m). Increasing the height of a partition from 65 to 72 in. (from 1.7 to 1.8 m) will increase path attenuation to an adjacent cubicle by 1–3 dB, depending upon ceiling height and speaker height and location.

6. Refer to Fig. 19.40*b*. This figure indicates signal attenuation due to distance for two different paths. Speech intensity at a conversational level is approximately 60 dBA at 3 ft (0.9 m) from

the speaker. Using the fact that sound in a free field attenuates 6 dB for every doubling of distance, and making the assumption that the sound field in a cubicle approaches that of a free field because of the large amount of highly absorptive material in the area, we obtain a sound intensity level of 54 dBA at 6 ft (1.8 m) from the speaker and 48 dBA at 12 ft (3.7 m). In practice, the received sound level is several decibels higher because, despite the high α of the space, there exist intraspace reflections that increase the sound level.

Referring again to Fig. 19.40*b*, we see that the minimum sound level at a receiver *within* the cubicle would be 55 to 56 dB, a level that no practical amount of background sound can mask. Thus, two occupants of a single large cubicle will always hear each other quite clearly. The attenuation of a partition in the diffracted paths (over and around a partition) depends upon the location and height of the speaker and varies from 4 to 8 dB. The attenuation of the signal in the transmitted path (through the partition) will be at least 10 dB. Based on these figures, it is recommended that the *minimum* horizontal distance between occupants of adjoining cubicles when seated at their workstations be 10 ft (3 m) for minimum speech privacy. (Degrees of speech privacy are discussed in the next section.) Speech levels in teamwork areas readily reach 66 dB. This necessitates either locating such areas away from normal working spaces or the use of full-height fixed or demountable partitions to completely enclose such areas. The spaces that require careful siting or complete enclosure because of raised voice levels (64 to 66 dB) include videoconferencing rooms, telecommunications spaces, and areas where workers use speakerphones or voice-activated computers. The latter two devices are usually forbidden in densely populated work areas where a reasonable degree of speech privacy is required for the conduct of regular business tasks.

7. Refer to Fig. 19.41. As pointed out previously, sound will be received via paths of least resistance. These are often flanking paths that do not become evident except in plan view. In Figure 19.41, the flanking paths are particularly important because the first reflection occurs at a window. Glass has negligible absorption and, because of its smoothness, exhibits specular reflection. As a result, the corner office occupant's voice will be heard clearly via the flanking paths shown, thus destroying the confidentiality of conversation in that office. Since offices on the building perimeter are usually reserved for middle and upper management, and since the large windows in such offices act to minimize the speech privacy so important to managerial personnel, the space designer has several options to ameliorate this condition:

a. Use full-height fixed partitions, with fixed glass vision panels if required, and doors rather than openings.
b. Use heavy drapes over the "offending" glass windows, although this option defeats the visual and daylighting purpose of the windows.
c. Locate spaces requiring confidentiality in groups, sound-buffered from open-office spaces by unoccupied areas such as storage rooms.

It is also important to note that although the arrow signifying a sound path in Fig. 19.41 shows reflection from the windows, the sound energy will also strike the exterior walls, which are usually plastered and therefore highly reflective. Here, the placement of absorbent acoustic material on all walls, to ceiling height, is not impractical, as it is with windows, but it does entail considerable expense.

8. Refer to Fig. 19.42. The furniture arrangement establishes the source location of speech energy and consequently all of the sound paths that contribute to speech privacy—or, more accurately, the lack of speech privacy. In layout (*a*), sound power, unattenuated except by distance, reflects off the *back* of the opposing aisle partition and travels to the occupant of the neighboring cubicle. Since the back of an acoustic partition is usually metallic and nonabsorbent, this arrangement would entail the additional expense of an absorbent rear surface on the corridor panels to maintain a degree of speech privacy between cubicles.

Changing the desk location in the same-shaped cubicle to that shown in Fig. 19.42*b* improves speech privacy considerably by reducing the SPL of both the reflected and flanking paths, since the speakers face a highly absorptive surface. It may be unnecessary to use absorbent material on the rear of the corridor panels. A disadvantage of this arrangement lies in the short distance between speakers and neighbors if the same pattern of cubicles is continued longitudinally. A second possible disadvantage may be employee dissatisfaction with a working position facing a blank wall.

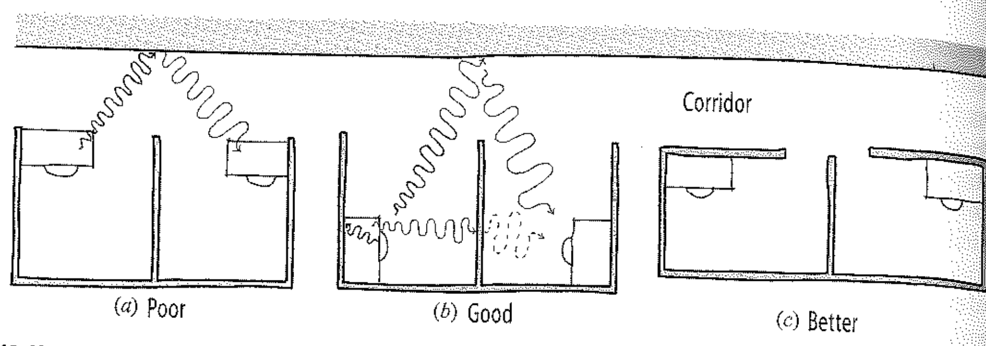


Fig. 19.42 *Open-office shapes and furniture arrangements have a marked effect on speech privacy. (a) A strong, unattenuated signal reflects from the opposite corridor wall directly into the adjoining office. The side-to-side 15-ft (4.6-m) total spacing with an intervening partition is barely satisfactory. (b) The sound reflected from the corridor wall is much weaker than in (a) because of increased distance and decreased voice intensity from the side. Lateral sound is also weak due to the attenuation at the first reflection off the absorbent partition. (c) Reflection from the corridor is eliminated by the use of a front closure partition with glass at the upper 18 in. (457 mm) for visual purposes. Side-to-side sound is weak due to wide spacing and the intervening partition. (Drawing by Nathan Majeski.)*

The arrangement in Fig. 19.42*c* uses the same area per cubicle. By changing its shape and adding a 6-ft-high (1.8 m) acoustic partition whose top 18 in. (457-mm) is glass, the designer has reduced the sound energy levels in all paths while overcoming any employee resentment related to working in a blank, unexposed corner. Furthermore, the problematic flanking path in Fig. 19.42*a* has been eliminated, as has probably any requirement for exterior acoustic absorption on the corridor partitions.

19.20 OPEN-OFFICE SPEECH PRIVACY LEVELS AND DESCRIPTORS

(a) Factors

The factors involved in determining the level of acoustic privacy that can be expected at a specific open-office location, as a result of neighboring speech sources, should be understood at this point. It may be helpful, however, to restate them. They are:

1. Loudness of the source(s).
2. Acoustic characteristics of the source(s). These include location, height above the floor, directivity, frequency spectrum, and information content. The last factor refers to the ability of a listener to make sense of what is being said or heard. Therefore, most types of non-information-bearing sound would not be considered intrusive sources of noise. A completely foreign language should also fall into this category, although in practice that is so only when the words and syllables are muffled. Clearly heard words in a foreign language do constitute a source of speech annoyance, although to a far lesser extent than those in a comprehended language. Speech privacy calculation procedures ignore foreign languages and assume that all speech is a possible source of annoyance.
3. Signal attenuation along each path between the source and the receiver. This factor is different for every normal position of even a single source, as, for instance, for a seated or standing source person.
4. Level and frequency content of background sound (deliberate masking, HVAC noise, continuous machinery noise, and the like).
5. Degree of privacy required. This is discussed in detail in the next subsection. It is important to keep in mind, however, that the three classifications—confidential, normal, and transitional (minimal, marginal)—are assumed to remain constant as long as the physical factors involved do not change. This ignores the oft-demonstrated fact that intrusive noise causes psychological and physiological reactions in some people that tend toward aggravation and increased severity with passage of time. A speech privacy situation originally classified as confidential may deteriorate to normal as the hearer's increasing sensitivity to noise causes him or her to strain to hear, and thereby to actually hear noise that ordinarily is masked. This is, in effect, another aspect of the cocktail party effect discussed in Chapter 17.

(b) Levels (Degrees) of Speech Privacy

Speech privacy is often achieved by masking intruding speech with background sound. By consensus among acousticians, the definitions of the three levels of speech privacy in an open office are:

1. *Confidential privacy*. Normal voice levels are audible but generally unintelligible. Raised voices are partially intelligible. Noise level is minimal. To achieve this level of privacy, the background sound level must be no more than 2 dB less than the intruding sound, and no more than about 3 dB more than the intruding sound, to satisfy the minimal noise level requirement. In this acoustic situation, approximately 95% of people will not sense any sound-intrusive disturbance and will be able to concentrate on most types of work.

2. *Normal privacy*. At this level, normal voice levels from adjacent spaces are heard but are not intelligible without concentration (i.e., by straining to hear and catch every syllable). Raised voices are generally intelligible. The overall noise level is low. This level of speech privacy is achieved when the background sound level is within 6 dB of (less than) the intruding speech level. This corresponds roughly to an intruding speech level of 50 to 54 dB, and a background sound level of 44 to 45 dB, that together give a range of 51 to 55 dB, levels that can be considered to meet the low-noise requirement.

3. *Transitional (minimal, marginal) privacy*. At this speech privacy level, speech at normal voice levels in adjacent open offices is readily understood most of the time, and the overall noise level is average. This noise level occurs when the intruding speech level is 10 dB or more than the background sound level. Since background sound is limited to about 50 dB, this privacy level would mean an intruding speech intensity of 60 dB or more. Since 60 dB is approximately normal speech at 3 ft (0.9 m), this "privacy" level would occur with two occupants in a single office or a single occupant receiving intruding noise from at least three neighboring offices. This speech intrusion level would be considered intolerable by about 40% of people and would negatively affect the work efficiency of a higher percentage.

In summary, it is interesting to compare these three open-office speech privacy levels with the "absolute" grading given in Table 19.5:

Open-Office Class	Table 19.5 Rating
Confidential	Good
Normal	Fair
Marginal	Poor

It should therefore be apparent that, by its very nature, an open office cannot achieve the top three grades of privacy listed in Table 19.5. If those levels of privacy are desired or required, fully enclosed spaces are necessary.

(c) Articulation Index (AI)

In order to quantify speech privacy for an open-office design, a single-number metric called the *Articulation Index* (AI) was developed in the 1970s by the acoustics consulting firm of Bolt, Beranek and Newman. This work was based in part upon studies of speech intelligibility by Bell Labs in the 1940s. Essentially, the AI relates speech intelligibility, speech intensity, and background sound level at the center of the five octave-band frequencies that encompass the spectrum of the human voice: 250, 500, 1000, 2000, and 4000 Hz. AI is determined by measuring the percentage of individual words that can be understood under specific speech and background sound levels. An AI of 0% indicates zero intelligibility and therefore ideal speech privacy. This, of course, does not mean silence; it means that with a specific combination of speech intensity level and background sound level, intelligibility is nil, and therefore speech privacy, defined as a lack of intelligible intruding speech, is ideal. At the other end of the scale, a high percentage of intelligible words yields a high AI and a correspondingly low speech privacy rating. In practice, the resultant AI figures are related to listener satisfaction and speech privacy descriptors, as shown in Table 19.9.

The calculation procedure for AI involves the use of weighting factors that are applied to intensity-level differences between speech and background

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TABLE 19.9 Articulation Index (AI) and Speech Privacy

AI	Persons Satisfied with Speech Privacy (%)	Open-Office Speech Privacy Descriptor
0–0.05	95–92%	Confidential
0.06–0.2	90–80%	Normal
0.21–0.3	79–65%	Minimal
>0.3	<65%	Unacceptable

sound levels at different frequencies in order to reflect the connection between intelligibility and frequency. As pointed out in Chapter 17, most of the information in English words is carried by consonants, whose frequencies are generally above 2 kHz. Thus, the problem frequently encountered in telephone conversations, of distinguishing between *f* and *s*, *b* and *v*, *t* and *d*, and so on, is due to excessive attenuation of the high frequencies that distinguish these letters from each other. The AI calculation emphasizes the importance of high frequencies to intelligibility by using the following weighting factors:

Octave Band Center Frequency (Hz)	Relative Weighting Factor
250	1.0
500	2.5
1000	3.5
2000	5.0
4000	4.0

The calculation of AI values for an actual open-office design is complex and laborious, since it considers all sound paths between each source and each receiver, including the acoustic characteristics of all reflective and absorptive surfaces in the path. The results are a specific AI factor for every receiver location. Because of the very large number of calculations involved, the analysis is done by computer. Changes in materials, plan arrangements, and dimensions can be made if the calculated AI does not satisfy the space's speech privacy requirement.

These changes can be predicted fairly accurately, since it has been demonstrated that a 3-dB change in the relative level of an intruding speech signal with respect to the background sound level will result in a 0.1-level change in AI. Thus, an increase of 3 dB in the background sound level or a decrease of 3 dB in the intruding signal (by increased absorption or path length) will have the effect of increasing the AI between the involved workstations by 0.10, which is the difference between normal and poor speech privacy. Since 3 dB is a barely perceptible change in intensity (see Table 17.3), we can appreciate how sensitive speech privacy is to small changes in intensities.

(d) Articulation Class

Numerous measurements in actual open-office installations have indicated that the absorption characteristics of the ceiling are the most important factors in speech privacy design. As noted in the previous section, the angles of incidence of speech sound on the ceiling range between 30° and 60°, with the majority of sound energy falling at the top of this range. A figure of merit for absorption, called the *Articulation Class* (AC), was established that indicates absorption effectiveness at angles of incidence between 45° and 55°. The usual range of AC is between 180 and 220 (no units), with higher numbers representing better absorption.

19.21 DESIGN RECOMMENDATIONS FOR SPEECH PRIVACY IN OPEN OFFICES

(a) General Factors

The architectural arrangement of spaces in an open-office design has a marked influence on speech privacy. Areas should be grouped according to their speech privacy requirements. Spaces rated as "confidential" should be placed on the perimeter of the open area to limit their exposure to speech intrusion, with the caveats relating to exterior windows and walls, discussed previously, being considered. The design emphasis for these areas should be not only an AI between 0.0 and 0.05, but also on a low overall sound level, *including* background noise. Similarly, high-noise-producing areas should be grouped and placed on the perimeter at a maximum distance from confidential speech privacy areas. Use of demountable full-height partitions for such spaces should be considered.

Because of reflection from perimeter walls, open-area spaces should be as large as practical, with absorbent perimeter walls. Ceiling height should be no less than 9 ft (2.7 m) clear, with a 3-ft (0.9 m) plenum above. Extreme care must be taken with air-conditioning ductwork, which, if untreated, will act as conduit for speech and noise via multiple ceiling outlets. Furthermore, these outlets, which were once relied upon to produce an even level of background sound, generally no longer do so. Most HVAC systems today are variable-air-volume (VAV) designs, whose noise levels vary ± 10 dB, making them useless as a reliable source of masking sound.

(b) Individual Office (Cubicle) Design

Offices should be designed for maximum closure and maximum partition length. Separation between occupants of adjacent offices should never be less than 12-ft (3.7-m) as a design target for normal privacy and 16 ft (4.9 m) for confidential privacy. Minimum office area should be 80 ft² (7.4 m²), with a design target of 100 to 120 ft² (9.3 to 11.1 m²) for normal privacy and 200 ft² (18.6 m²) for confidential privacy. Desk arrangements should be checked for optimum speech paths (for privacy), recognizing that office furniture arrangements need not be uniform in all offices (see Section 19.19).

(c) Ceilings

As the ceiling is the most important design element in speech privacy, care must be taken to avoid unintentional strongly reflective speech paths, as from metal pan air diffusers, flat lighting fixture diffusers, and the like. If the use of such or similar items is unavoidable, highly absorptive vertical baffle strips may be placed on their perimeter to block sound paths. In general, ceiling tiles should have an Articulation Class rating of 220 minimum, and minimum absorption coefficients (α) at incidence angles of 30° to 60° as follows:

Frequency (Hz)	α
250	0.65
500	0.65–0.75
1000	0.85
2000	0.90
4000	0.90

(d) Partitions

As explained in Subsection 19.19(a), the minimum height of partitions should be 65 in. (1.7 m), with 72-in.- (1.8-m) high units separating offices from aisles and dividing departmental groups. The AC rating, if available, should range from 200 to 220. STC ratings, as explained in Section 19.11, depend to an extent upon speaker locations and vary from 20 to 26. Joints between partitions should be carefully sealed, as even small openings can seriously compromise a partition's already limited efficiency. All partitions should reach the floor, although the lower portion is not always absorptive in low-speech-privacy areas.

(e) Floors

Although carpeted floors do not seriously affect overall sound absorption, they do drastically reduce chair-movement and footfall sounds. For this reason, all floors in open-office areas should be carpeted. The difference in effectiveness of shal-low-pile carpet compared to deep-pile carpet is minimal, and the same differential can be achieved by using a polyurethane cushion backing in lieu of the more common jute pad. The principal purpose of carpeting is to cushion the footfall impact so that its energy is not introduced into the structure. This subject is covered in detail in the discussion of structure-borne sound that follows.

(f) Lighting Fixtures

Flat-bottom lighting fixtures must never be used. Fixtures should not be placed directly over partitions, in order to avoid an interoffice speech reflection path. Experience has shown that the best lighting fixture (from the speech privacy point of view) is one with deep parabolic reflector cells and overall dimensions of 1 ft × 4 ft (0.3 × 1.2 m) or 2 ft × 4 ft (0.6 × 1.2 m).

(g) Masking Sound

It is imperative that the level of masking sound be uniform throughout an open-office area, and at as low a level as will yield the desired speech privacy. Nonuniformity will immediately be noticed as people move about, and the masking sound itself will become a source of auditory annoyance. For a similar reason, loudspeakers should not be visible. Visible units become themselves a source of interest initially and then a source of annoyance. Speakers should be placed *in* the plenum, preferably facing up to increase dispersion and improve uniformity. Speakers mounted in the ceiling and facing down should be avoided. Most ceiling tiles in open-office

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spaces have a low CAC so that sound will easily penetrate into the office area below the ceiling.

A masking sound system should comprise a signal (noise) generator, a sophisticated equalizer for shaping the signal, an amplifier with appropriate controls, and a distribution system to feed the speakers. Speakers are normally 12 in. (305 mm) in diameter, and are installed in a grid on 12- to 16-in. (305-to 406-mm) centers. The amplifier should be arranged so that volume levels can be remotely controlled. This permits time control so that the background sound volume can be reduced automatically after working hours. This is necessary so that the few people working late are not annoyed by relatively loud background sound in the absence of intruding speech.

The noise produced by a masking sound system is variously described as white noise, noise of air rushing through an opening (whoosh sound), noise of water in piping, and the like. The actual sound can be tailored to the user's preference by adjusting the filters in the system's equalizer. Generally, masking sound emphasizes low frequencies, because higher frequencies are immediately noticed as an annoying hiss. As noted in Section 19.16, the background sound level should not exceed 48 to 50 dBA. In some installations, the masking sound system doubles as a public address system, although this practice is not recommended because the sound/noise stops during an announcement, and when it returns it is noticed. Background sound must be designed so as to blend into the ambience of the background, and anything that disturbs the hidden quality of masking sound is to be avoided.

(h) Design Procedure

Unfortunately, due to the large number of variables involved in open-office speech privacy design, a straightforward manual design method that will yield reliable results does not exist. However, a number of computer programs are available that will calculate the AI for any location as a result of a specified speech source intrusion. On the basis of these calculations, changes can be made to the design and the program rerun to achieve improvements where the calculated AI is excessive. The most effective way to perform a complete design is then, on the basis of the preceding calculations, to construct a full-scale mock-up that can then be field-tested and "tuned." Although this is expensive and time-consuming, it is frequently far cheaper than making the requisite changes after construction of an unacceptable solution.

One of the distinct advantages of this two-step design procedure is that it enables a designer to equalize the acoustic absorption "strength" of various paths so that the attenuations of major paths are equal. There is no economic or engineering sense in a system that is much more effective for one path than for another, since sound will always choose the path of least acoustic resistance. To accomplish this balancing, the designer has many variables to juggle. They include barrier height and material, ceiling material, baffle sizes and positions (if used), distances between the source and receiver, position and directions of sources, and level of background sound.

(i) Standards

The acoustic design and testing of open offices is covered by a group of American Society for Testing and Materials (ASTM, see Section 19.37) standards that should be in the hands of anyone engaged in open-office design. The standards are available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM E1573-02—*Standard Test Method for Evaluating Masking Sound in Open Offices Using A-Weighted and One-Third Octave Band Sound Pressure Levels.* This test method specifies the procedures that can be used to evaluate the spatial and temporal uniformity of masking sound in open offices using A-weighted sound levels. It also specifies the procedure for evaluating the masking sound spectrum and level using ⅓-octave band sound pressure levels.

ASTM E1110-01—*Standard Classification for Determination of Articulation Class.* This classification provides a single figure rating that can be used for comparing building systems and subsystems for speech privacy purposes. Excluded from this classification are applications involving female speakers and children, languages other than English, and sound spectra other than speech.

ASTM E1111-02—*Standard Test Method for Measuring the Interzone Attenuation of Ceiling Systems.* This test method is intended to provide measurements of the sound-reflective characteristics of ceiling systems when used in conjunction with partial-height space dividers.

ASTM E1130-02e1—*Standard Test Method for Objective Measurement of Speech Privacy in Open Offices Using Articulation Index.* This method describes a field test for measuring speech privacy objectively between locations in open offices. It relies upon acoustical measurement, published information on speech levels, and standard methods for assessing speech communication. This test method does not measure the performance of individual open-office components that affect speech privacy; it measures the privacy that results from a particular configuration of components. This method relies upon the AI, which predicts the intelligibility of speech for a group of talkers and listeners.

ASTM E1179-87(2003)—*Standard Specification for Sound Sources Used for Testing Open Office Components and Systems.* This specification states the requirements for sound sources used for measuring the speech privacy between open offices or for measuring the laboratory performance of acoustical components. The sound source is a loudspeaker located in an enclosure and driven with an appropriate test signal.

ASTM E1264-98—*Standard Classification for Acoustical Ceiling Products.* This classification covers ceiling products that provide acoustical performance and interior finish in buildings. It classifies acoustical ceilings by type, pattern, and certain ratings for acoustical performance, light reflectance, and fire safety.

ASTM E1374-02—*Standard Guide for Open Office Acoustics and Applicable ASTM Standards.* This guide discusses the acoustical principles and interactions that affect the acoustical environment and acoustical privacy in an open office. In this context, it describes the application and use of the series of ASTM standards that apply to open offices.

ASTM E1375-90(2002)—*Standard Test Method for Measuring the Interzone Attenuation of Furniture Panels Used as Acoustical Barriers.* This test method covers the measurement of the interzone attenuation of furniture panels used as acoustical barriers in open-plan spaces to provide speech privacy or sound isolation between working positions.

ASTM E1376-90(2002)—*Standard Test Method for Measuring the Interzone Attenuation of Sound Reflected by Wall Finishes and Furniture Panels.* This laboratory test method measures the degree to which reflected sound is attenuated by the most commonly found vertical surfaces in open-plan spaces. The vertical surfaces covered by this test method include wall finishes such as sound-absorbent panels and furniture panels or screens. It does not cover such items as window finishes or furniture other than panels.

STRUCTURE-BORNE NOISE

19.22 STRUCTURE-BORNE IMPACT NOISE

The term noise will be used in lieu of sound in the following discussion of structure-borne, impact, and equipment noise control. Although use of the term noise assumes that a decision has been made that a particular sound is unwanted, this is a very reasonable assumption for the situations to be discussed. Use of the term noise gets to the point.

Structure-borne noise is at least as serious a problem as airborne noise for the following reasons:

1. There is no air cushion between the source and the structure; thus, high-intensity energy is introduced into the structure, through which it travels with minimum attenuation and at great speed.

2. Sound, once introduced into the structure, is attenuated well only by discontinuities in the structure. Since the structure must have structural integrity to carry the loads, discontinuities of the type that will stop noise are complex and expensive.

3. The entire structure constitutes a network of parallel paths for sound. Therefore, partial solutions are useless, since sound will find flanking paths. The entire structure must be soundproofed to yield good results.

4. Unlike the case of airborne noise, additional mass does not usually block structure-borne noise, particularly in long spans where a floor can act as a diaphragm, thereby improving the structure-to-air noise transfer efficiency (like a drum).

5. The increasing use of exposed structural ceilings eliminates the attenuation that can be introduced by a plenum above a hung ceiling. This is particularly bad, since most structure-borne

noise is carried by floor structures (rather than walls), which radiate sound up and down. The discussion that follows will be limited to impact noise. Refer to Section 19.26 for a brief treatment of vibration, which is felt rather than heard and is, in effect, a very low-frequency noise. Many of the practices and techniques that will minimize impact noise will also reduce vibration.

19.23 CONTROL OF IMPACT NOISE

Impact noise problems can be controlled in two ways—by preventing or minimizing the impact and by attenuating it once it has occurred. Prevention is discussed first; attenuation is covered in Section 19.25. Impact on floors is more serious than wall impact because the latter is partially attenuated at the wall/floor joint, whereas the former is introduced directly into the building framework. The following discussion addresses each of the solutions shown in Fig. 19.43.

(a) Cushion the Impact

See Fig. 19.43*a*. This obvious solution will frequently eliminate all but severe problems. Resilient cushioning materials in common use are floor tile of rubber and cork, or carpeting on pads, in ascending order of impact insulation. See Section 19.24 and Appendix L for quantitative data on impact insulation.

(b) Float the Floor

See Fig. 19.43*b*. Since the key to elimination of structure-borne sound is *isolation*, separating the impacted floor from the structural floor by a resilient element is extremely effective. This element can be rubber or mineral wool pads, or blankets, or special spring metal sleepers. The effectiveness depends upon the mass of the floating floor, compliance of the resilient support, and degree of isolation of the floating floor. The last element is extremely important, since flanking paths via end contacts with walls can short-circuit the floating element's sound impedance and defeat the system. With floating floors it is important that:

1. The mass of the floating floor be large enough to spread the loads properly. Otherwise, the pad will compress and deform sufficiently to transmit the impact.
2. Total construction be airtight. Airtight is soundtight.
3. Particular care be exercised where partitions rest on the floating floor (see Fig. 19.44*a*).
4. Short circuits at walls or by penetrations be avoided; see Fig. 19.10*b*. Details of proper construction techniques are given in *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings* (1968).
5. Construction throughout be consistent. Mixed construction types invite flanking noise paths (see Fig. 19.44*b*).

(c) Suspend the Ceiling—and Use an Absorber in the Cavity

See Fig. 19.43*c*, *d*. As stated, the most disturbing noise is that radiated down from the ceiling. A flexibly suspended ceiling with an acoustic absorbent layer suspended in it can be very effective if not

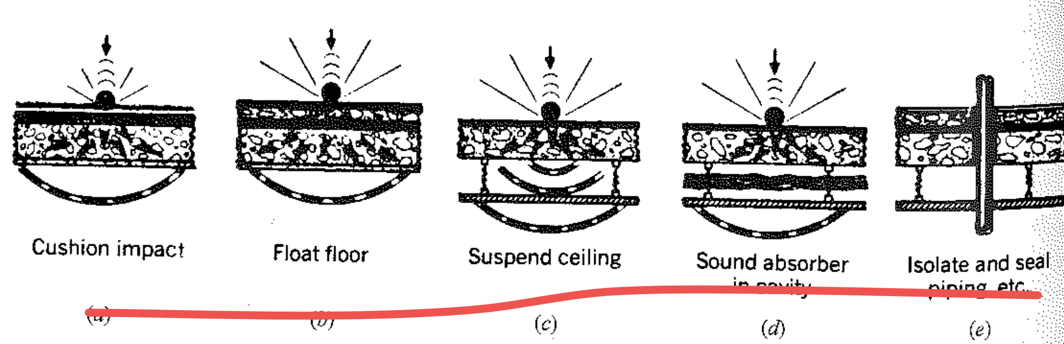


Fig. 19.43 Methods of controlling impact sound transmission through floors. (Reprinted from *Quieting: A Practical Guide to Noise Control*, 1986.)

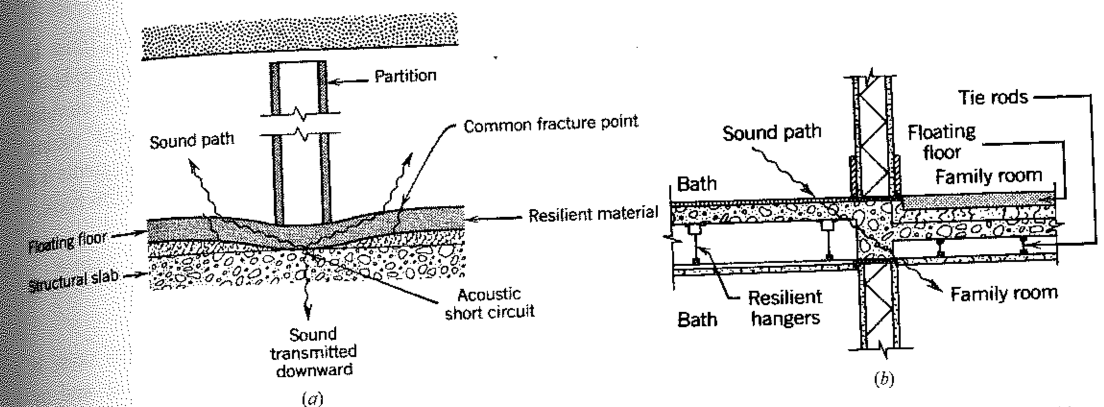


Fig. 19.44 (a) Caution must be exercised when supporting partitions on floating floors to prevent structural failures or short-circuiting of the floating element, as illustrated. (b) Flanking paths in mixed-construction type floors. The FHA does not recommend mixing construction types unless provisions have been made to prevent flanking (e.g., expansion joints or breaks in all structural paths between each space). (Reprinted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, 1968.)

flanked by paths leading into the walls and from there reradiating into the space below. It is imperative that the entire floor slab above be decoupled from the walls below by resilient separators.

(d) Isolate All Piping

See Fig. 19.43*e*. All rigid structures such as piping must be isolated so as not to form a flanking path, and penetrations must be caulked with resilient sealant so as not to constitute an air-sound leakage path.

19.24 IMPACT INSULATION CLASS

The impact insulation class (IIC) is a single-number, impact isolation rating for floor construction, similar in intent and derivation to STC wall ratings. Tests are made with a standard tapping machine and noise levels measured in ⅓-octave bands. These are plotted and compared to a standard contour, approximately as with the sound transmission class. Details of typical floor constructions along with IIC ratings are given in Appendix L. Resilient floor finishes on any of the floor constructions not specifically provided with them will add to the IIC ratings approximately as follows:

1/16-in. (1.6-mm) vinyl tile	0
⅛-in. (3-mm) linoleum or rubber tile	4 ± 1
¼-in. (6-mm) cork tile	10 ± 2
Low-pile carpet on fiber pad	12 ± 2
Low-pile carpet on foam rubber pad	18 ± 3
High-pile carpet on foam rubber pad	24 ± 3

MECHANICAL SYSTEM NOISE CONTROL

19.25 MECHANICAL NOISE SOURCES

Mechanical devices make noise. And generally, the more power they consume, the more noise they make. In many of today's buildings, 40% of the total construction budget is spent on mechanical systems located throughout a building.

In most buildings, the primary sources of mechanical noise are the components of the air-conditioning and air-handling systems such as fans, compressors, cooling towers, condensers, ductwork, dampers, mixing boxes, induction units, and diffusers. The curve of Fig. 19.45 depicts typical air-handling system noise and indicates the portions of the spectrum produced by each group of components. Pumps are another source of mechanical noise, which (along with the noise of flowing liquid) is transmitted along pipes to locations throughout the building.

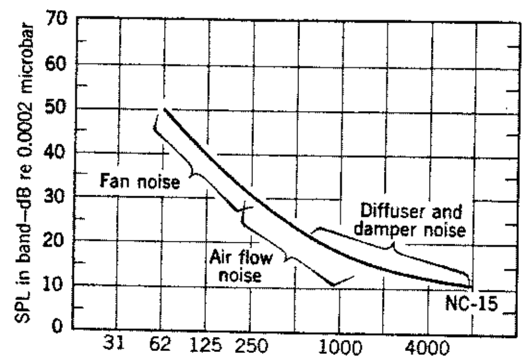


Fig. 19.45 *Sound pressure level frequency spectrum of noise from HVAC system components.*

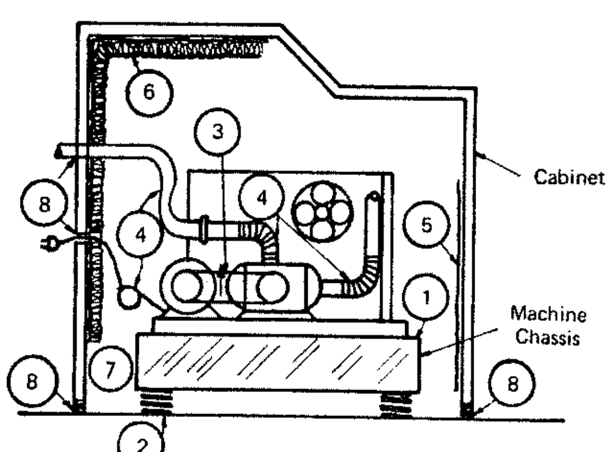
Elevators, escalators, and freight elevators also introduce mechanical noise into buildings. Escalators and freight elevators pose few problems, since they are localized in a specific area and have low operation speeds. Passenger elevator car operation, however, is rapid, and it affects large areas. In addition, the motors and controls are located on or above the prime upper floors of a building. Motor, shaftway, and other equipment noise must be properly controlled to prevent annoyance to building tenants located near the shaftways or elevator penthouses and mechanical equipment rooms. Vibration isolation of these major components is a specialized problem beyond the scope of this book.

19.26 QUIETING OF MACHINES

Machines cause noise by vibration. This noise is imparted directly to the surrounding air and by vibrational contact to the surrounding structure. Therefore, there are three ways to reduce this noise:

1. Reduce the vibration itself.
2. Reduce the airborne noise by decoupling the vibration from efficient radiating sources.
3. Decouple the vibrating source from the structure.

Refer to Fig. 19.46. Items 1, 3, and 4 reduce vibration; items 4, 5, 6, and 7 reduce and decouple the vibration from the radiating cabinet; and items 2 and 8 decouple the vibrating source from the structure. Once a noise becomes airborne or structure-borne, the aforementioned isolation techniques are employed.



1. Install motors, pumps, fans, etc. on most massive part of the machine.
2. Install such components on resilient mounts or vibration isolators.
3. Use belt drive or roller drive systems in place of gear trains.
4. Use flexible hoses and wiring instead of rigid piping and stiff wiring.
5. Apply vibration damping materials to surfaces undergoing most vibration.
6. Install acoustical lining to reduce noise buildup inside machine.
7. Minimize mechanical contact between the cabinet and the machine chassis.
8. Seal openings at the base and other parts of the cabinet to prevent noise leakage.

Fig. 19.46 *Techniques used to reduce the transmission of airborne and structure-borne noise from machines and appliances. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *1968.)*

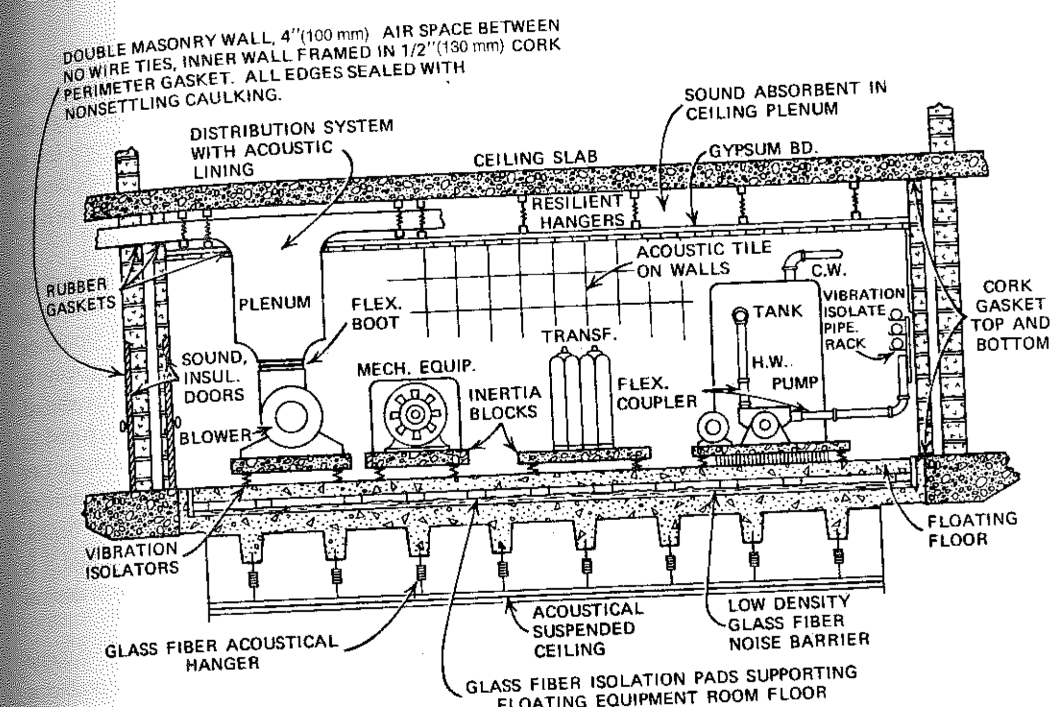


Fig. 19.47 *Soundproofing a mechanical equipment room. Additional noise reduction to the space below can be achieved by inserting a layer of highly absorbent material in the space above the suspended acoustical ceiling. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *1968.)*

Vibration reduction takes two forms, damping and isolation. One form of damping is accomplished by rigidly coupling the vibrating source to a large mass, frequently called an *inertia block*. Much of the energy is absorbed and dissipated as friction; the remainder results in lower-amplitude vibration (Fig. 19.47). Isolation is accomplished by supporting the vibrating mass on resilient supports. These take many forms and can be used in combinations. Thus, machines are supported on fibrous, rubber, or spring steel vibration isolators, and the entire mass can be supported on a floating floor, which in turn rests on resilient vibration isolators, as in Fig. 19.47. Large machines are supported on special commercial "sandwiches" of asbestos, lead, cork, and other strong, resilient materials. Piping is supported on cork pads and hung on resilient hangers.

Use of a diesel-driven electric generator for load peaking or cogeneration can cause very serious noise and vibration problems. The ideal solution to this situation is to completely isolate the unit in a separate outbuilding that is designed specifically to contain the very high noise level produced. If that is not practical and an inside location is necessary, a complete enclosure may be required to ameliorate the noise problem.

Vibration damping can be an even more serious problem, which can be solved satisfactorily with sufficient mass and proper vibration isolation. In the case of vibrating sheet metal, soft foam-type damping material glued directly to the metal is effective in damping. Flexible joints in all pipes and ducts connected to vibrating machines are mandatory. This includes flexible conduit connectors to all motors, transformers, and lighting fixtures using magnetic ballasts.

19.27 DUCT SYSTEM NOISE REDUCTION

Design of a quiet duct system entails more than specifying an absorptive duct lining. Air turbulence generates noise. Turbulence increases as the velocity of airflow increases and anywhere in the duct system where smooth laminar flow is disturbed, such as at sharp bends. The permissible "sharpness" of a bend depends in turn upon air velocity; the higher the air velocity, the more aerodynamic the duct system must be to prevent turbulence and, therefore, noise. Table 19.10 demonstrates this principle. The farther one proceeds upstream from a point of turbulence, the higher the air velocity may be from a noise perspective, since truly laminar flow is essentially noiseless. In principle, velocities should be as low as practical, since air turbulence noise increases exponentially with velocity.

Sound travels as easily against as with the airflow in ductwork. Therefore, both supply and return systems must be lined to control transmission of fan noise. Maximum fan noise reduction occurs at bends in the ductwork. For maximum fan noise reduction in short runs, a pair of 90° bends is sometimes deliberately inserted. However, because 90° bends also introduce turbulence that generates noise, introducing bends as fan noise attenuators can be counterproductive at air velocities above 600 fpm (3 m/s). Another disadvantage of bends is added system friction and the additional energy and cost required to move air. This point will be discussed further in the next section.

Other design approaches that create a quiet system include smooth transitions at changes of duct size and large-radius bends with turning vanes, the purpose of which is to reduce turbulence. Attenuation drops rapidly as duct size increases; therefore, ducts should not be deliberately oversized. Cross-talk between rooms and between ducts can be minimized by using lined ducts, separating adjacent ducts as much as possible, and gluing damping material on the outside and lining on the inside. Damping material is particularly effective in preventing the thin metal walls of ducts from resonating. Mufflers and silencers are effective in reducing the high-frequency components of fan noise, but much less so with low frequencies. The pressure drop these devices introduce, which can be considerable, must be compensated for in the fan selection.

The *ASHRAE Handbook—HVAC Applications* should be consulted for recommendations on noise control in air-handling units, plenums, housings, and ducts. Figure 19.48 shows some of the ways in which cross-talk and flanking noises can be reduced. Figure 19.49 shows some techniques employed for quieting duct noise. Active noise cancellation (see Section 19.28) is particularly useful in duct systems since it does not reduce airflow, as do liners, baffles, and other mechanical silencing devices, and it is effective at low frequencies, whereas these devices are not.

The increased use of variable-air-volume (VAV) systems has introduced some noise problems that should not be neglected. VAV system noise can be minimized by following a few basic design rules. Maintain minimum system static pressure since fan noise increases exponentially with static pressure. Select the air volume modulating device at the fan with care, as it can be a noise source. Since outlet air volume control involves duct area restriction with attendant velocity increase and resultant noise, such a design must include some sort of downstream silencing equipment. Ceiling diffuser acoustic characteristics must be coordinated with design air velocity and with any requirement for masking sound. Finally, avoid the use of throttling dampers on ceiling diffusers since a partially closed damper can generate very high noise levels.

TABLE 19.10 Maximum Air Speeds in Ducts to Yield NC-15 or NC-25 Background Levels[a]

Location	*Supply*		*Return*	
	NC-15	NC-25	NC-15	NC-25
Slot speed at min. ½-in. (13-mm) opening	250 fpm	350 fpm	300 fpm	420 fpm
10 ft (3 m) of duct before opening	300	420	350	490
Next 20 ft (6 m)	400	560	450	630
Next 20 ft (6 m)	500	700	570	800
Next 20 ft (6 m)	640	900	700	980
Next 20 ft (6 m)	800	1120	900	1260
Next 20 ft (6 m)	1000	1400	1100	1540
Next 20 ft (6 m)	1300	1820	1450	2030
Next 20 ft (6 m)	1600	2240	1800	2520

[a]Ducts with 1- to 2-in. (25- to 50-mm) inside duct lining, all duct sizes.

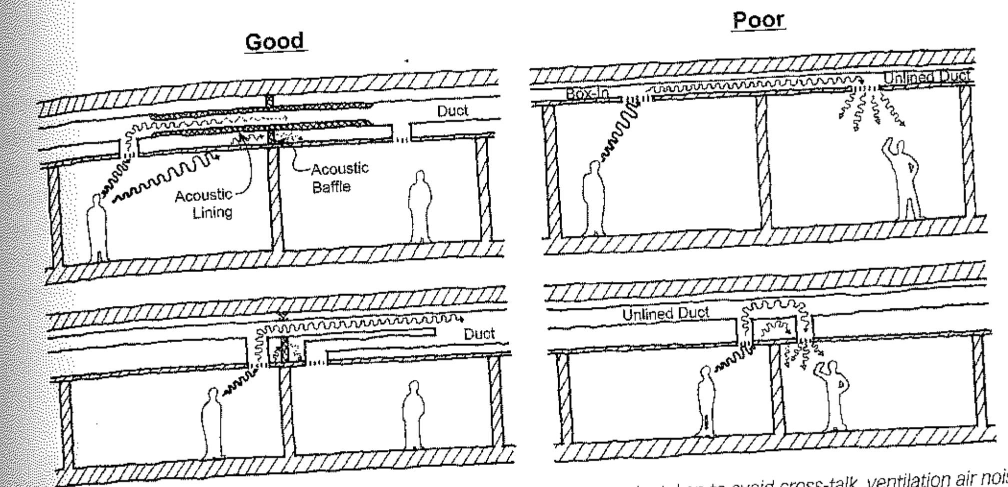


Fig. 19.48 Since ducts are efficient sound transmission paths, precautions must be taken to avoid cross-talk, ventilation air noise, and equipment noise. Dwelling units should be serviced by separate supply and return ducts that branch off a main duct system. Avoid running ducts as a common supply or return between rooms unless they are properly baffled and lined with sound-absorbing material. The common practice, in wood-frame structures, of using troughs between joists as a common return duct between rooms and between separate dwelling units results in serious noise transmission problems. Caulk or seal around ducts at all points of penetration through partitions. Use double-wall ducts, acoustical lining, flexible boots, and resilient hangers where required. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, 1968. Redrawn by Jonathan Meendering.)*

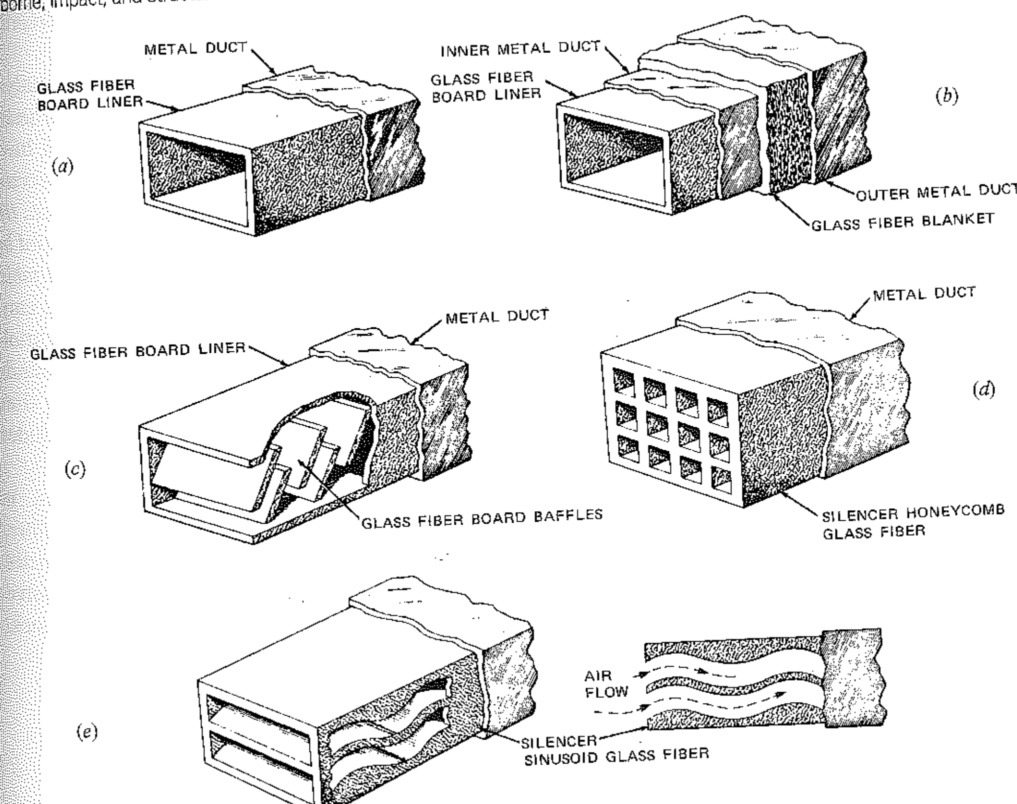


Fig. 19.49 Unlined duct has negligible sound attenuation. Inside lining (a) gives 2–3 dB attenuation per foot in the range 1–2 kHz, dropping rapidly above and below those frequencies and giving negligible low-frequency attenuation. Double lining (b) gives higher attenuation and reduces cross-talk between ducts. Duct silencers and baffles (c–e) give high broadband attenuation: a maximum of 10–12 dB/ft (3.0-3.7 dB/m) in the range 1–2 kHz and lower above and below. They are useful to reduce fan noise in short runs but cause considerable pressure drop. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, 1968.)*

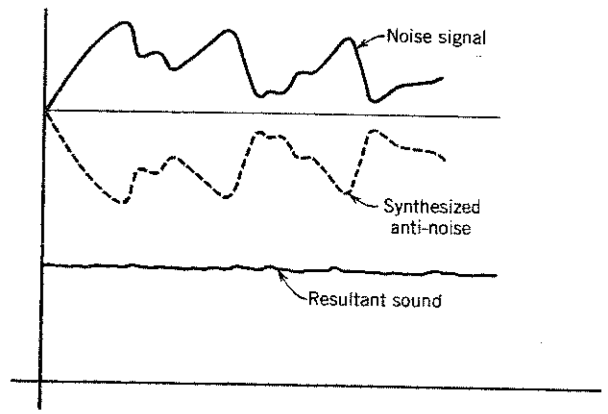


Fig. 19.50 *Silencing of noise by introduction of a synthesized noise signal exactly out of phase with the original signal. The resultant sound is effectively zero—that is, silence.*

19.28 ACTIVE NOISE CANCELLATION

Since noise is a phenomenon consisting of acoustic wave energy transmitted at certain frequencies, it is theoretically possible to *eliminate* (not mask) noise by simultaneous transmission of identical wave energy exactly out of phase with the noise. The sum of the two energy waves is zero—hence silence (Fig. 19.50). The phase matching, however, must be exact; if the injected out-of-phase noise is not precisely a negative image of the original noise, then not only will the signals not cancel but they may even increase the noise level. The technique for accomplishing noise cancellation is straightforward in theory but much less so in practice. A microphone samples a noise source and feeds that signal into an analysis/synthesis device. This, as the name implies, analyzes the frequency and amplitude content of the noise and synthesizes the anti-noise, which is then fed to a loudspeaker in the original noise path. The resultant residual noise is detected by a downstream microphone and fed back into the controller as a feedback correction signal.

This entire procedure is shown in block diagram form in Fig. 19.51. The technical problems that must be overcome are formidable. Without delving deeply into the physics involved, we can describe them qualitatively.

1. It takes a finite amount of time to analyze the frequency content of a noise and to synthesize the anti-noise. If the noise is random it will have changed by the time the anti-noise signal is injected and will therefore not be canceled. As a result, *the only type of noise that can effectively be attenuated by anti-noise is one that is continuous and/or predictable.* Random noise, such as that of a barking dog, cannot be actively attenuated with the present technology. Candidates for noise cancellation are sounds like those produced by operating machinery, that is, continuous and repetitive sounds. This includes very-low-frequency noise.

2. The analysis and synthesis process is achieved by a device called an *adaptive digital filter.* For technical reasons, the higher the frequencies (pitch) involved, the more complex and expensive are the required digital electronics, microphones, and loudspeakers. This further narrows the range of practical noise-cancellation candidates to those producing low frequencies, such as blowers, fans, rotors, internal combustion engines and their exhausts, transformers (hum), air movement in ducts, fluid movement in pipes, and the like.

3. The waveform of the noise, its modes, and its dispersion in space impact heavily on the type and amount of equipment required to effect attenuation economically (i.e., commercially). The simplest type of noise to treat is one that is confined by some sort of waveguide, at low frequency, and exhibits constant sound pressure and phase. Such a wave is known as a *plane wave*, and it can be "treated" with a single sampling microphone, a single loudspeaker, and a single processor.

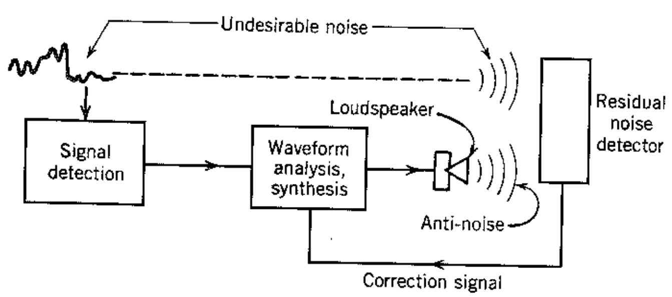


Fig. 19.51 *Block diagram of an active noise-cancellation system. The noise signal is detected, its periodicity determined, its waveform analyzed, and an out-of-phase noise is synthesized and injected into the acoustic environment. A residual noise detector provides a feedback signal that acts to improve noise cancellation.*

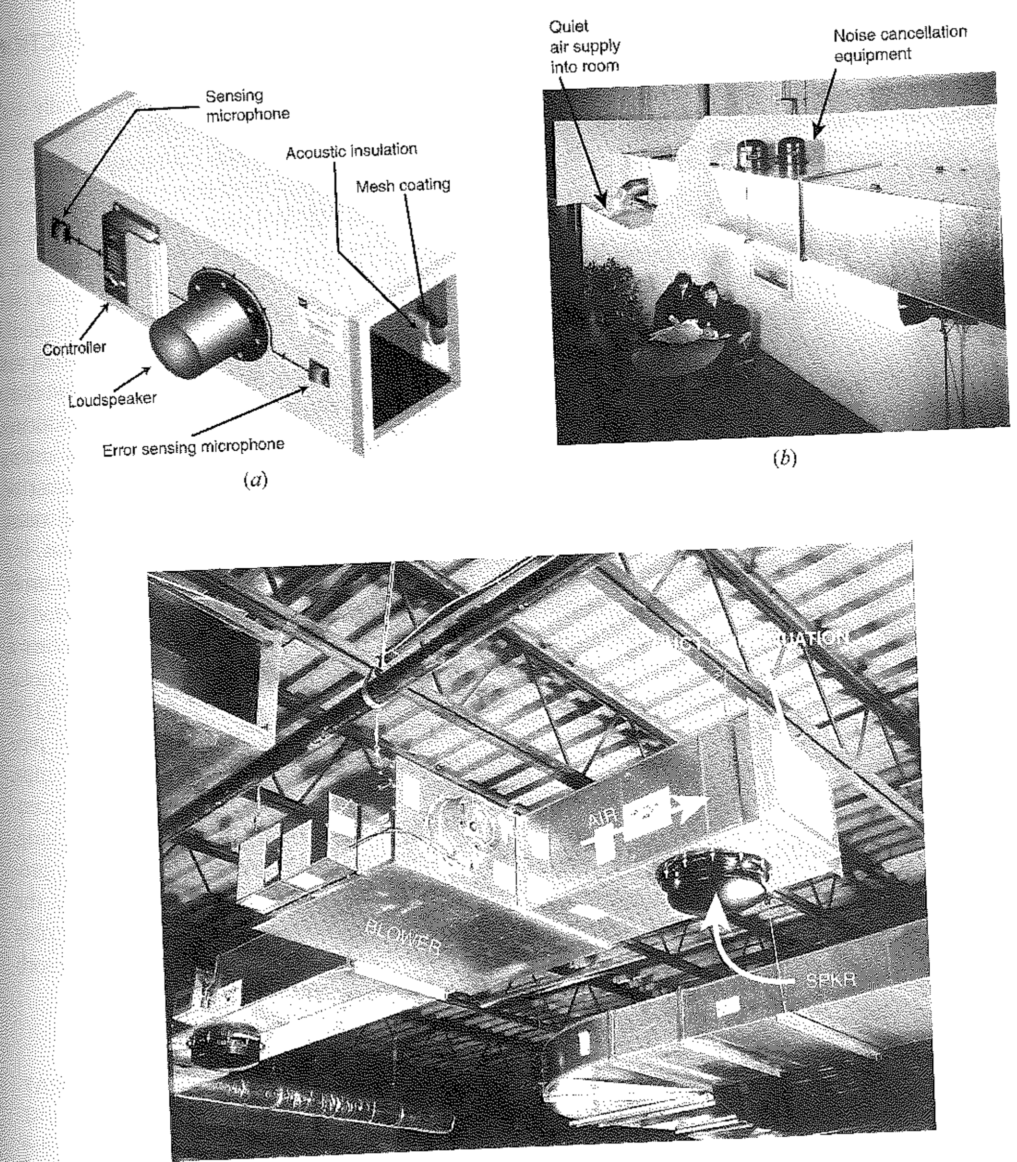


Fig. 19.52 *Active duct-noise-cancellation equipment. (a) The system components, consisting of the sensing and error-signal microphones, controller, and a loudspeaker, are built into a duct section of the required size, which is inserted into the duct system. (b) A mock-up of an office installation showing the relative size and positions of a dual-channel system. (c) Photograph of a multichannel duct-noise-cancellation system in a new office building (designed with large, unlined HVAC ducts). (Courtesy of Digisonix.)*

Considering the three stated criteria, an ideal candidate for economic noise cancellation treatment is duct noise, which is low frequency, continuous, and a plane wave. Figure 19.52 shows the construction of a typical commercial duct-noise-suppression unit, plus application photographs. Practical duct-noise-cancellation equipment in use today can reduce levels from NC-50 to NC-35 and is particularly effective at the "rumble" frequencies below 200 Hz.

Important auxiliary advantages of active duct-noise cancellation are energy conservation and economic benefits. Passive duct-noise reduction, particularly at low frequency, requires massive noise absorbers, requiring 7 to 10 ft (2.1 to 3.0 m) of duct for installation. See Fig. 19.49*c–e*. In addition to the high first cost of these devices and their installation, they introduce a static pressure loss of ½ in. to 1½ in. w.g. (125 to 375 Pa), depending upon airflow and speed. This, in turn, requires a higher horsepower (and noisier) fan. Economic analysis of such designs generally shows an advantage for active noise-cancellation equipment. Such an analysis should be performed for every design where duct silencers are desired or required.

Another important application of active noise cancellation, already in wide use, is in the area of hearing conservation for people exposed to high noise levels at work. Here the out-of-phase noise is introduced into miniature loudspeakers (earphones) in an acoustically transparent headset. This allows the wearer to hear random sounds (such as speech) clearly, while repetitive cyclic noise from engines and the like is attenuated (Fig. 19.53).

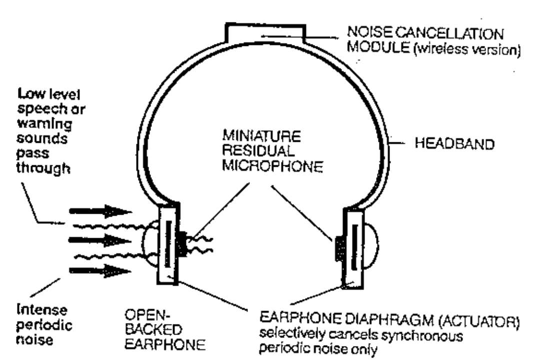


Fig. 19.53 *Schematic diagram of a headset with active noise cancellation. Because of the physical proximity of all the elements, only a single microphone is used. (Courtesy of Noise Cancellation Technologies.)*

Other areas where active noise cancellation is already in use include engine exhausts, heavy machine vibration, interiors of luxury automobiles, military and space vehicles, and selected shipboard spaces. Applications will undoubtedly increase with advances in digital signal processing technology, equipment miniaturization, and reduction in equipment costs.

19.29 PIPING SYSTEM NOISE REDUCTION

As with airflow, noise increases exponentially with liquid flow velocity. Piping is not a major noise source normally, since the radiating diameter is small, except for flow velocities much in excess of 8 fps (2.4 m/s) where a pipe is in contact with the structure. This is, of course, most serious where a pipe passes through NC-15 to NC-25 areas (see Table 19.8). Domestic water system mains should be limited to 50 psi (345 kPa) in other than tall buildings and pressure in branches to 35 psi (240 kPa). In high-rise structures, pressure-reducing valves will be required in high-pressure mains to meet these recommendations. Piping must be designed to prevent water hammer, and noise sources must be located away from quiet areas.

Pumps, like all rotating equipment, are sources of vibration and noise and should be treated as described in Section 19.26. Figure 19.54 shows a typical pump installation with appropriate noise reduction measures. For at least a distance of 100 pipe diameters beyond the pump, resilient pipe hangers should be used. With centrifugal pumps, as with fans and blowers, machine sound concentrates in narrow bands and, if extremely disturbing, can be attenuated with resonant filters. Reciprocating pumps are more difficult to control, as the pulsations are more vibration than noise. Flexible connections and U-joints in the piping will absorb much of this vibration.

19.30 ELECTRICAL EQUIPMENT NOISE

Electrical equipment is generally overlooked as a noise source, and this is unwise. Most electrical noise is a 120-Hz hum. This can be very disturbing because the frequency is so low and, as we have noted repeatedly, low-frequency noise is difficult to attenuate passively. Transformer noise levels

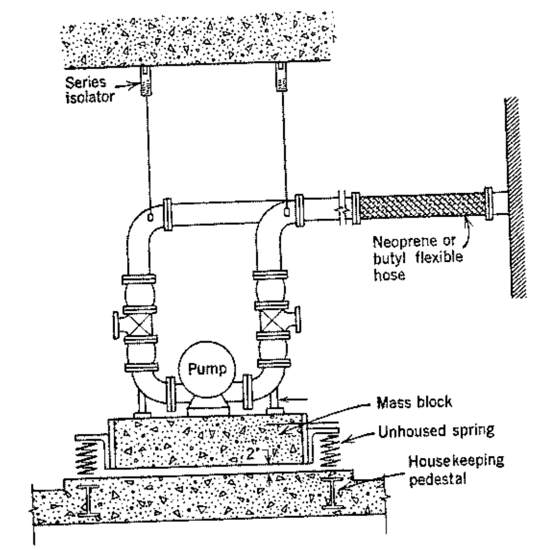


Fig. 19.54 *Typical pump installation with appropriate vibration isolation and damping measures.*

are dictated by National Electrical Manufacturers Association (NEMA) and American National Standards Institute (ANSI) standards. For a premium price, lower-noise units are obtainable. Table 19.11 lists maximum noise levels for dry-type units. Most manufacturers warranty noise below these levels. Oil- and silicone-filled units are normally quieter than dry-type transformers, as are units designed for lower temperature rise. Transformer noise can be minimized by these steps:

1. Mount the unit on vibration isolators.
2. If the transformer is wall-hung, use resilient hangers. If it is floor-mounted, place it on a massive slab if possible.
3. Locate the unit so that reflections do not amplify the sound. Sound-absorbent material on the walls behind the units is not useful at 120 Hz. Only cavity resonators will absorb appreciable amounts of sound at that frequency.

TABLE 19.11 Maximum Sound Levels: Dry-Type Transformers

kVA	Decibels (NEMA Standard)
0–9	40
10–50	45
51–150	50
151–300	55
301–500	60

4. Use only flexible conduit connections.
5. Avoid locating transformers adjacent to, or immediately outside, quiet areas. A common error in this regard is placing a transformer pad immediately below the window of an NC 15–25 area.

The second major source of 120-Hz hum is conventional core-and-coil discharge lamp ballasts. These include magnetic ballasts for fluorescent and all high-intensity discharge (HID) sources. Fortunately, electronic ballasts, which are practically noiseless, are rapidly replacing core-and-coil ballasts in fluorescent fixtures, and to a lesser extent in HID units. Table 19.12 lists recommended applications of non-electronic fluorescent ballasts. Conventional coil-type HID ballasts can be very noisy, and care must be exercised in their placement. With all ballasts, the method of mounting has a marked effect on the radiated noise. As pointed out earlier, when a small vibrating source is coupled rigidly to a larger body, noise is amplified because of increased source-to-air coupling. Since core-and-coil fluorescent ballasts for linear fluorescent lamps are necessarily closely coupled to large metal fixtures for heat dissipation purposes, the sound radiation is greatly amplified. A large number of such fluorescent fixtures mounted in a plenum can create a serious noise problem. Solution of the problem lies either in ballast replacement or in the use of absorptive material in plenums, flexible conduit connection to fixtures,

TABLE 19.12 Acoustic Criteria for Selection of Conventional Core-and-Coil Fluorescent Lamp Ballasts

For an Installation in:	Use of Ballasts with This Rating Will Usually Be Satisfactory
TV or radio station, church, synagogue	A
Office, residence, library, reception or reading room, school study hall	B
Noisy office, doctor's or dentist's office, classroom	C
Industrial applications	D

and resilient fixture hanging. In severe cases, ballasts can be remote-mounted. Coil-type HID ballasts are inherently noisier than fluorescent ones but, like ballasts for compact fluorescent lamps, are generally less troublesome, being coupled to small radiating bodies.

19.31 NOISE PROBLEMS DUE TO EQUIPMENT LOCATION

Roof-mounted HVAC units have proven to be very economical yet very noisy. Vibration, short duct runs, and sound reflections are serious problems that can be solved with vibration isolators, sound mufflers, and careful location of equipment. Roof-mounted cooling towers are a particular problem when they are located adjacent to a taller building. This problem has led to a spate of lawsuits and noise control legislation in many cities. For this reason, particular attention should be paid to all exterior equipment during the design process.

In high-rise buildings, problems are caused by conflicts between the stringent noise requirements of the prime upper floor space and the near presence of elevator machine rooms, mechanical equipment rooms, and cooling towers. These problems are almost impossible to solve after construction and require the services of an acoustics expert during design.

19.32 SOUND ISOLATION ENCLOSURES, BARRIERS, AND DAMPING

In buildings with concentrated high-level noise sources, such as certain types of machinery, it is always more desirable to reduce the noise at its source than to attempt to treat the larger enclosing space. This is most effectively accomplished by enclosing the noise source with materials that provide a combination of reverberant noise reduction by absorption (as explained in Section 18.9 and Fig. 18.10) and blocking of airborne sound with high transmission loss (as detailed in Sections 19.7 to 19.12). These materials are available in the form of curtains, panels, and prefabricated partial and full enclosures tailored to the specific characteristics of the noise source (Fig. 19.55). Such enclosures are not normally the responsibility of the building designer. It is, however, important to know that they will be used, as well as their characteristics, so that appropriate isolation can be designed into the building for the residual sound that is radiated from the enclosures.

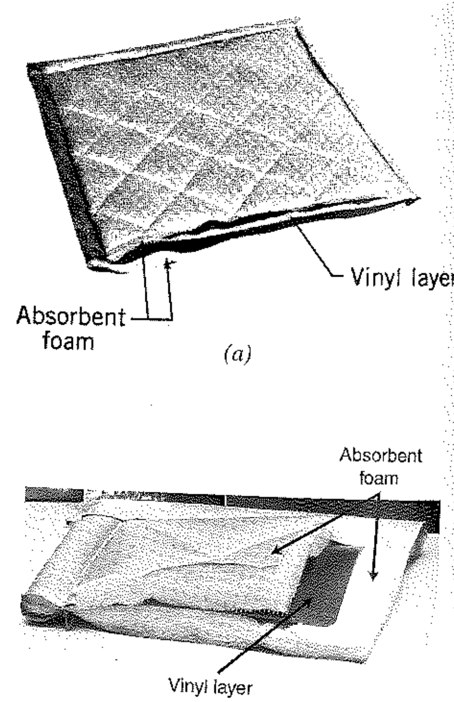


Fig. 19.55 (a) Typical flexible nonmetallic composite acoustical barrier material that can be used as a free-hanging curtain or applied to a rigid surface. It consists of a layer of flexible vinyl sandwiched between two layers of fiberglass or other acoustic foam. The construction is seen clearly in the cutaway (b). The material is most effective when applied with an air space between it and any rigid support barrier. (Courtesy of E-A-R Specialty Composites, division of AEARO Co.)

Where a noise is at least partially the result of vibrating (sheet) metal enclosures, as for instance on laundry machines, mixers, bins, chutes, polishing drums, and the like, a very effective noise control technique is to damp the vibration. This can be done by permanent attachment of a layer of foam to the vibrating metal, which, by minute flexing of the foam mass, converts the vibration energy to heat. The noise reduction can be further enhanced by adding a heavy, limp barrier material to the outside of the foam. Such combinations are called *composite damping barrier materials*, several of which are illustrated in Fig. 19.56. The foam layer also acts to decouple the barrier and thereby increase the noise attenuation.

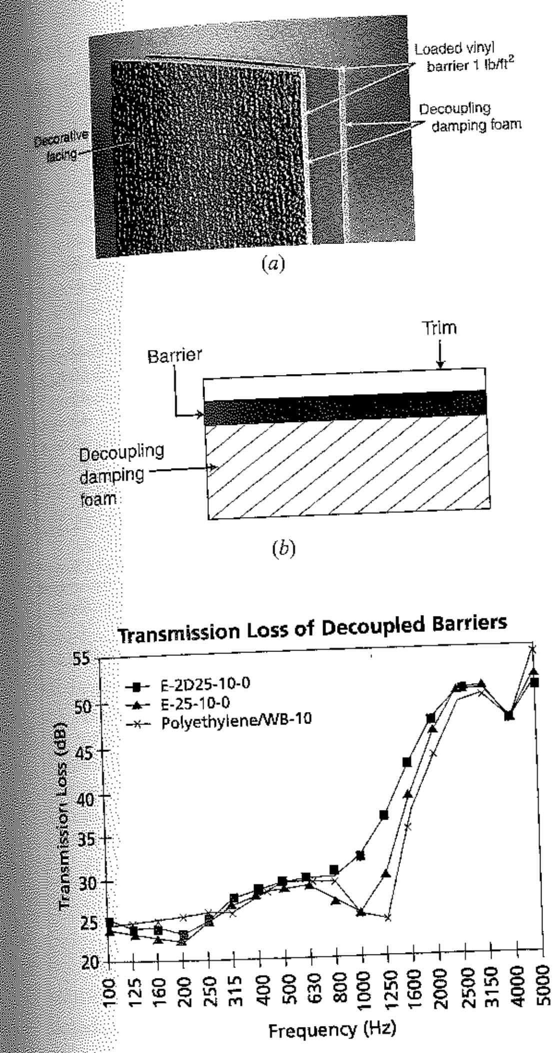


Fig. 19.56 Composite damped, decoupled barrier material comprising a layer of damping foam plus an integral layer of loaded vinyl barrier material. The exterior may be covered (a) with a decorative cover layer. The foam layer acts to damp the vibrating surface to which it adheres (b) and to decouple the barrier layer. Preliminary attenuation test data (c) for a composite consisting of ¼ in. (6.4 mm) foam and 1 lb/ft² (4.9 kg/m²) loaded vinyl. (Courtesy of E-A-R Specialty Composites, division of AEARO Co.)

STC AND IIC RECOMMENDATIONS AND CRITERIA

Recommendations for background noise levels (NC criteria) are given in Table 19.8. Criteria for partition insulation (STC) and impact insulation (IIC) are given in the following sections and in Table 19.13.

19.33 MULTIPLE-OCCUPANCY RESIDENTIAL STC/IIC CRITERIA

The most important acoustical design criteria for residential work in the United States are issued by the Department of Housing and Urban Development in conjunction with the Federal Housing Administration (HUD/FHA). The reader is referred to the latest issue of *A Guide to Airborne, Impact and Structure-Borne Noise Control* and to subsequent HUD/FHA publications. Tables 19.14 and 19.15 give the essential data presented in the current edition of the *Guide*.

The recommendations are divided into grades I, II, and III. Grade II is the most important category and is applicable primarily in residential urban and suburban areas considered to have an average noise environment. The nighttime exterior noise levels may be about 40 to 45 dBA, and the permissible interior noise environment characteristics should not exceed NC 25–30. Grade I is suburban, with a quiet noise environment characterized by a nighttime exterior noise level of about 35 to 40 dBA. *Grade I STC/IIC criteria are 3 points higher than those of grade II.*

TABLE 19.13 Recommended STC for Partitions; Specific Occupancies

	Wall, Partition, or Panel Between		*Sound Insulation Requirement; Background Level in Room Being Considered*	
Type of Occupancy	**Room Being Considered and**	**Adjacent Area**	**Quiet**	**Normal**
Normal school buildings without extraordinary or unusual activities or requirements	Classrooms	Adjacent classrooms	STC 42	STC 40
		Corridor or public areas	STC 40	STC 38
		Kitchen and dining areas	STC 50	STC 47
		Shops	STC 50	STC 47
		Recreation areas	STC 45	STC 42
		Music rooms	STC 55	STC 50
		Mechanical equipment rooms	STC 50	STC 45
		Toilet areas	STC 45	STC 42
	Music practice rooms	Adjacent practice rooms	STC 55	STC 50
		Corridor and public areas	STC 45	STC 42
Executive areas, doctors' suites; confidential privacy requirements	Office	Adjacent offices	STC 50	STC 45
		General office areas	STC 48	STC 45
		Corridor or lobby	STC 45	STC 42
		Washrooms and toilet areas	STC 50	STC 47
Normal office; normal privacy requirements; any occupancy using rooms for group meetings	Office	Adjacent offices	STC 40	STC 38
		Corridor, lobby, exterior	STC 40	STC 38
		Washrooms, kitchen, dining	STC 42	STC 40
	Conference rooms	Other conference rooms	STC 45	STC 42
		Adjacent offices	STC 45	STC 42
		Corridor or lobby	STC 42	STC 40
		Exterior of building	STC 40	STC 38
		Kitchen and dining areas	STC 45	STC 42
Large offices, drafting areas, banking floors, etc.	Large general office areas	Corridors, lobby, exterior	STC 38	STC 35
		Data-processing area	STC 40	STC 38
		Kitchen and dining areas	STC 40	STC 38
Motels and urban hotels Hospitals and dormitories	Bedrooms	Adjacent bedrooms[a]	STC 52	STC 50
		Bathroom[a]	STC 50	STC 45
		Living rooms[a]	STC 45	STC 42
		Dining areas	STC 45	STC 42
		Corridor, lobby, or public spaces	STC 45	STC 42

Source: Courtesy of U.S. Gypsum.

[a]Separate occupancy.

The fundamental criteria for airborne sound insulation between dwelling units are, for grade II:

Wall partitions	STC > 52
Floor-ceiling assemblies	IIC > 52

These apply where similar function spaces are contiguous, such as bedroom to bedroom and living room to living room. Where this is not the case, the insulation must be increased to meet the higher sensitivity requirement.

Grade III recommendations are minimal and can be characterized as noisy, with an average nighttime exterior noise level of about 55 dBA or higher. *Grade III STC/IIC recommendations are 4 points lower than those of grade II.*

19.34 SPECIFIC OCCUPANCIES

(a) Schools

School buildings house spaces of many kinds—classrooms, auditoriums, gymnasiums, cafeterias, shop areas, swimming pools, and music suites—that pose acoustics problems.

TABLE 19.14 Criteria for Airborne Sound Insulation of Partitions between Dwelling Units

Partition Function between Dwellings			
Apt. A		**Apt. B**	**Grade II STC**
Bedroom	to	Bedroom	52
Living room	to	Bedroom[a]	54
Kitchen[b]	to	Bedroom[a]	55
Bathroom	to	Bedroom[a]	56
Corridor	to	Bedroom[a,c]	52
Living room	to	Living room	52
Kitchen[b]	to	Living room[a]	52
Bathroom	to	Living room	54
Corridor	to	Living room[a,c,d]	52
Kitchen	to	Kitchen[e]	50
Bathroom	to	Kitchen	52
Corridor	to	Kitchen[a,c,d]	52
Bathroom	to	Bathroom	50
Corridor	to	Bathroom[a,c]	48

Source: Reprinted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings* (1968). For Grade I, add 3 points; for Grade III, subtract 4 points.

[a]Whenever a partition wall may serve to separate several functional spaces, the highest criterion must prevail.

[b]Or dining or family or recreation room.

[c]It is assumed that there is no entrance door leading from the corridor to the living unit.

[d]Criterion applies to the partition. Doors in corridor partitions must have the rating of the partition, not vice versa.

[e]Double wall construction is recommended to minimize kitchen impact noises.

TABLE 19.15 Criteria for Airborne and Impact Sound Insulation of Floor-Ceiling Assemblies between Dwelling Units

Assembly Function between Dwellings			*Grade II*	
Apt. A		**Apt. B**	**STC**	**IIC**
Bedroom	Above	Bedroom	52	52
Living room	Above	Bedroom[a]	54	57
Kitchen[b]	Above	Bedroom[a,c]	55	62
Family room	Above	Bedroom[a,d]	56	62
Corridor	Above	Bedroom[a]	52	62
Bedroom	Above	Living room[e]	54	52
Living room	Above	Living room	52	52
Kitchen	Above	Living room[a,c]	52	57
Family room	Above	Living room[a,d]	54	60
Corridor	Above	Living room[a]	52	57
Bedroom	Above	Kitchen[c,e]	55	50
Living room	Above	Kitchen[c,e]	52	52
Kitchen	Above	Kitchen[c]	50	52
Bathroom	Above	Kitchen[a,c]	52	52
Family room	Above	Kitchen[a,c,d]	52	58
Corridor	Above	Kitchen[a,c]	48	52
Bedroom	Above	Family room[e]	56	48
Living room	Above	Family room[e]	54	50
Kitchen	Above	Family room[e]	52	52
Bathroom	Above	Bathroom[c]	50	50
Corridor	Above	Corridor	48	48

Source: Reprinted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings* (1968). For Grade I, add 3 points; for Grade III, subtract 4 points.

[a]This arrangement requires greater impact sound insulation than the converse, where a sensitive area is above a less sensitive area.

[b]Or dining or family or recreation room.

[c]It is assumed that plumbing fixtures, appliances, and piping are installed with proper vibration isolation.

[d]The airborne STC criteria in this table apply as well to vertical partitions between these two spaces.

[e]This arrangement requires equivalent airborne sound insulation and perhaps less impact sound insulation than the converse.

1. *Auditoriums.* All auditoriums require a sound system for some of the activities accommodated (see Figs. 18.24 and 18.27). The most difficult aspect, architecturally, is integration of a loudspeaker system into the design. To provide proper sound reinforcement, loudspeakers must be located properly without large obstructions. To accomplish this, the loudspeaker system should be incorporated in the earliest design stages.

In general, a school auditorium is a multipurpose facility. It should be designed to meet speech requirements and also should be suitable for the school's music activities. Often a modified gymnasium (gymnatorium) or cafeteria (cafetorium) functions as an auditorium. Obviously, acoustic compromises occur in such facilities. Large areas of sound-absorbing treatment in either kind of space make them unsuitable as auditoriums and for most events that require speech amplification.

2. *Classrooms.* Typical classrooms are approximately 30 ft square (2.8 m^2) with 10-ft (3-m) ceilings. Adequate speech communication is easily achieved in a room of this size. Classroom acoustic design usually involves:

a. Locating sound-absorbing treatment to reduce classroom noise levels
b. Ensuring adequate privacy between adjacent spaces
c. Control of air-handling system noise

Acoustic tile ceilings provide adequate sound absorption for most classrooms. An NRC of 0.7 is recommended (see Section 18.10).

Partition systems must provide sufficient insulation to prevent disturbance from activities in other classrooms and corridors. Such partitions should run full-height from floor to ceiling slab or roof construction. If return-air transfer ducts are needed, their noise reduction characteristics must be as good as those of the walls or doors that they penetrate (for NC data, see Table 19.8). Unit ventilators commonly used for classrooms produce approximately the required level of background sound.

3. *Music Suites.* School music programs usually range from individual instruction to band and choral concerts. The teaching spaces required for such a program include practice rooms, ensemble rooms, and large rehearsal spaces. Both room acoustics design and sound isolation are important in music suites. Privacy between adjacent spaces is critical, since simultaneous use is necessary.

4. *Dining Areas.* The activity in cafeterias or lunchrooms usually generates a great deal of noise. The kitchen and serving areas should be separated from the eating spaces. Ceilings and wall areas in the cafeteria should be treated with sound-absorbing material. Unless the ceiling is completely treated with a highly efficient sound-absorbing material, the environment will be unsatisfactory due to its high noise level. The minimum NRC of this material should be 0.8.

5. *Gymnasiums.* Activities in gymnasiums create so much noise that even extensive treatment will not quiet these spaces. A quiet gymnasium probably would be unsatisfactory in any case, since spectators are conditioned to consider the noise as an enjoyable aspect of athletic events. However, to provide a proper environment for normal sports activities, the ceiling area should absorb sound. In addition, if a sound amplification system is to be used, sound-absorbing wall treatment may be required to eliminate echoes that would reduce the intelligibility of announcements. An NRC of 0.7 is suggested with sound-absorbent material to be ceiling-mounted.

If a gymnasium will also serve as an auditorium, loudspeaker system placement requires special consideration. For example, the loudspeakers should be located above the source location for speeches and plays.

6. *Swimming Pools.* The acoustic environment of swimming pools is often chaotic. Most sound-absorbing materials disintegrate in the high-humidity conditions prevalent in pool areas. Use special sound-absorbing units that have moisture-resistant properties.

7. *Shops.* Metal, woodworking, and scenery shops in schools contain many noise sources—saws, planers, drill presses, and manual tools. Each generates high airborne and structure-borne noise levels. Consolidating noisy areas and maximizing the distance between them and quiet spaces are essential. Ceiling and wall absorptive treatment with an NRC of at least 0.75 is recommended.

(b) Houses of Worship

The basic activities of these buildings usually combine speech and music. Thus, the worship environment must be acoustically hospitable to both. The architectural plan also must respond to religious requirements, including the relative positioning of pulpits, lecterns, the altar (if any), and the choir.

Successful acoustics can be achieved by designing the overall environment for music and providing special assistance for speech. Large congregational spaces frequently include a sound-reflecting canopy over the pulpit to direct the speaker's voice to the congregation. In some large buildings, a loudspeaker located above the canopy further reinforces speech from the pulpit. The choir and organ communicate with the entire volume of the building and, therefore, benefit from a reverberant environment.

(c) Offices

Although office buildings may contain public spaces, auditoriums, and restaurants, prime occupancy is in office areas. Most acoustics problems in office buildings relate to privacy—either between spaces within a single firm or between adjacent firms. Speech privacy has been discussed at length in Sections 19.16 through 19.21, including consideration of open-plan offices. Mechanical and electrical equipment noise problems are discussed in Sections 19.25 through 19.32.

(d) Apartment Buildings

Large apartment buildings house hundreds and even thousands of residents. Privacy and freedom from annoyance are high on the list of tenant requirements. See the HUD/FHA criteria in Section 19.33.

The performance of partitions is compromised in many designs by careless planning of convenience outlets, medicine cabinets, and mechanical services. Direct-exhaust duct connections between apartments and back-to-back placement of medicine cabinets result in loss of privacy. Back-to-back convenience outlets must be avoided.

Installation of rugs or carpeting provides the best protection against footfall noise. Many leases now require that a tenant provide such impact-reducing floor covering over most of the floor area in an apartment. Good design also dictates that similar spaces in adjacent apartments be grouped—bedrooms next to bedrooms, for example. Absorptive material in bedrooms should be ceiling mounted. A minimum NRC of 0.6 is recommended.

Apartment house site selection seldom includes consideration of acoustics. Nevertheless, truck routes, superhighways, and airports can be annoying "neighbors." Cooling towers serving adjacent buildings must be considered during the planning stages.

OUTDOOR ACOUSTIC CONSIDERATIONS

19.35 SOUND POWER AND PRESSURE LEVELS IN FREE SPACE (OUTDOORS)

The equations in Section 18.8 are not applicable to outdoor sound propagation, in which the large reflective component of the indoor condition is absent. Although the propagation of sound outdoors may not appear to be of immediate importance in architectural acoustics, outdoor noise sources such as traffic, cooling towers, and aircraft are frequently loud enough to disturb activities within or immediately adjacent to a building. Conversely, the noise made by building equipment such as cooling towers, heat pumps, and even window air conditioners may be loud enough to disturb neighbors in a nearby building. For this reason, it is desirable to have some basic understanding of outdoor sound propagation.

For preliminary evaluation of an outdoor noise problem, assuming a small nondirectional source on the ground, the sound pressure level can be determined from Equations 18.5 and 18.6. For large sources such as cooling towers and traffic, which do not exhibit inverse square properties, sound level estimates are best made on the basis of experience and empirical data beyond the scope of this book (see Magrab, 1975; Schaudinischky, 1976). For small outdoor sources, the equipment power level can be estimated by measuring the sound pressure level at 5 ft (1.5 m) and adding 15 dB. Other factors (such as moisture in the air, the presence of trees, wind, and temperature gradients) will affect outdoor sound propagation to some extent, but they can be ignored except when great distances (i.e., over 1000 ft [305 m]) are involved. Barriers, which are the most effective outdoor attenuators, were discussed in Section 19.14.

19.36 BUILDING SITING

Building siting, vis-à-vis exterior noise sources, is as important as interior structural design. Since this subject is somewhat beyond our scope of concern, the discussion is brief. Buildings should be sited, with respect to noise sources:

1. To use natural terrain noise barriers (Fig. 19.57*a*).
2. Regarding trees as noise barriers, to rely only on very thickly wooded areas (Fig. 19.57*b*).
3. To avoid naturally poor sites (Fig. 19.57*c*).
4. To avoid sound reflection from other buildings (Fig. 19.57*d*).

Point 4 is also important in a multiwing building, in avoiding U-shapes or other configurations where a central court becomes an echo chamber.

Where avoidance of an exterior noise source is impossible, quiet zones can be buffered from noises by placing higher-noise areas on the noisy side of a building. Thus, in a school, classrooms and offices can be buffered by a cafeteria and gym; in a residence, bedrooms by living rooms and corridors; in an office building, private offices by noisier clerical offices; and so on.

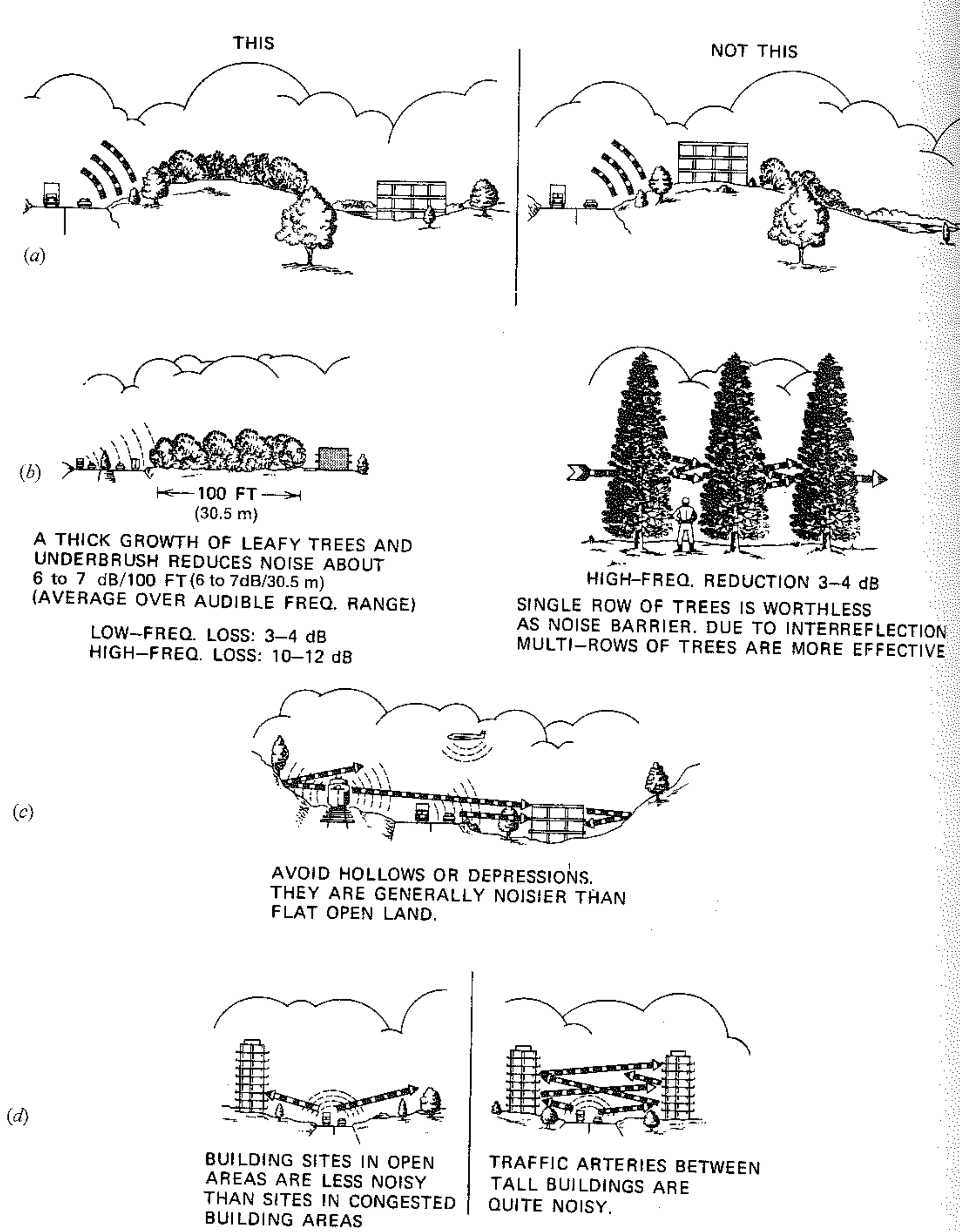


Fig. 19.57 (a) Use of natural noise barriers. (b) Effectiveness of wooded areas as noise barriers, showing noise reduction of trees. (c) An example of a poor building site. (d) Building site issues near traffic arteries and other buildings. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, 1968.)

REFERENCE MATERIAL

19.37 GLOSSARY

A-Scale. A filtering system with characteristics that roughly match the response characteristics of the human ear. Referred to as dBA.

Absorption Coefficient α. The ratio of the sound absorbed to the sound incident on a material or device.

Anechoic Room. A room that provides a free field acoustic testing environment like the outdoors. All the sound emanating from a source is essentially absorbed at the surfaces of the room.

ANSI. American National Standards Institute, a nonprofit national technical association that publishes standards covering definitions, test methods, recommended practices, and specifications of materials.

Articulation Class (AC). A figure of merit for acoustic absorption indicating the absorption efficiency of a material for angles of incidence of the sound wave between 45° and 55°. The range is 150 to 250 (no units), with higher numbers indicating better absorption.

Articulation Index (AI). A numerical index in the range of 0.0 to 1.0 indicating the degree of speech intelligibility in an open-office design, measured with background noise, including masking sound, if any. Also a measure of speech privacy. An index of 0.0 indicates no speech intelligibility, hence ideal speech privacy; an index of 1.0 indicates perfect speech intelligibility and therefore no speech privacy.

ASTM. Formerly the American Society for Testing and Materials, now simply ASTM, a nonprofit national technical society that publishes definitions, standards, test methods, recommended installation practices, and specifications for materials. ASTM is a consensus group of the entire building materials industry. It sets standards for products and establishes methods for testing.

Baffle or Barrier, Sound. A shielding structure or partition used to increase the effective length of a sound transmission path between two locations.

Ceiling Attenuation Class (CAC). A single number or range of numbers for evaluating the effectiveness of an acoustical ceiling construction in isolating audible airborne sound transmission, tested at 16 one-third-octave frequencies. Higher numbers indicate more effectiveness in preventing noise between rooms. Tested in accordance with ASTM E1414. Previously described as the Ceiling Sound Transmission Class (CSTC) or Sound Transmission Class (STC).

Critical Frequency. The lowest frequency at which the wavelength of a bending wave, traveling in a structure, is the same as the wavelength in air at that frequency.

Damping. Dissipation of structure-borne noise. This is usually accomplished by using a material with a high internal energy-absorbing capacity (i.e., high internal damping).

Decibel (dB). A measurement approach adopted for convenience in representing vastly different sound quantities.

Diffraction. The tendency of sound waves to flow readily around obstacles that are small in comparison to the wavelength of the sound.

Diffuse Sound Field. A region where sound at any given point is made up of sound waves with all angles of incidence.

Direct Sound Field. A region in which all or most of the sound arrives directly from the source without reflection.

FIIC. Field Impact Insulation Class, which is determined by an actual field test. Also see *FSTC*, Field Sound Transmission Class, also determined by an actual field test.

Flanking Sound Path. The transmission of sound or noise from one room to another by indirect paths rather than directly through an intervening partition.

Flutter. A multiple echo set up between parallel reflecting surfaces.

Free Sound Field (Free Field). A region in a homogeneous medium free from boundaries.

In a free field, the sound pressure level decreases 6 dB for a doubling of the distance from a point source.

FSTC. Field Sound Transmission Class, which is determined by an actual field test performed per ASTM E336. Also see *FIIC*, Field Impact Insulation Class, also determined by an actual field test.

Impact Insulation Class (IIC). A single-figure rating that provides an estimate of the impact sound-isolating performance of a floor-ceiling assembly.

Intensity. The amount of sound energy per second that is carried across a unit area.

Intensity Level (IL). A measure of the acoustic power passing through a unit area expressed in the decibel scale and referenced to some standard base (usually 10^{-12} W/cm^2).

Interference. The destructive or reinforcing action of two or more waves arriving at the same position simultaneously.

Loudness. A subjective human definition of the intensity of a sound.

Masking. The presence of a background sound increases the level to which a sound signal must be raised in order to be heard or distinguished. If the level of the background sound is significantly higher than that of the sound signal, the signal cannot be heard. This effect is known as masking.

Mass Law. States that the transmission loss of walls (in part of the frequency range) is controlled entirely by the mass per unit area of the panel. It also states that the transmission loss increases 6 dB for each doubling of frequency or each doubling of the panel mass per unit area.

Noise. Any undesired sounds, usually of different frequencies, resulting in an objectionable or irritating sensation.

Noise Reduction (NR). (1) The reduction in sound pressure level caused by making an alteration to a sound source. (2) The difference in sound pressure level measured between two adjacent rooms caused by the transmission loss of an intervening barrier.

Noise Reduction Coefficient (NRC). The average sound absorption coefficient (to the nearest 0.05) measured at the four one-third octave bands centered on frequencies of 250, 500, 1000, and 2000 Hz.

Octave Band. A range of frequency where the highest frequency of the band is double the lowest frequency. The band is usually specified by its center frequency.

Phon. Loudness level, at a particular frequency, equal to the 1000-Hz decibel level of that equal-loudness contour.

Pink Noise. Wide-spectrum noise whose amplitude drops 3 dB per octave with increasing frequency (equal energy per octave). Useful for masking.

Random Noise. A noise whose magnitude and/or frequency cannot be predicted precisely at any given time. A rough approximation of random noise is the static heard on a radio between stations (see *Noise, Pink Noise, White Noise*).

Reverberation. A persistence or echoing of previously generated sound caused by reflection of acoustic waves from the surfaces of enclosed spaces.

Reverberation Time. The time required for a sound to decay to a value one-millionth of its original intensity or to reduce 60 dB after the sound source has stopped.

Sabin. The unit of acoustic absorption. One sabin (ft^2) (m^2) is the absorption of 1 ft^2 (m^2) of perfect sound-absorbing material or open space with no reflecting surfaces.

Sound Absorption Coefficient. The fraction of the incident energy absorbed (not reflected) by a material when a sound wave strikes it is the sound absorption coefficient of that material. Usually represented by the Greek letter alpha (α).

Sound Barrier. A material installed to prevent the passage of sound from one area to another. Sound-deadening board and lead sheet or special insulation make good sound barriers.

Sound Level Meter. An instrument for the direct measurement of sound pressure level. Sound level meters may also incorporate octave-band filters for measuring sound directly in octave bands.

Sound Power Level (PWL). A measure of the total airborne acoustic power generated by a noise source, expressed in the decibel scale and referenced to some standard base (usually 10^{-12} W).

Sound Pressure Level (SPL). A measure of the air pressure change caused by a sound wave. Expressed in the decibel scale and referenced to some standard base (usually 0.0002 μbar).

Sound Transmission Class (STC). A single-number rating of a building element's efficacy in blocking the transmission of sound compared to a standard transmission attenuation/frequency curve. See also *Ceiling Attenuation Class*.

Transmission Loss (TL). The reduction of airborne sound power caused by placing a wall or barrier between the reverberant sound field of a source and its receiver. Transmission loss is a property of the wall or barrier.

White Noise. Noise of a wide frequency range in which the amplitude of the noise is essentially the same in all frequency bands (equal energy per frequency band).

19.38 REFERENCE STANDARDS

See Section 19.11(h) for a description of the contents of these standards.

ASTM C423-02a. *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*

ASTM E90-04. *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements*

ASTM E336-97e1. *Standard Test Method for Measurement of Airborne Sound Insulation in Buildings*

ASTM E413-04. *Classification for Rating Sound Insulation*

ASTM E795-00. *Standard Practices for Mounting Test Specimens During Sound Absorption Tests*

ASTM E1110-01. *Standard Classification for Determination of Articulation Class*

ASTM E1111-02. *Standard Test Method for Measuring the Interzone Attenuation of Ceiling Systems*

ASTM E1130-02e1. *Standard Test Method for Objective Measurement of Speech Privacy in Open Offices Using Articulation Index*

ASTM E1179-87(2003). *Standard Specification for Sound Sources Used for Testing Open Office Components and Systems*

ASTM E1264-98. *Standard Classification for Acoustical Ceiling Products*

ASTM E1374-02. *Standard Guide for Open Office Acoustics and Applicable ASTM Standards*

ASTM E1375-90(2002). *Standard Test Method for Measuring the Interzone Attenuation of Furniture Panels Used as Acoustical Barriers*

ASTM E1376-90(2002). *Standard Test Method for Measuring the Interzone Attenuation of Sound Reflected by Wall Finishes and Furniture Panels*

ASTM E1414-00a. *Standard Test Method for Airborne Sound Attenuation Between Rooms Sharing a Common Ceiling Plenum*

ASTM E1573-02. *Standard Test Method for Evaluating Masking Sound in Open Offices Using A-Weighted and One-third Octave Band Sound Pressure Levels*

ISO 717-1, 1996. (International Organization for Standardization). *Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 1: Airborne Sound Insulation*

ISO 717-2, 1996. *Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 2: Impact Sound Insulation.*

19.39 UNITS AND CONVERSIONS

See Table 19.16.

TABLE 19.16 Acoustic Units and Conversions

Variable	MKS Units	CGS Units
Force	kilogram-meter/s^2 = newton	gram-cm/s^2 = dyne
Intensity	watts/meter^2	watts/cm^2
Pressure	newton meter^2 = pascals	dynes/cm^2 = microbars

In Conversion:

Quantity	Multiply	By	To Obtain
Force	newtons	10^5	dynes
	dynes	10^{-5}	newtons
Intensity	watts/cm^2	10^4	watts/m^2
	watts/m^2	10^{-4}	watts/cm^2
Pressure	pascals	10	microbars
	microbar	10^{-1}	pascals

Note: One atmosphere = 1 bar = 10^6 μbar.

19.40 SYMBOLS

See Table 19.17.

TABLE 19.17 Symbols and Abbreviations Used Commonly in Acoustics

A	Total absorption, sabins; area in unit being used
A_R	Absorption in receiving room, sabins
$A_{1,2\cdots}$	Total absorption of each material in a space, sabins
AC	Articulation Class
c	Velocity of sound, feet per second
CAC	Ceiling Attenuation Class
d	Distance from source, meters or feet
dB	Decibel
f	Frequency of sound, hertz (Hz)
I	Intensity, W/cm^2
I_a	Absorbed energy, W/cm^2
I_i	Incident energy, W/cm^2
I_0	Reference intensity, 10^{-16} W/cm^2
IIC	Impact Insulation Class, no units
IL	Intensity level, decibels
NC	Noise criterion, no units
NRC	Noise reduction coefficient, no units
NR	Noise reduction, decibels
p	Pressure, pascals or microbars
p_0	Reference base pressure, 2×10^{-5} Pa
P	Acoustic power, watts
Pa	Pascal, unit of pressure (SI)
PWL	Sound power level, decibels
R	Room constant, square feet (meters)
r	Distance from source, meters or feet
S	Surface area, in unit being used
SPL	Sound pressure level, decibels
STC	Sound Transmission Class, no units
T_R	Reverberation time, seconds
TL	Transmission loss, decibels
V	Volume (geometric)
W,P	Sound power, watts
W_0	Reference base sound power, 10^{-12} W
a, α	Absorption coefficient (no units)
$\bar{a}$, $\bar{\alpha}$	Average absorption coefficient (no units)
λ	Wavelength, feet or meters
Σ	Sum of, or total (no units)
$\Sigma S\alpha = \Sigma A$	Total absorption, sabins
Δ	Change in a quantity or difference between two quantities

Note: Where definitions are expressed in I-P units, SI units are also understood, with proper conversion factors, and vice versa.

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