chapter 1

Introduction to Architectural Acoustics and Basic Principles

William J. Cavanaugh

1.1 INTRODUCTION

The acoustical environment in and around buildings is influenced by numerous interrelated and interdependent factors associated with the building planning-design-construction process. From the very outset of any building development, the selection of the site, the location of buildings on the site, and even the arrangement of spaces within the building can, and often do, influence the extent of the acoustical problems involved. The materials and construction elements that shape the finished spaces determine how sounds will be perceived in that space, as well as how they will be transmitted to adjacent spaces. The architect, the engineer, the building technologist, and the constructor all play a part in the control of the acoustical environment. With some fundamental understanding of basic acoustical principles (that is, how materials and structures control sound), many problems can be avoided altogether or, at least, solved in the early stages of the project at greatly reduced cost. "Corrective" measures are inevitably most costly after the building is finished and occupied—if indeed a solution is possible at all.

Increasingly, federal, state, and local building codes and standards require attention to the acoustical aspects of building design. The need for special attention to acoustics is obvious in a concert auditorium or radio studio building. However, most of the problems involve the ordinary spaces where people work and live. In response to the Environmental Protection Act of 1970, most major federal agencies in the United States have developed criteria and standards promoting safe and comfortable working and living environments. Almost all of these have implications for building design professionals. For example, the U.S. Department of Labor is concerned with protection of workers' hearing in the industrial environment and has established standards setting maximum worker noise exposure levels. Industrial buildings can have significant effects on an industrial worker's individual environment. The U.S. Department of Housing and Urban Development is similarly responsible for ensuring that federally subsidized housing developments are not located in excessively noisy environments or, if they must be, that suitable sound attenuation features are incorporated into the building design. Some state agencies require special sound attenuation features on all public buildings constructed near major airports or major highways. Local municipal building codes are, with increasing frequency, adopting provisions that require adequate attention to acoustical privacy between dwelling units and adequate control of noise transmission from building systems equipment. The U.S. General

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Services Administration, the largest builder of office space for the federal government, has adopted, as a matter of policy, the "open-plan" concept for future office construction. Acoustics is perhaps the major concern in the ultimate acceptability of such office working environments.

Finally, as people became more aware of their own wants and needs concerning their living and working environments and realize that something can be done to improve conditions, these demands initially are reflected in engineering design criteria and ultimately in building codes and standards. Entirely new to the second edition is the excellent introduction to acoustics in sustainable design contributed by Ethan Salter in Chapter 7. Acoustics is now considered in rating systems for schools, healthcare facilities, and office interiors, and is expected to expand to practically all building types in the years ahead.

1.2 BASIC CONCEPTS

Every building acoustics consideration can be thought of as a system of sources, paths, and receivers of sound. Even the most complex problem can be broken down into one or more sources to be studied along with the paths over which the sound will be transmitted to the eventual receptors of the sound. Whether a source is one we want to hear or is an undesired source (i.e., noise), control can be exercised at each element of the system. Figure 1.1 illustrates that even in a simple lecture auditorium, both desired (speech from the lecturer as well as from and between the listeners) and undesired sounds (air-conditioning system sounds, etc.) may be present and must be controlled. Naturally, the building design and technology have the most influence on the transmission paths. However, understanding the source and receiver aspects of a given situation may be essential to realize an effective overall resolution of the problem. For example, the selection and specification of the quietest available types of mechanical/electrical equipment may obviate the need for later design of special noise and vibration control building elements. Similarly, locating a particularly noisy operation or activity within a building so that it is remote from critical occupancies can save later concern, as well as the considerable cost of extraordinary sound attenuation features in the enclosing construction.

For the most part, effective control of the acoustical environment in buildings involves at least a conceptual understanding of the basic properties of sound, how it is propagated throughout typical building spaces, and how it is influenced by various building materials and construction systems. Such understanding is essential for those

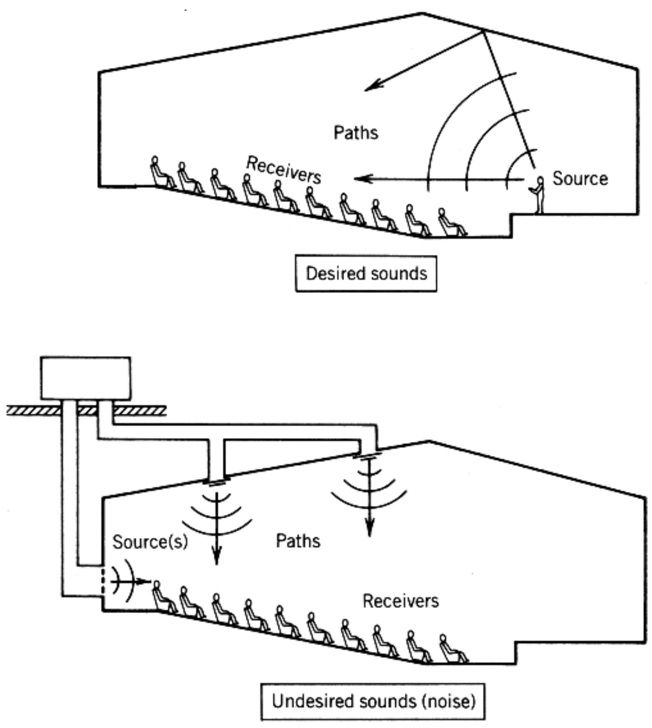

Figure 1.1 Every building acoustics problem, whether the enhancement of desired sounds or the control of undesired sounds (noise), can be considered in terms of a system of sound sources, paths, and receivers. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

concerned with the complete building design/construction process who will influence the fundamental decisions concerning the building to be constructed. Just as with the numerous other disciplines involved in the overall building environment (thermal comfort, lighting, energy conservation, and so forth), the solutions to acoustics problems require no small amount of experienced judgment and just plain common sense. After all, people do not respond to just one aspect of their environment. Acoustics, therefore, is rarely the most important aspect, but it is a significant part of that environment and its effective control will help produce good buildings.

Fundamentals of Sound and Its Control

Sound has certain measurable physical attributes that must be understood, at least in a conceptual way, if one is to understand the basic procedures for controlling sound in buildings. Sound is generated whenever there is a disturbance of an elastic medium. Once this disturbance occurs, whether it is in air by the vibrating string of a musical

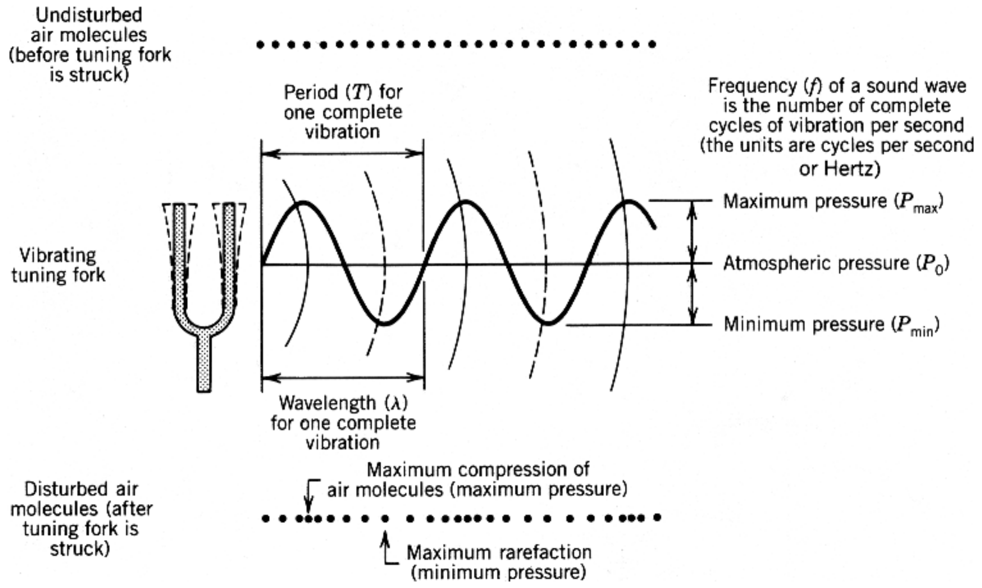

Figure 1.2 Tuning fork illustrates how a simple pure tone develops. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

instrument or in a solid floor surface by the impact of a dropped object, the sound wave will propagate away from the source at a rate that depends on the elastic properties of the medium.

Sound, in perhaps its simplest form, can be generated by striking a tuning fork, as illustrated in Figure 1.2. The arms of the tuning fork are set into vibration and the air molecules immediately adjacent to the vibrating surface are alternately compressed and rarefied as the surface goes through each complete to-and-fro movement. This cyclical disturbance (compression and rarefaction of the air molecules) is passed on to the adjacent molecules and thus travels outward from the source. The outwardly progressing sound may be thought of as a "chain reaction" of vibrations constantly being transferred to adjacent molecules, much like the disturbance created in a crowded subway train when a few more people try to squeeze on. The originally disturbed air molecules do not continue to move away from the source. Instead, they move back and forth within a limited zone and simply transfer their energy to the adjacent molecules. Although the last person squeezing on the train cannot move very far, the disturbance created can be felt by people at some distance.

The pressure disturbance created by the vibrating tuning fork cannot be seen by the naked eye, but ultimately the sound wave may reach a human ear, causing the eardrum to vibrate and, through a marvelously complex mechanism, finally produce the sensation of hearing in that person's brain. Although our own ears are perhaps the most sophisticated sound-measuring device available, humans have developed some useful measuring instruments that closely approximate the sensitivity of the ear and give us numerical quantities necessary for scientific experimentation and engineering applications. With a simple sound wave generated in air by a vibrating tuning fork (as with all other more complex sound waves), there are basically two measurable quantities of interest: the *frequency* of the sound wave and its *magnitude*.

Frequency

The frequency of a sound wave is simply the number of complete vibrations occurring per unit of time. Musicians refer to this as pitch, and this basic frequency or rate of repetition of the vibration defines its character. Low-frequency sounds, such as a deep bass voice, are classified as "boomy." High-frequency sounds, such as a steam jet, may have a "hissing" character.

The unit of measure is the *hertz* and is abbreviated Hz (older acoustical textbooks and publications may use cycles per second or cps). The tuning fork described earlier generates sound at just a single frequency. A simple musical tone would have a fundamental tone along with one or more harmonically related tones. All other common sounds—music, speech, and noise—are more complex because they contain sound energy (i.e., vibrations) over considerably wider ranges of the human-audible spectrum (about 20 to 20,000 Hz for young persons with normal healthy ears). Figure 1.3 illustrates how these simple and more complex common sounds compare.

Figure 1.4 illustrates the frequency ranges for some typical sounds, including the frequencies where peak or predominant intensities are likely to occur. For comparison, the piano keyboard and its frequency range is shown.

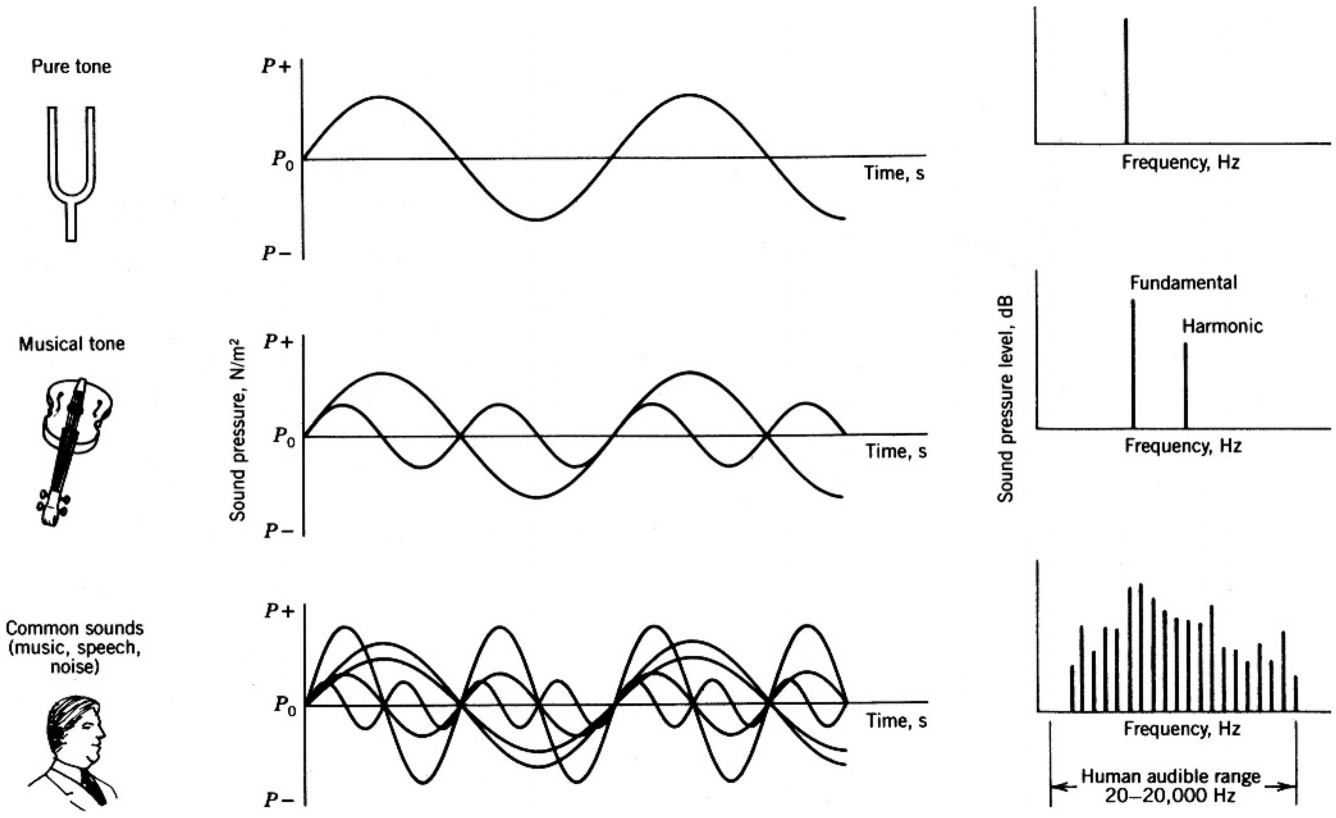

Figure 1.3 Comparison of simple and more complex everyday sounds. Simple, pure, and musical tones contain sound energy at a fundamental frequency or fundamental plus harmonically related frequencies only. Common everyday sounds contain sound energy over a wide range of the human audible spectrum. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

Thus, most of the sounds around us generally contain energy to some degree over rather wide ranges of the audible frequency range.

Frequency Bands

For measurement purposes, the audible frequency range may be divided into convenient subdivisions such as those shown in Figure 1.5. Measurements may be made over the entire range or, utilizing electronic filters in the measurement system, the frequency range may be divided into segments such as octave bands or $\frac{1}{2}$-, $\frac{1}{3}$-, $\frac{1}{10}$-octave bands. Octave bands generally yield sufficient frequency information about a sound source. In some laboratory measurements, such as in measuring the sound transmission loss characteristics of walls, however, $\frac{1}{3}$-octave-band measurements are made. The sound sources commonly encountered in buildings, as well as the acoustical performance of products and materials for sound control, are frequency dependent (i.e., vary with frequency). It is important to keep in mind that a wide range of frequencies is involved, even if simple averages or single number values are ultimately used to describe sound levels or to specify products.

Wavelength of Sound

Another fundamental property of a sound wave that is related to its frequency is its wavelength. This is the distance within which the complete cycle of disturbance takes place. There is a basic relationship between the velocity of sound in a medium (e.g., air or concrete) and its frequency and wavelength; that relationship is given by the expression:

$$c = f\lambda$$

where

c = velocity of sound

f = frequency

λ = wavelength

For example, middle C on the piano has a frequency of 256 Hz. In air, where sound travels about 1100 ft/sec, the

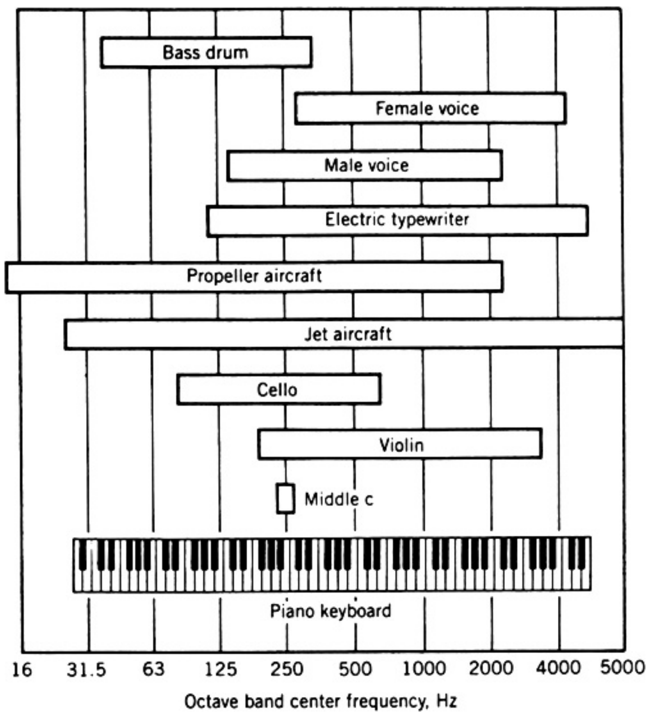

Figure 1.4 Comparison of frequency ranges for some common sounds with that of a piano keyboard. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

wavelength would be 4.3 ft. If a 256-Hz sound wave were excited in water, where the speed of sound increases to 4,500 ft/sec, the wavelength would be 12 ft. Correspondingly, in a solid concrete structure, where sound travels even faster (10,200 ft/sec), the wavelength would be 24 ft.

It is useful to keep in mind the range of wavelengths encountered in the audible frequency range for various building acoustics problems. For example, in the laboratory, sound transmission loss and other measurements on building components are usually made starting at the $\frac{1}{3}$-octave band, centered at 125 Hz, up through the $\frac{1}{3}$-octave band, centered at 4000 Hz. The wavelengths corresponding to these frequency limits are approximately 8.8 and 0.28 ft, respectively. Generally speaking, it takes rather massive, large elements to control low-frequency sound where the wavelengths are large. In contrast, thinner, smaller building elements can provide effective sound control—by absorption, for example—at high frequencies where the wavelengths are smaller.

Magnitude of Sound

In addition to the character (i.e., frequency) of a sound, also of concern is the intensity or magnitude of acoustical energy contained in the sound wave. Sound intensity is proportional to the amplitude of the pressure disturbance above and below the undisturbed atmospheric pressure (refer to Figure 1.2). The pressure fluctuations may be minute, yet a healthy ear has the ability to detect very faint sound pressure differences down to as little as 0.000000003 psi (pounds per square inch). At the same time, the human ear can tolerate for short periods the painful roar of a jet engine at close range that may be a million times as intense, say 3×10^{-2} psi. While sustained exposure to such intense sounds can cause hearing damage, the range of intensities or pressures that define the magnitude of sound energy is, like the wide range of frequencies, very

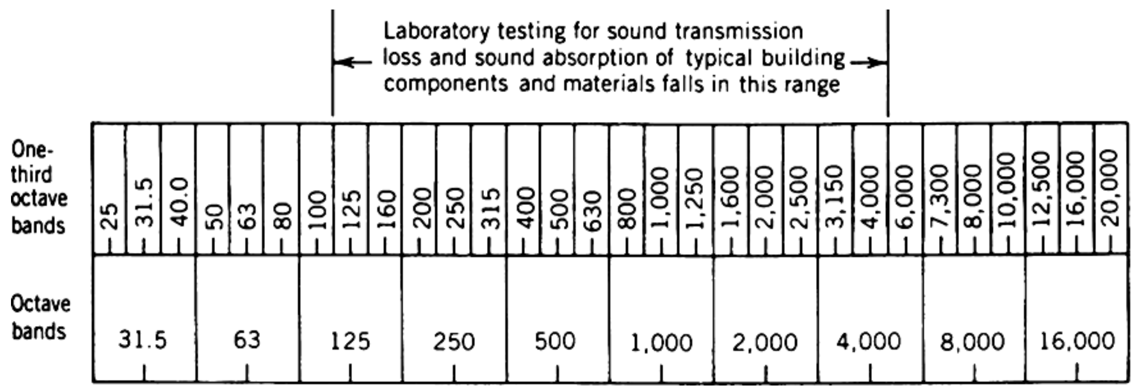

Figure 1.5 Audible frequency range divided into standard octave and $\frac{1}{3}$-octave frequency bands, which are convenient segments for measurement and analysis. Laboratory test standards for the acoustical performance of many building components extend from bands centered at 100 Hz to those at 4000 Hz. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

large nevertheless. Because of the wide range, as well as the fact that the human ear responds roughly in a logarithmic way to sound intensities, a logarithm-based measurement unit called the *decibel* has been adopted for sound level measurements. The decibel unit is abbreviated dB.

Decibel Scale

The decibel scale starts at 0 for some chosen reference value and compares other intensities or pressures to that reference value. For sound pressure level measurements, a reference value of 0.00002 newtons/square meter (2×10^{-5} N/m^2) is chosen. This is the threshold of hearing for a typical healthy young person. The sound pressure level in decibels for any sound for which the pressure is known is given by the following expression:

$$L_p = 20 \log \frac{p}{p_0}$$

where

L_p = sound pressure level in decibels (dB)

p = measured sound pressure of concern

p_o = preference sound pressure, usually taken to be 2×10^{-5} N/m^2 (older texts and publications may show the equivalent reference values of 0.0002 microbar or 2×10^{-4} dyne/cm^2).

Fortunately, acoustical instruments give the measured decibel values directly. However, since this is basically a logarithmic scale, there are a few precautions to be observed when combining decibel units, as will be discussed later in this chapter.

Figure 1.6 shows an "acoustical thermometer" of common sounds compared in terms of a measure of pressure (psi), as well as in terms of sound pressure level (in dB). The convenience of the "compressed" decibel scale is obvious in dealing with this enormous range of sound magnitudes that can be accommodated rather well by a healthy human ear. Also shown in Figure 1.6 is the relative subjective description a typical listener might assign to the various levels of sound pressure, from "very faint" (below 20 dBA) to "painful" (above 120 dBA).

Figure 1.7 shows frequency spectra for three common types of sound in octave bands of frequency compared to upper and lower threshold limits. For example, the air-conditioning fan spectrum contains a great deal of low-frequency sound compared to the mid- and high-frequency range, which results in its sounding "boomy" to an observer. An air jet, in contrast, is generally just the reverse and contains predominantly high-frequency "hissy" sound energy. Human speech not only covers a relatively wide

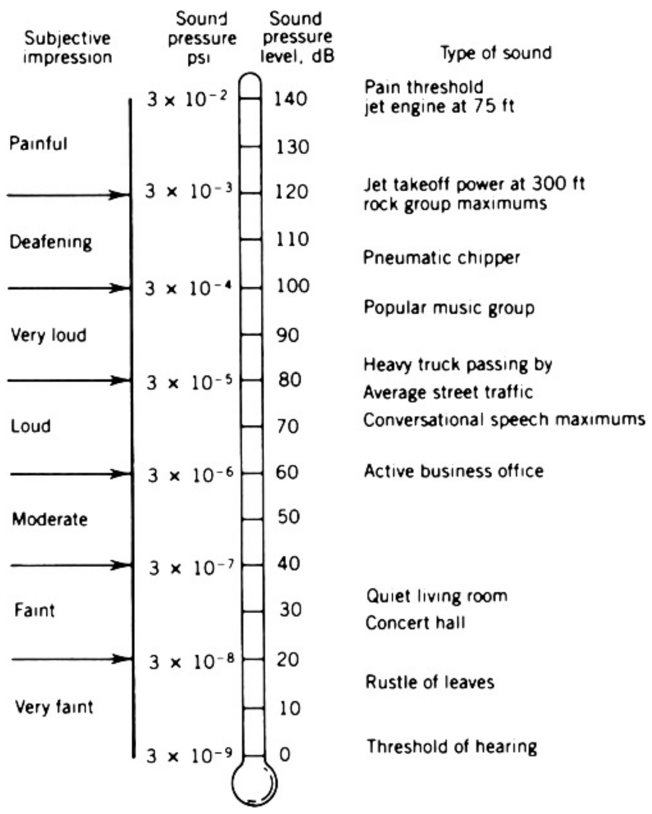

Figure 1.6 Acoustical thermometer compares the magnitude of sound pressures of sounds, in pounds per square inch, with the equivalent logarithmic quantities, decibels, used in acoustical standards. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

range of frequencies, but at the same time also has fluctuating levels with time in the process of continuous speech. The dynamic range of speech is some 30 dB between the lowest and highest speech sound levels produced.

Fortunately, it is not always necessary to deal with the full frequency range of various sounds of concern in many building acoustics problems. When the frequency characteristics are known for a type of sound source and are generally repeatable and/or are constant, simple single-number sound level values may be adequate. Figure 1.8 shows typical octave band spectra for various transportation noise sources, along with their simple sound level equivalent values. Over the past several decades, an enormous amount of measured data on aircraft, rail, and highway transportation sources (as well as on other environmental sounds) has been accumulated by international and national agencies. The automobile, aircraft, and truck sound level spectra illustrated in Figure 1.8, for example, are from the U.S. Environmental Protection Agency. Chapter 3 describes an application of the use of such data

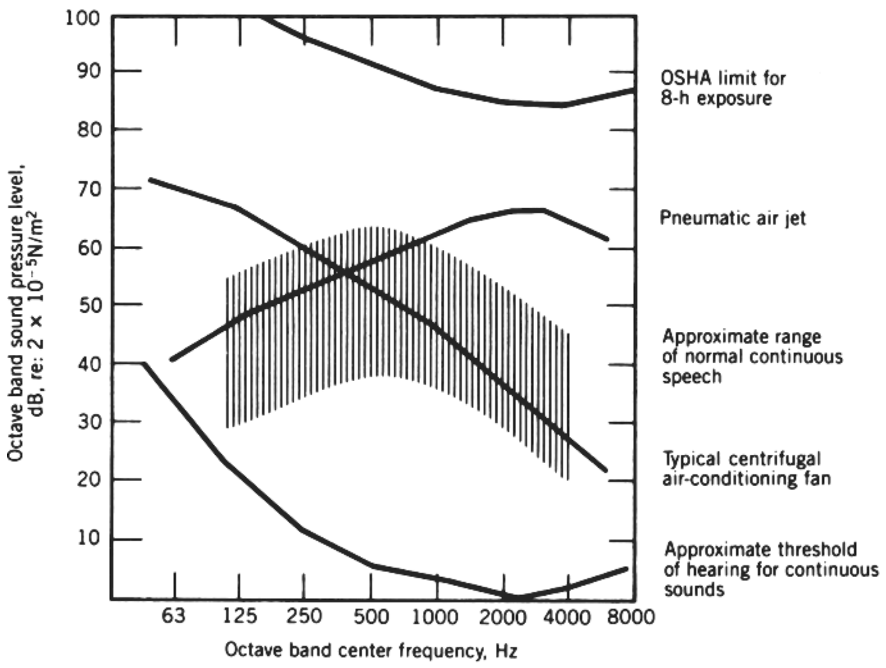

Figure 1.7 Typical octave band spectra of common sounds compared to the threshold of audibility for healthy, young ears and hearing damage risk criteria. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

in the acoustical design of the outside enclosing walls, windows, and roofs of buildings.

"Simple" Frequency-Weighted Sound Levels

The human ear does not simply add up all the energy for a sound over the entire audible range and interpret this value as the *loudness* of the sound. The human ear discriminates against low-frequency sounds (i.e., it "weights" or ignores some of the low-frequency sound energy). A given sound level will appear to be louder in the mid- and high-frequency ranges than that same level at lower frequencies. Electronic filters or "weighting networks" can be incorporated in a sound level meter to permit the instrument to approximate this characteristic and to read out sound level values that correspond well with the way the human ear judges the relative loudness of sounds.

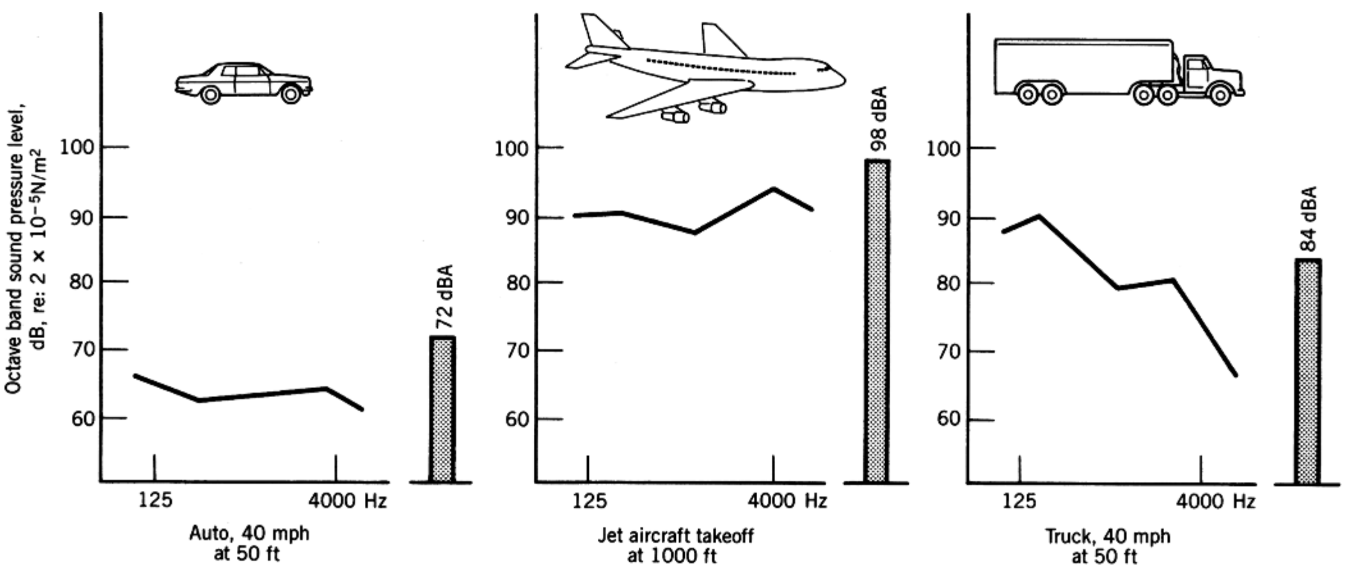

Figure 1.8 Examples of common exterior noise levels from transportation sources. (Data from U.S. Environmental Protection Agency report, EPA 560/9-79-100, Nov. 1978.) (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

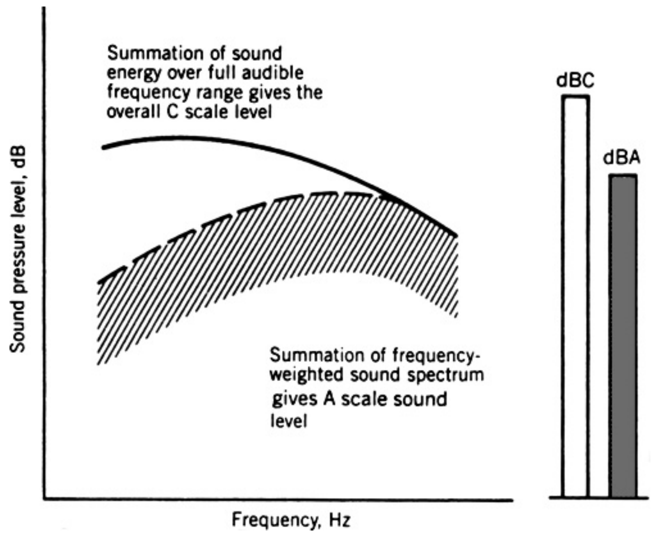

Figure 1.9 Frequency-weighting characteristic of standard sound level meters, which yield simple, commonly used overall sound levels (decibels with A-scale weighting in dBA and decibels with C-scale, or essentially unweighted flat frequency weighting, in dBC). (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

Figure 1.9 illustrates the conversion of a sound source spectrum measured over the full frequency range to single-number values. Two frequency weightings are commonly used on standard simple sound level meters: C scale and A scale. The C scale is a "flat" frequency weighting; essentially, all the sound energy is summed up and converted to an overall value. The unit is usually identified as dBC to denote the frequency-weighting network used. The A-scale network corresponds to the way a human ear responds to the loudness of sounds; the low-frequency sounds are filtered out or ignored, just as the ear does, and a weighted sound level value is read on the meter. Such simple A-scale sound levels are actually the most common and useful descriptors for many of the sounds encountered in buildings. A-scale sound levels, which are expressed in dBA units, are adequate for the simplified analysis of many problems and for the specification of simple sound tests as long as the frequency content of the noise sources of concern are known or implied beforehand. Figure 1.10 shows the range of many common interior and exterior sound sources as would be measured with A frequency weighting using a standard sound level. For example, in a quiet residence one might expect sound levels in the 30- to 50-dBA range. In a typical factory environment, however, a worker could be exposed to levels from as low as 60 dBA to more than 100 dBA.

Time-Varying Sound Levels

Both indoor and outdoor environmental sound levels usually vary markedly with time, whether in a relatively quiet setting such as remote rural areas or in highly developed downtown communities. With such time-varying sounds, as with the weather, there is no single, simple convenient metric to completely describe the quality and quantity of sound energy present.

Figure 1.11, from a U.S. Environmental Protection Agency report, shows a 10-minute time history of typical outdoor sound as would be measured on a quiet suburban street on a typical, otherwise uneventful, afternoon. The maximum sound level of 73 dBA occurs instantaneously when a sports car passes on a nearby street. The generally lowest sound levels of this 10-minute sample, that is, those exceeded 90% of the sample time, are about 44 dBA. This is referred to as the 90 percentile level of L_{90}. The one percentile level (L_1) is the level exceeded only 1% of the sample observation period and is generally taken to be representative of the maximum sound levels expected during an observation period (1% of this 10-min sample is 6 sec).

Clearly, most outdoor sounds like those shown in Figure 1.11 must be described in statistical terms, such as the above, to properly describe the sound environment. Indeed, many community noise standards written with simple unqualified limiting values, not properly defined, are not only difficult to evaluate but encourage situations where the noise code is unenforceable and largely ignored. Unrealistically low ordinance limits often cannot be enforced as a practical matter, since many normal activity sounds would be in violation. In other words, an arbitrary low limiting value would not be reasonable and would end up being disregarded.

In recent decades, largely as the result of the passage of the U.S. Environmental Protection Act of 1970 mandating that all federal agencies develop environmental standards, and with recent availability of sophisticated sound measurement instrumentation, a more meaningful and straightforward metric for measuring and evaluating time-varying sounds has come into use: *the energy equivalent sound level* (L_{eq}). The L_{eq} is the hypothetical equivalent steady sound level containing all of the acoustical energy in an actual time-varying sound sample over a given time period. For the time-varying sound of Figure 1.11, the corresponding L_{eq} value is 58 dBA. Thus, the L_{eq} more accurately represents the actual acoustical energy present in a fluctuating sound over the observation period. The duration of the observation period must be stated; use of the descriptor L_{eq} alone is insufficient. One must always

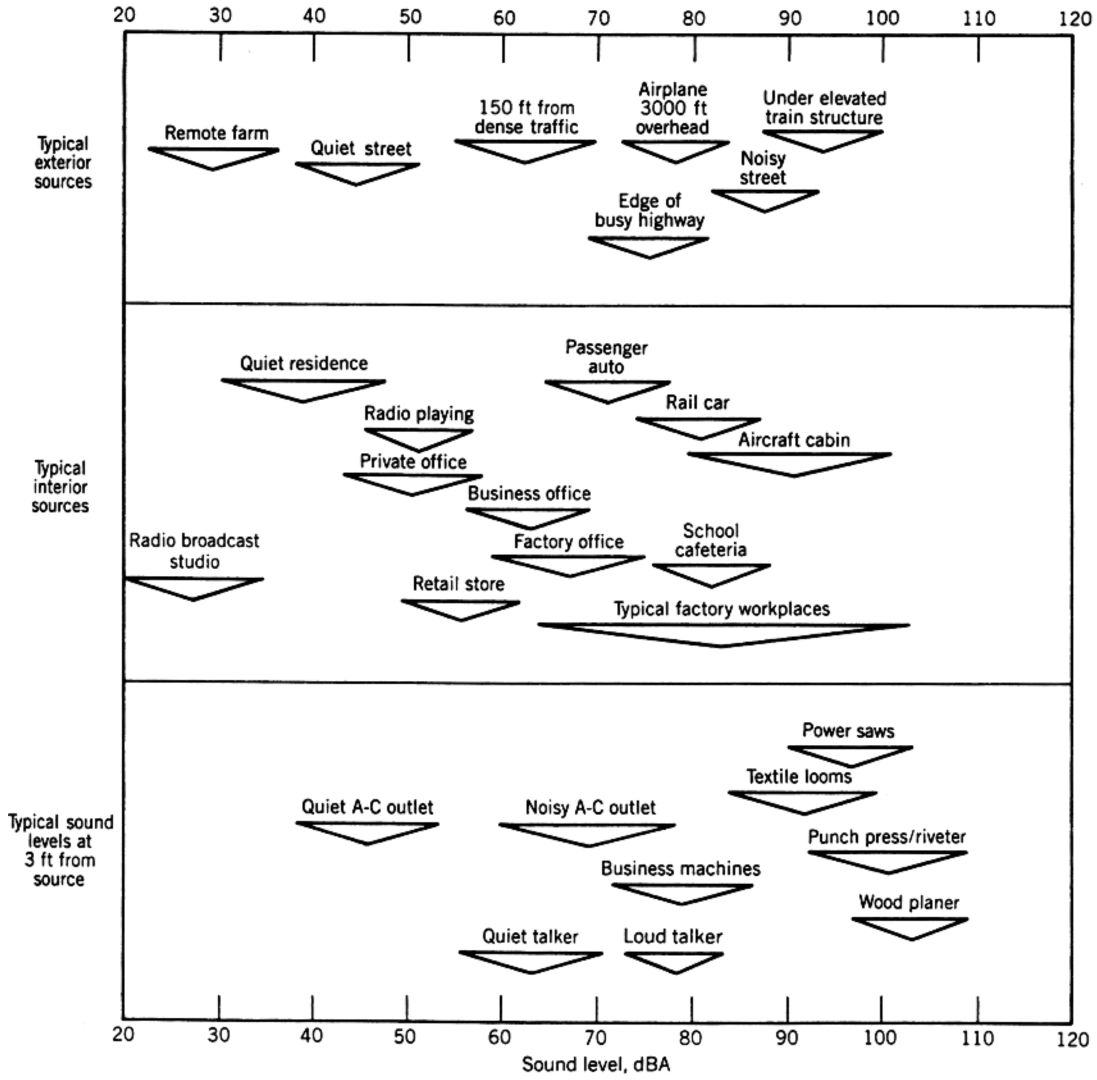

Figure 1.10 Ranges of sound levels in decibels with A-scale frequency weighting, in dBA, for common interior and exterior sound sources. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

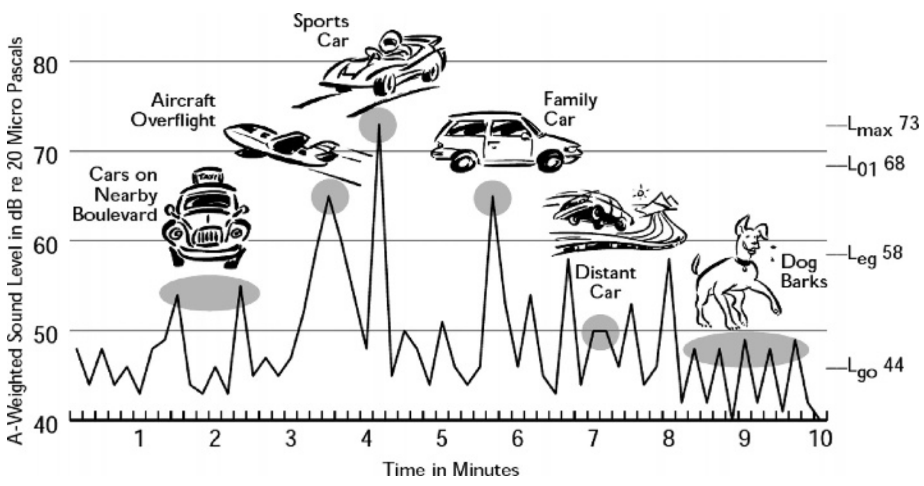

Figure 1.11 Typical outdoor sound measured on a quiet suburban street. (From Cavanaugh, William J., and Tocci, Gregory C., "Environmental Noise . . .The Invisible Pollutant," *Environmental Excellence in South Carolina* 1, no. 1 (1998).

TABLE 1.1 Land-Use Categories and Metrics for Transit Noise Impact Criteria

LAND-USE CATEGORY	NOISE METRIC (dBA)	DESCRIPTION OF LAND-USE CATEGORY
1	Outdoor $L_{eq}(h)^a$	Tracts of land where quiet is an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land uses as outdoor amphitheaters and concert pavilions, as well as national historic landmarks with significant outdoor use.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals, and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor $L_{eq}(h)^a$	Institutional land uses with primarily daytime and evening use. This category includes schools, libraries, and churches, where it is important to avoid interference with such activities as speech, meditation, and concentration on reading material. Buildings with interior spaces where quiet is important, such as medical offices, conference rooms, recording studios, and concert halls fall into this category. Places for meditation or study associated with cemeteries, monuments, and museums. Certain historical sites, parks, and recreational facilities are also included.

[a]L_{eq} for the noisiest hour of transit-related activity during hours of noise sensitivity. From U.S. Federal Transit Administration Report DOT-T-95-16, *Transit Noise and Vibration Impact Assessment* (April 1995).

indicate the time period for which the L_{eq} applies (e.g., a "worst" hour, $L_{eq(1h)}$).

Practically all federal standards (the Department of Housing and Urban Development [HUD], the Federal Highway Administration [FHWA], the Federal Aviation Administration [FAA], and other agencies) now rely upon L_{eq} values in their standards for environmental sound. In addition, many local and state codes have adopted L_{eq} values in their environmental sound ordinances. The L_{eq} metric, as well as other statistical measures, are normally used in studies in addressing environmental sound issues.

A further refinement of the L_{eq} methodology for analysis of time-varying sounds in communities is the *day-night equivalent sound level* (L_{dn}). The L_{eq} values would be summed up over a 24-hour period and a 10-dB penalty would be added for the more sensitive sleeping hours. In other words, noise events occurring during the nighttime hours (usually, 10:00 p.m. to 7:00 a.m.) would be considered to be 10 dB higher in level than they actually measure. This methodology is extensively used in dealing with airport, transit system, and other outdoor noise events, and a significant body of research shows that L_{dn} values correlate quite well with a community's response to noise impact. Table 1.1 shows an example of categorization of various land uses where $L_{eq(hourly)}$ and L_{dn} noise metrics may be used in assessing transit system noise impact.

Combining Decibels

Sound energy levels in decibel units from independent sound sources may not be added directly. The sound pressure levels must be converted back to arithmetic units and added and then reconverted to decibel units. For example, if two sound sources each measured 50 dB when operated independently, they would measure 53 dB when operated together. Figure 1.12 is a nomogram for easily "adding" (i.e., combining) two sound energy levels. From Figure 1.12 it can be seen that two identical sources (difference between the two sound levels is 0 dB) will result in an increase in sound level of 3 dB with both sources operating. Similarly, if there is a 10-dB or greater difference between two sources, there would be negligible contribution from the "quieter" source. Figure 1.12 also illustrates the addition of a source measuring 54 dB and one measuring 50 dB. The "combined" sound level of 55.5 dB is always

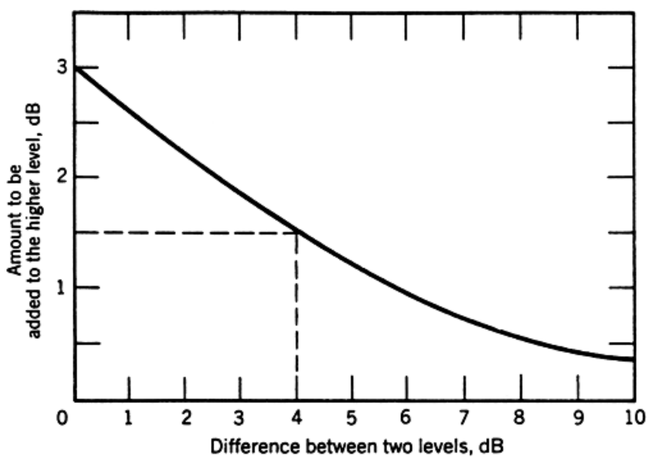

Figure 1.12 Nomograph for combining two sound sources in decibels. In the example shown, two sound sources produce sound levels of 50 and 54 dB, respectively. What level would be produced with both sources operating together? Difference, 54 − 50 = 4 dB; amount to be added to the higher level, 1.5 dB; sound level with both sources operating, 54 + 1.5 = 55.5 or 56 dB. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

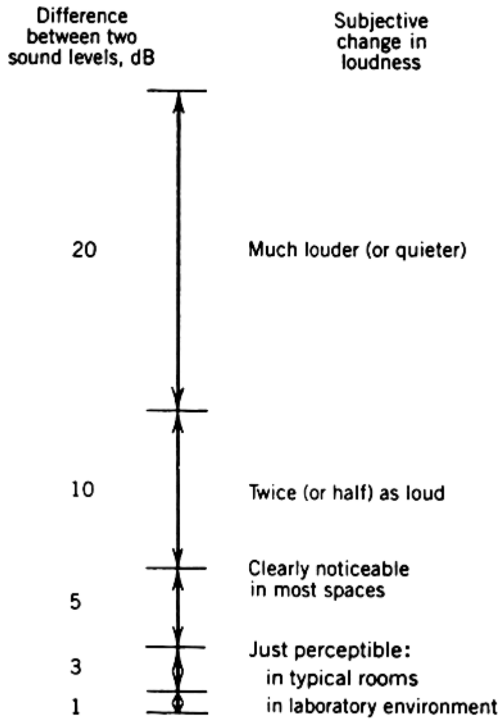

Figure 1.13 Subjective meaning of relative changes in sound levels measured in decibels. (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

higher than the higher value. In other words, the louder source dominates. Thus, whenever multiple sound sources are involved, the total sound output may be estimated using the nomogram of Figure 1.12 simply by combining two sources at a time.

Relative Change in Sound Levels

The relative subjective change between two sound source levels or conditions is often of interest in evaluating the effectiveness of various sound control measures. Figure 1.13 shows that a 1-dB change in sound level is just detectable in a controlled laboratory environment. A 3-dB change (which is actually a doubling of the sound energy level) would be just perceptible in a typical room environment. In contrast, a 10-dB change is required to cause a subjective sensation of doubling (or halving) of loudness. These rather unusual characteristics of human hearing response must be borne in mind in dealing with practical sound control problems in buildings. In other words, a 1- or 2-dB improvement alone may not represent a significant result and may not be worth the cost of the control measure.

Sound Outdoors versus Sound Indoors

To fully appreciate how sound behaves inside rooms and is transmitted from space to space within buildings, it is helpful to consider first how sound behaves outdoors (see Figure 1.14). With a simple nondirective source, the sound intensity will fall off as the distance from the source is increased. The sound wave moving outward from the source spreads its energy over an ever-increasing spherical area. This commonly observed decay of sound level with distance in a "free-field" acoustical environment follows the so-called inverse square law. For simple point sources, the falloff rate is 6 dB per doubling of distance from the source. In effect, when the radius of the sphere over which the sound has spread doubles, this results in a spherical area four times greater and a sound level reduced by 10 log 4, or 6 dB. If the source is a long, narrow, cylindrical radiator of sound (as might be the case with a steady stream of road traffic), the rate of falloff would be reduced to 3 dB per doubling. In any case, typical sources outdoors generally fall within the falloff rate of 6 or 3 dB per doubling of distance. In addition, some further losses (or gains) may be present in real-life situations, due to atmospheric effects, wind, temperature, ground foliage, and so forth. However, these effects can usually be neglected for first-order approximation of expected sound losses outdoors where distances are not very large.

Indoors, however, sound intensity will fall off with distance only very near the source (in most building situations, within several feet). As one continues to move away from the source, the reflected sound from the floor, walls, and ceiling of the room begins to overwhelm the direct sound component that continues to be emitted from the source. Within the reflected or so-called reverberant sound field, the sound level remains generally constant throughout the room no matter how far away from the source a listener is located. If the room surfaces are basically hard and sound reflective (plaster, concrete, glass, etc.), there will be very little loss of sound at each impact of the sound wave on the room surfaces, and the built-up reflected sound level will be relatively high. If soft, porous materials (rugs, draperies, acoustical tiles, etc.) are placed on the room surfaces, there will be appreciable losses each time the reflected sound waves encounter the room surfaces. Accordingly, the built-up reflected sound levels will be lower. This is the principal effect of placing sound-absorbing materials on the surfaces of rooms (i.e., to lower the sound level in the reverberant acoustic field dominated by reflected sound). Ultimately, if completely efficient sound-absorbing materials are placed on all boundary surfaces of a room, outdoor conditions would be approximated where only the direct sound remains.

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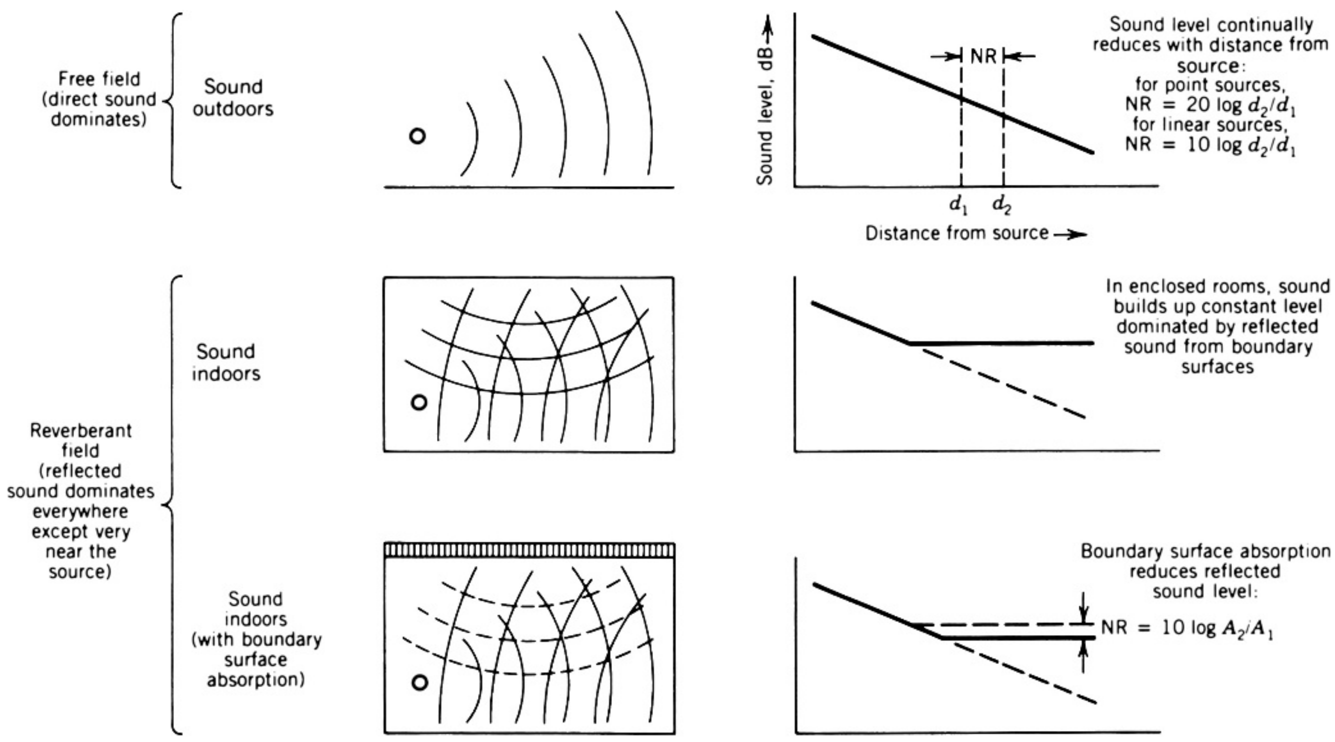

Figure 1.14 Diagrams showing the relative differences in sound behavior outdoors (free field) vs. indoors (reverberant field). (From William J. Cavanaugh, "Acoustics—General Principles," in *Encyclopedia of Architecture: Design, Engineering & Construction*, ed. Joseph A. Wilkes. Copyright © 1988 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

Note: The application of absorbing materials on the room surfaces does not affect in any way the direct sound, which continues to decay with distance from the source.

Sound-Absorbing Materials

Sound-absorbing materials, carpeting, acoustical tiles, and other specially fabricated absorbing products can absorb appreciable amounts of sound energy. The sound-absorbing efficiency of a material is given by its sound absorption coefficient (α). The sound absorption coefficient is a ratio of the incident sound to the reflected sound and may vary from 0 (no absorption, or perfect reflection) to 1 (complete absorption, or no reflection). Sound absorption coefficients are determined from laboratory measurements. For typical building applications, the most meaningful sound absorption data is obtained from relatively large samples of a material measured in a large reverberant chamber in accordance with standardized test procedures (American Society for Testing and Materials [ASTM] Method of Test C423).

Figure 1.15 illustrates the typical sound-absorbing characteristics of various generic types of sound-absorbing materials. Porous materials (fibrous or interconnecting cellular plastic forms, etc.) account for most of the prefabricated factory-finished products available. The overall thickness, including any spacing of the material from a backup surface, influences absorption in the low-frequency range. The thicker the porous material and/or the deeper the airspace behind the absorbing layer, the higher will be the low-frequency sound absorption coefficients. The surface facing applied to or on the porous material for architectural finish reasons (durability, light reflectance, appearance, etc.) influences the high-frequency absorption of the assembly. The more open and acoustically transparent the assembly, the less will be the effect on the mid- and high-frequency sound absorption coefficients. Sound reflection from the solid areas between the openings, perforations, or fissures of a surface facing material tends to reduce absorption efficiency of the material at high frequencies.

Volume or "cavity"-type absorbers and thin panel membrane absorbers, also indicated on Figure 1.15, are effective primarily in the low-frequency range. In all sound-absorbing materials and assemblies, however, the basic mechanism is friction. Sound energy is dissipated as the incident sound moves through the porous material or neck of the cavity or as it sets a thin membrane into vibration. Chapter 2 describes the absorption performance

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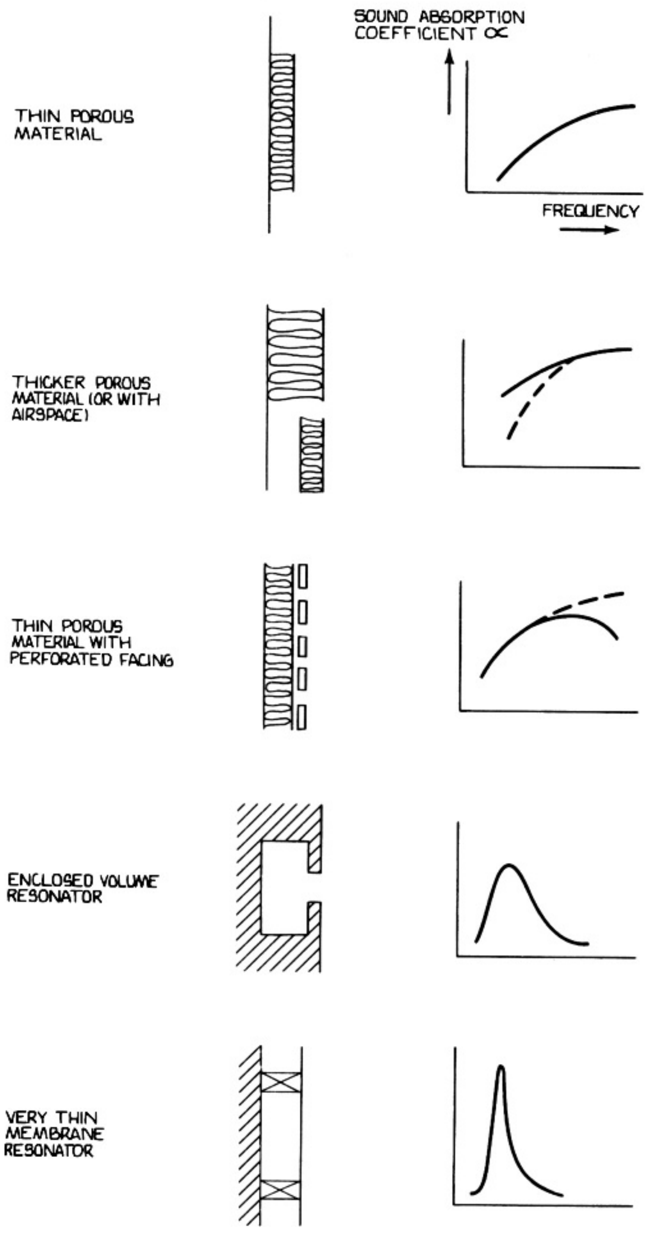

Figure 1.15 Sound-absorbing characteristics of typical acoustical materials. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

characteristics of a wide range of common building materials and of materials designed specifically for high sound absorption.

Noise Reduction Coefficient

An industry-wide accepted method of describing the "average" sound absorption characteristics of an acoustical material is the noise reduction coefficient (NRC). The NRC is the arithmetic average of the measured sound absorption coefficients at 250-, 500-, 1000-, and 2000-Hz test frequencies, rounded off to the nearest 0.05.

Further discussion on sound-absorbing materials may be found in Chapter 2, including tables of acoustical performance values for common building materials and for products and systems specifically designed to provide efficient sound-absorbing surfaces. In general, effective sound absorption is achieved when the sound absorption coefficients exceed about 0.4 (i.e., 40% of the incident sound is absorbed and 60% is reflected back into the room). In contrast, materials having coefficients of 0.8 or greater (80% absorbed and 20% reflected) are considered very effective absorbers. The average NRC values may be considered in the same manner as absorption coefficients at specific frequencies. However, when using NRC values, remember that the average value is obtained using coefficients from 250 through 2000 Hz. If sound absorption is needed above or below this range, particularly at 125 and 63 Hz, NRC values may not be adequate. For example, if low-frequency echoes from an auditorium rear wall present a problem, the NRC values will not provide an indication of sound absorptivity below 250 Hz. Sound absorption coefficients on the low-frequency performance of the rear wall material being considered would be needed.

Reduction of Room Sound Levels

The reduction of reverberant sound levels in rooms may be determined from the following expression (see also Figure 1.14):

$$\mathrm{NR} = 10 \log \frac{A_2}{A_1}$$

where

NR = reduction in reverberant sound level in decibels between two different conditions of room absorption

A_1 = total absorption in square feet or square meters initially present in room (sum of room surface areas times their absorption coefficients)

A_2 = total absorption in square feet or square meters after new absorbing material is added

Typically, room reverberant sound levels can be reduced by up to about 10 dB over an initial "hard" room condition by application of efficient sound-absorbing ceiling treatment and floor carpeting. The simple nomogram of Figure 1.15 may be used for estimating this reduction

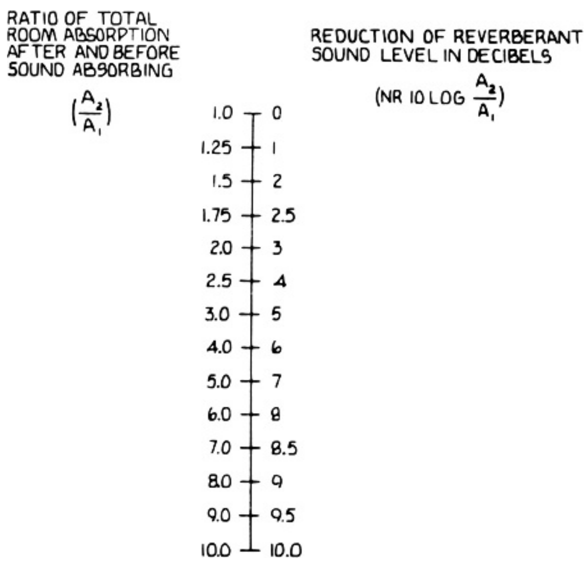

Figure 1.16 Reduction of room reverberant sound level by added sound-absorbing material. Example: Given a room with 100 ft^2 (sabins) of total sound absorption, estimate NR with 800 ft^2 of new absorption added. $A_1 = 100$ ft^2; $A_2 = 100 + 800 = 900$ ft^2; NR $= 10 \log \frac{900}{100} = 10 \log 9 = 9.5$ dB. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

in typical rooms. For example, a classroom finished basically in hard materials may have a total initial absorption (A_1) of 100 ft^2 (determined by adding all the surface areas times their absorption coefficients). If a new acoustical tile ceiling added 800 ft^2 of new absorption, A_2 would correspondingly increase ($A_2 = 800 + 100 = 900$ ft^2). From Figure 1.16, a ratio of $A_2/A_1 = 900/100 = 9$ would indicate a reduction of 9.5 dB. In other words, the classroom would be almost 10 dB quieter with the new sound-absorbing ceiling no matter how loud the source is. Reduction of room activity noise levels of this order of magnitude can be significant (refer to Figure 1.13.)

However, remember that the surface treatment does not affect or reduce the direct sound in any way. In other words, the best we can do in any room is to approximate outdoors, where the direct sound coming from the source will always remain. For example, an outdoor picnic may still be a noisy affair even though just about all of the outdoor room is totally absorptive.

Reverberation in Rooms

In addition to providing control of continuous room sound levels, surface-applied sound-absorbing materials in a room affect the persistence or "lingering" of sound after a source is stopped. The reverberation period (time in seconds for the sound level to decay 60 dB after the source is turned off) is directly proportional to the cubic volume of the space and inversely proportional to the total sound absorption present:

$$T = 0.05\frac{V}{A} \quad \text{(English units), or}$$

$$T = 0.16\frac{V}{A} \quad \text{(metric units)}$$

where

T = reverberation time in seconds

V = volume in cubic feet (or cubic meters)

A = total absorption in square feet (or square meters) (sum of room surfaces times their sound absorption coefficients plus the sound absorption provided by furnishings or audience, etc.)

Using the sound absorption coefficients of the performance tables in Chapter 2, the reverberation period may be computed for most building spaces where the room dimensions are within about a 1:5 aspect ratio. The sound field in very wide rooms with low ceilings, for example, does not decay in a manner that permits direct use of the above expression. Similarly, in highly absorbent, outdoorlike spaces, the expression does not apply, because, by definition, the concept of reverberation becomes meaningless where a sound field is not dominated by repeated reflections from the bounding surfaces. However, for most typical rooms in buildings, the expression can yield a good estimate of the reverberation period. Note too that because the sound absorption coefficients of most building materials vary with frequency, the reverberation calculations must be carried out at representative low-, mid-, and high-frequency ranges (e.g., in octave bands from 125 through 4000 Hz). For less critical rooms, a single computation at a representative mid-frequency range (e.g., 1000 Hz) may be adequate. Needless to say, new computer technology makes extensive and rapid calculation of reverberation-based metrics very convenient, especially for critical music performance halls and spaces for organ and liturgical music (see Chapters 4 and 6).

Sound Transmission between Rooms

When greater reduction of sound is required than is achievable by room sound-absorbing treatment alone, full enclosure of the receiver by means of separate rooms may be necessary. Figure 1.17 illustrates schematically the simple case of sound transmission between adjacent enclosed

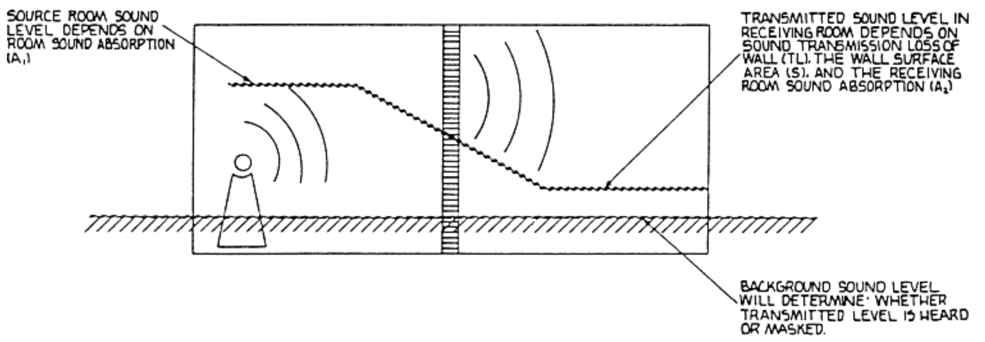

Figure 1.17 Essential elements in sound transmission between rooms. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

rooms. In essence, a sound source will develop a reverberant sound field in one room (the source room) and its sound pressure level will depend on the total absorption provided by the source room boundary surfaces. In this simple case, assuming that the sound can travel to the adjacent room (the receiving room) only via the common separating wall, the transmitted sound level to the receiving room will depend on three factors: (1) the sound-isolating properties of the wall (i.e., sound transmission loss), (2) the total surface area of the common wall that radiates sound into the adjacent receiving room, and (3) the total sound absorption present in the receiving room. The reduction of sound between rooms is given by the expression:

$$L_1 - L_2 = \mathrm{TL} + 10 \log \frac{A_2}{S}$$

where

L_1 = sound pressure level in the source room in decibels

L_2 = sound pressure level in the receiving room in decibels

TL = sound transmission loss of the common wall in decibels

A_2 = total sound absorption in the receiving room in square feet (or square meters)

S = common wall surface area in square feet (or square meters)

The transmitted sound level L_2 in any given situation will be audible and possibly disturbing to receiving-room occupants if it exceeds the ambient or background sound level in the room. Thus, the background sound level is an extremely important part of any sound isolation problem. The background sound level may be thought of as the residual sound level present whether or not the offending noise is present in the source room. The common wall may be thought of as a large diaphragm radiating sound into the receiving room—the larger it is, the more sound is radiated. In contrast, absorbing material in the receiving room tends to reduce the built-up reflected sound radiated into the receiving room. Thus, the A_2/S correction term in the room-to-room sound reduction expression accounts for the particular environment in which a wall construction is used. This correction is rarely more than ±5 dB but can be significant, especially at low frequencies.

The major loss in sound energy from room to room is, however, provided by the common wall (or floor/ceiling) construction itself. Typical lightweight partition or floor systems may have sound transmission losses of the order of 20 dB. Massive and/or double constructions can achieve sound transmission loss values of 40 to 60 dB or greater. (See also the performance tables in Chapter 2.)

Sound Transmission Loss

A basic acoustical property of a sound-isolating wall or floor/ceiling system is, then, its ability to resist being set into vibration by impinging sound waves and thus to dissipate significant amounts of sound energy. The heavier and more complex the construction, the greater will be its ability to reduce sound transmission from one side to the other. The sound-reducing capability of a construction is measured by its sound transmission loss (TL). The sound transmission loss is a logarithmic ratio of the transmitted sound power to the sound power incident on the source-room side of the construction. A construction that transmits or lets through only small amounts of the incident sound energy will have a high sound transmission loss. For example, a 4-inch-thick brick wall might have a mid-frequency sound transmission loss of about 40 dB. This means that only 1/10,000 of the incident sound energy is transmitted. Recall from Figure 1.13 that a 10-dB change in sound level represents a significant reduction (i.e., a halving of the subjective loudness of a sound). Accordingly, a 40-dB change represents an even more dramatic reduction. Reductions in room-to-room sound level of 20 to 50 dB or more are generally needed to effectively isolate typical building activities from one another.

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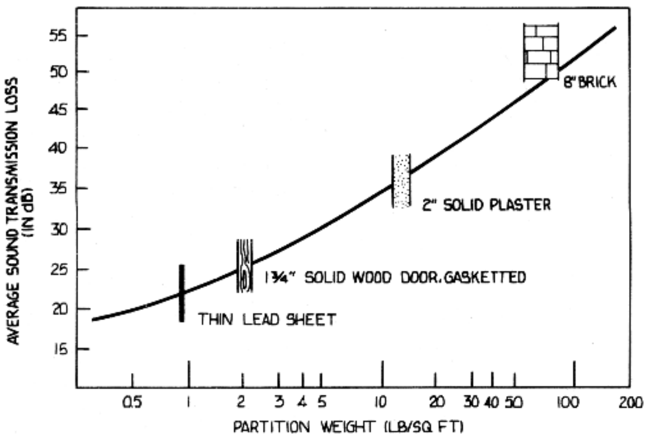

Figure 1.18 Average airborne sound transmission loss for single homogeneous partitions. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

Single Homogeneous Walls

Figure 1.18 helps illustrate the general effects of mass in the sound transmission loss performance of constructions. For single homogeneous constructions, the average sound transmission loss (average from 125 to 4000 Hz) increases with increasing weight. For example, a 15-psf (pounds per square foot) plaster wall (2-in. solid plaster) would have an average sound transmission loss of about 35 dB. Doubling the partition weight (and thickness) to 30 psf (4 in.) would increase the average sound transmission loss to 40 dB. Another doubling to 60 psf (6 in.) would yield a TL of 45 dB. Clearly, single homogeneous constructions quickly reach a point of diminishing returns where increased weight and thickness are no longer practical.

Double Walls

Figure 1.19 shows the advantage of complexity over merely increasing the weight of the sound-isolating construction. The 2-inch solid plaster partition discussed earlier yielded an average TL of 35 dB. Without any overall increase in weight, if the 2-inch plaster were split into two independent 1-inch leaves and separated by a 3-inch airspace, an average increase of about 8 dB would result (from Figure 1.19, the increase would be 2 dB at 125 Hz and 12 dB at 4000 Hz). In other words, double-layer construction is one way to beat the "mass law" limits of single homogeneous partition materials. This explains why so many prefabricated operable or demountable wall systems (as well as other constructions that use double-layered

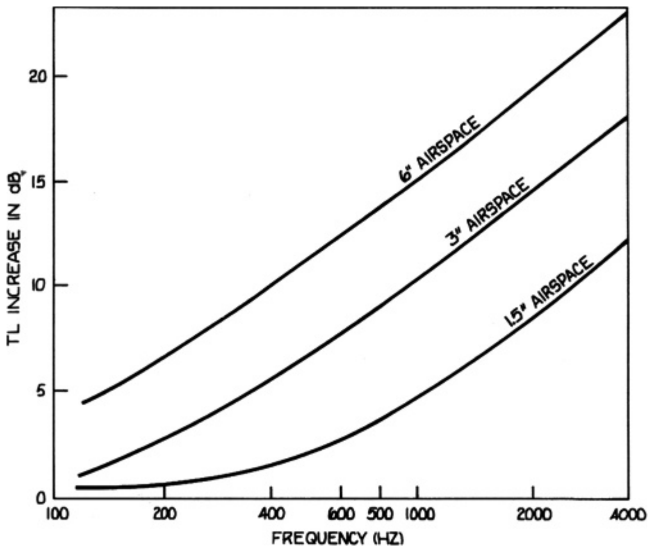

Figure 1.19 Increase in airborne sound transmission loss using double-layer construction with airspace (weight of two leaves equal). (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

elements) can achieve relatively high sound transmission loss values with relatively low overall surface weights.

Many constructions, such as sheet metal or gypsum board stud wall systems or wood joist floor systems with gypsum board ceilings, fall somewhere between ideal mass law performance and ideal double-construction performance. In addition to optimizing the sound isolation performance of various building elements, consideration is also given to improved methods of connecting and sealing the individual elements so that maximum performance can be realized in the field.

Note also from Figure 1.19 that relatively large airspaces between the two elements of a double construction are required to achieve significant improvement over single-layer performance. Airspaces of less than about $1\frac{1}{2}$ inch do not really yield very much improvement over the equivalent single-mass performance. This explains why some thin glazed double thermal insulating window systems with airspaces of $\frac{1}{4}$ to $\frac{1}{2}$ inch have disappointing sound transmission loss performance, even though adequate thermal insulation may be achieved.

Cavity Absorption in Double Constructions

When the full advantages of both mass and complexity have been utilized in double-leaf constructions, a further improvement in performance can be realized by sound-absorbing material within the cavity of the construction. Fibrous, glass, or mineral wool-type insulation materials can reduce the sound energy within the cavity volume and thus increase the overall sound energy loss through the construction. If the construction is such that the two sides are extensively coupled together by internal supporting elements, the cavity absorption will have significantly less effect than if the two sides are well isolated from one another. For example, typical masonry block constructions, where the two sides of the block are intimately joined by the very rigid core elements, gain very little by cavity absorption. In contrast, a double-layer gypsum board or steel panel system on widely spaced framing members can gain as much as 3 to 5 dB in improved sound isolation performance over the same construction without cavity absorption.

Cavity absorption also provides a mufflerlike effect to reduce sound transmission at penetrations of a double-leaf construction for electrical conduit or at other locations where shrinkage cracks may develop. On balance, whenever maximum sound-isolating performance is desired with most double-leaf structures, cavity absorption can contribute to improved results.

Composite Constructions

Often the common walls between rooms are made up of more than one component (doors, windows, two different partition elements, etc.). Unless the sound transmission loss performance of each of the components is identical, the effective sound transmission loss performance of the composite construction will fall below that of the most effective single component and approach that of the weaker element. Figure 1.20 permits the determination of the effective sound transmission loss of a two-element composite assembly. For example, assume a 200-ft^2 section of a 4-in. brick wall has an average TL of 40 dB. If a 7 × 3 ft pass door having an average TL of 25 dB is cut into the brick wall, the effective TL of the composite wall can be found as follows:

$$\mathrm{TL}_{\mathrm{wall}} - \mathrm{TL}_{\mathrm{door}} = 40 - 25 = 15\ \mathrm{dB}$$

$$\text{Percent of wall occupied by door} = \frac{21}{200} \approx 10\%$$

From Figure 1.20, the amount to be subtracted from $\mathrm{TL}_{\mathrm{wall}} = 6$ dB. Therefore, the effective sound transmission loss of the wall with door = 40 − 6, or 34 dB.

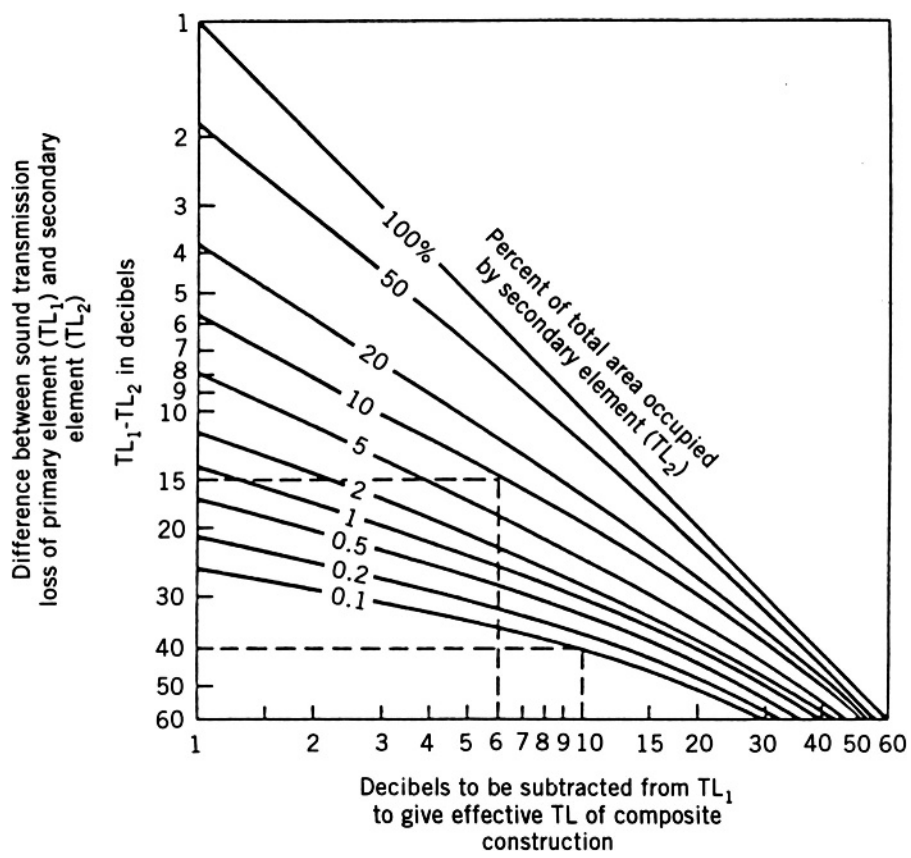

Figure 1.20 Effective transmission loss of composite acoustic barriers made up of two elements. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

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Similarly, the effect of sound leaks in a partition system can be evaluated. For example, 0.1% of crack area in a 100-ft^2 section of 4-in. brick wall would lower the sound transmission loss from 40 to 30 dB:

$$TL_{wall} - TL_{crack} = 40 - 0 = 40\,\text{dB}$$
$$\text{Percent of crack area} = 0.1\%$$

From Figure 1.20, the amount to be subtracted from TL_{wall} = 10 dB. Therefore, the effective sound transmission loss of the wall with 0.1% crack is 40 − 10 or 30 dB. One-tenth of one percent of a 100-ft^2 wall would represent a total of only about 14 in.^{2} of accumulated crack area!

Sound Leaks

From the preceding discussion, the relative significance of any direct sound leakage through a construction is quite apparent. In fixed permanent wall or floor/ceiling systems, the leakage at intersections with floors, side walls, and so forth can often be avoided by "one-time" applied sealants during the initial installation. Figure 1.21 shows the reported laboratory results for a gypsum partition system with and without a typical perimeter crack. Degradation in performance by some 23 dB from a partition system potential performance of more than 50 dB can be a very real concern in typical field situations. Hidden sound leaks can occur in spite of even the best field supervision of the installation (above suspended ceilings, behind convector covers, etc.).

With lightweight operable or demountable partition systems, the problem of sound leakage at the numerous panel joints, floor, ceiling tracks, and side wall intersections is even more demanding. Materials and systems must be detailed and specified to assure positive panel joint seals that will perform effectively over the expected life of the partition installation. A fixed partition is relatively easy to seal. In operable or demountable partitions, the seals themselves must also be operable and durable over the life cycle of the installation, with minimum maintenance required.

Flanking

Besides direct sound leaks within the perimeter of a given common wall or floor/ceiling system, significant sound transmission may occur between adjacent rooms via so-called flanking paths. There are literally hundreds of possibilities for sound to bypass the obvious common partition path, and their relative importance is directly proportional to the sound isolation performance desired. Flanking becomes increasingly important with higher sound isolation performance. The sound transmission path over the partition via a suspended ceiling, against which the partition terminates, is a common condition. Others include interconnecting air-conditioning ducts or plenums, doors opening to adjacent rooms via a common corridor, and adjacent exterior windows. The list could go on, but Figure 1.22 gives an idea of the many possible flanking paths that must be considered in addition to the potential leaks occurring within the perimeter of the partition or floor/ceiling assembly itself.

Where partitions terminate at a common suspended ceiling over two adjacent rooms, a serious room-to-room sound-flanking problem may exist, as also shown in Figure 1.22. The room-to-room sound isolation performance of suspended ceiling systems, ceiling attenuation class (CAC), is determined in the laboratory by standard test procedures (see laboratory test methods discussed later). The test measures the overall room-to-room sound attenuation, considering that the source-room sound follows a complex path to a receiving room (i.e., it passes through the ceiling in the source room along the common plenum over the partition and down throughout the suspended ceiling in the receiving room). Measured sound attenuation data for this rather complex room-to-room sound path can vary from about 20 to 40 dB or more, depending on the type of ceiling assembly used. Some lightweight acoustical ceiling boards may fall at the low end of this range, and other dense, mineral-fiber, back-sealed ceiling systems with tightly splined joints may perform at the upper end of this range or greater. Where high

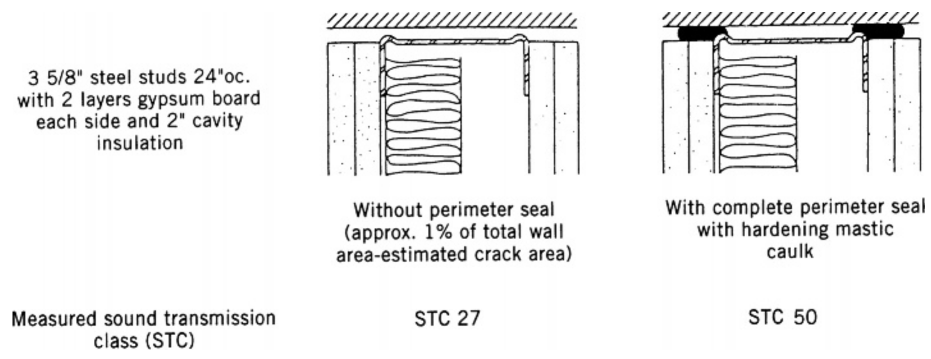

Figure 1.21 Typical sound leak encountered in building construction. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

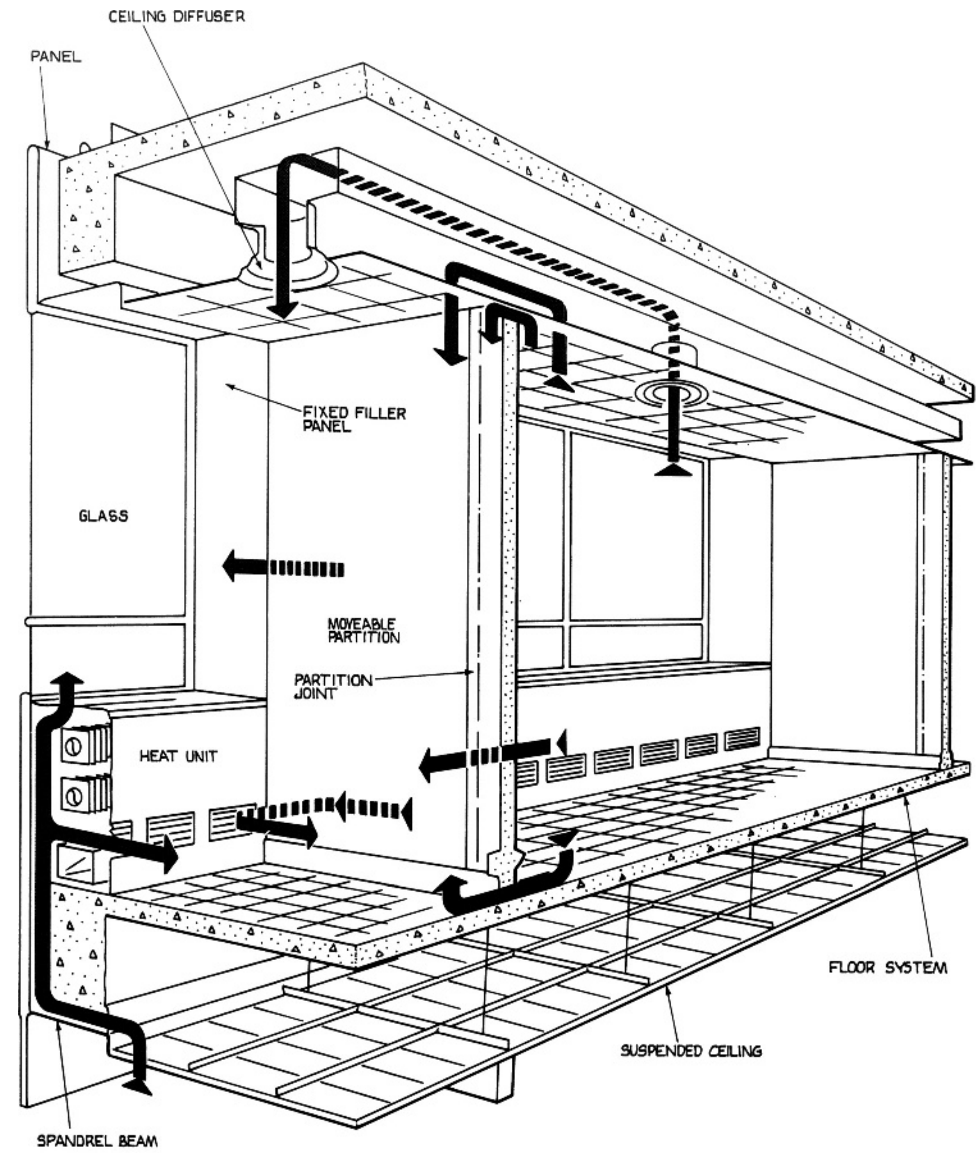

Figure 1.22 Some sound leakage and flanking transmission paths between rooms. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

values of room-to-room isolation are required, it is often necessary to design sound barriers to increase the room-to-room sound loss via the ceiling path with additional impervious elements, either vertically above the partition line or horizontally on the back side of the suspended ceiling system. In general, the sound isolation via the ceiling path must be at least equivalent to that via the common partition for balanced engineering design between the adjacent rooms.

Similarly, acoustical data for evaluating room-to-room sound transmission via air plenum distribution systems serving two adjacent rooms are available from products or systems tested in accordance with available standards (e.g., Air Diffusion Council Method of Test AD-63). All such paths via air-conditioning ducts, interconnecting secondary spaces, and so forth must be investigated to avoid serious reduction in field performance of an otherwise effective sound isolation common wall system. As a general rule, the higher the expected sound isolation performance of a construction, the greater the concern need be about flanking. Indeed, the achievement of room-to-room sound isolation values of more than about 50 dB in typical field situations requires extraordinary care in handling all possible flanking paths.

Laboratory Measurement of Airborne Sound Transmission Loss

Standardized methods are used throughout the world for the laboratory measurement of airborne sound transmission loss of building partitions, floor/ceiling assemblies, doors, windows, and so forth (e.g., ASTM E90). Obviously, in laboratory testing, all of the variables normally

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encountered in the field can be controlled to the extent necessary to measure the sound-isolating properties of just a partition or floor/ceiling assembly alone. The requirements of current testing standards have been established to yield as realistic and practical results as is possible. For example, a sufficiently large specimen must be tested (not less than 8 × 6 ft). Similarly, the test specimens must be representative of the assembly to be used in field situations and must be installed in a manner that duplicates normal field conditions to the extent possible. All of these requirements, as well as the special requirements of the laboratory facility and the measurement procedure, are very precisely defined in the standards.

The test specimen is mounted in an opening between two acoustically isolated test rooms and the sound transmission loss is determined from measurement of the reduction of sound between the rooms with a high-level sound source operating in one of the rooms. The measurements are carried out in continuous $\frac{1}{3}$-octave bands with center frequencies from 125 to 4000 Hz. This frequency range is wide enough to cover the low, middle, and high ranges of the audible spectrum. The laboratory test rooms are carefully isolated from one another to avoid flanking of sound between rooms by paths other than through the test specimen itself. Measurement of the sound transmission loss of a test specimen under the procedures of ASTM E90 will yield values that are representative of the maximum sound-isolating capability of a partition system. Figure 1.23 indicates typical laboratory test results for two partitions: (1) a simple fixed partition $4\frac{5}{8}$ in. thick, constructed of 2 × 4 wood studs with $\frac{1}{2}$-in. gypsum board outer surfaces, and (2) a 6-in.-thick reinforced concrete floor slab. Note that, in general, the concrete floor system has higher sound transmission loss values over the entire frequency range from 125 to 4000 Hz. This is largely due to the substantial mass of the construction compared to the lightweight partition. Furthermore, the stud partition exhibits significant "dips" in the transmission loss performance curve (e.g., at 3,150 and 125 Hz) compared to that for the concrete slab.

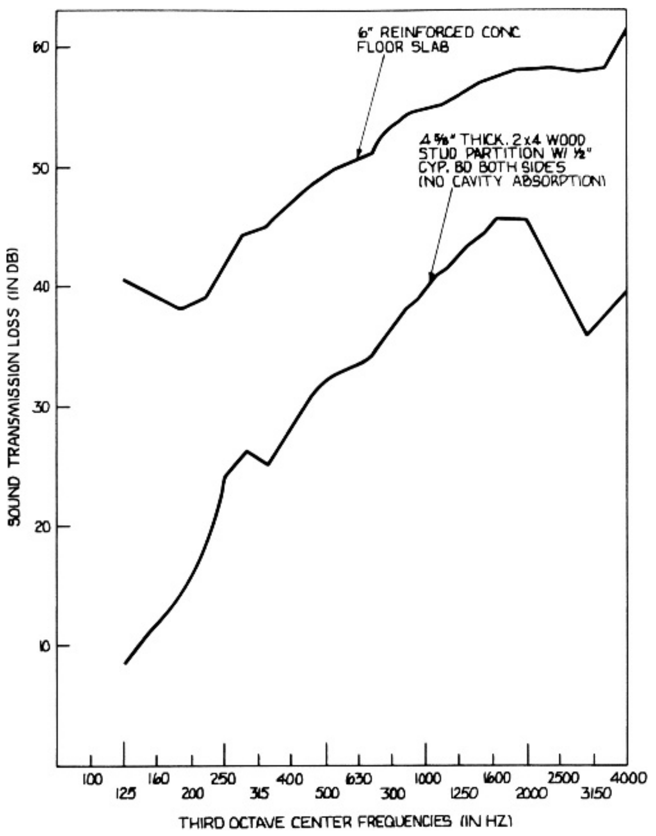

Figure 1.23 Laboratory-measured sound transmission loss for two typical constructions. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

Sound Transmission Class

For design and specification purposes, a single-number descriptor is usually desirable to indicate the sound isolation capability of a partition system. It can be seen with the test data for the constructions of Figure 1.23 that any simple arithmetic averaging of the test results over the full frequency range might be misleading, especially for partition performance where large dips occur. To overcome the limitations of simple averaging, a system of rating based on fitting the test data curves (sound transmission class, STC) was established. The procedures for rating the sound transmission loss performance are standardized in ASTM E413. Figure 1.24 shows the appropriate STC curves fitted to the laboratory data curves for the partitions of Figure 1.23 in accordance with the rules of ASTM E413. The fitting procedure allows for an average deviation of 2 dB below the STC curve in each of 16 third-octave measurement bands (or a total deviation of 32 dB). In addition, a maximum 8-dB deficiency is allowable in any single test frequency band.

In Figure 1.24, it can be seen that the 8-dB maximum deficiency governs the fit of the STC 32 curve in the case of the fixed gypsum board partition construction. With the heavy concrete floor construction, the allowable deficiencies are spread over a wider portion of the test range. The classification procedure is designed to penalize poor performance and not allow especially good performance at other frequency ranges to "fill in" any critical performance gaps. In general, however, the STC value does give

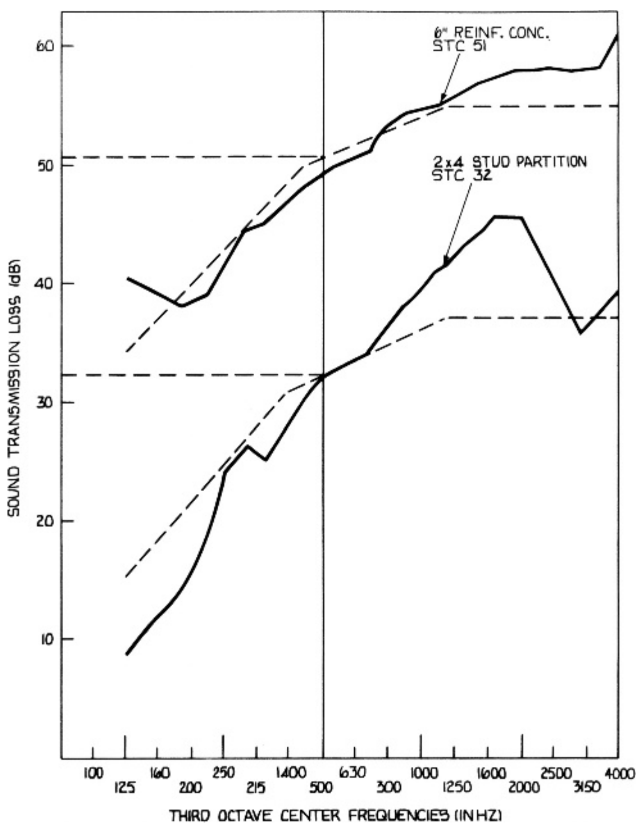

Figure 1.24 Sound transmission class (STC) curves fitted to laboratory data. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

a rough approximation of the TL value in the 500-Hz, or mid-frequency, range.

Chapter 2 includes performance tables of STC values for some common constructions. These may be compared with currently available laboratory test data in manufacturers' specification information for various specific products and systems being considered for a building design.

Ceiling Attenuation Class

For the case of sound transmission between adjacent rooms via the suspended ceilings over the rooms that share a common plenum (see Figure 1.22), a special laboratory test method is used. The method measures the room-to-room sound attenuation with the source-room sound passing through the ceiling, along the common ceiling plenum, and then down through the ceiling again into the receiving room. The method of test is ASTM E 1414-91a (1996), "Airborne Sound Attenuation Between Rooms Sharing a Common Ceiling Plenum." This method has replaced an earlier method of test, AMA-1-II (1967). The attenuation data are rated in accordance with the procedures of ASTM E 413-87 (1994), "Rating Sound Insulation," to yield a similar single-number, ceiling attenuation class for the common suspended ceiling system over the two adjacent rooms.

Field Measurement of Airborne Sound Transmission Loss

In actual building installations, it must be remembered that airborne sound is transmitted from room to room not only via the common constructions separating the rooms but also by many other potential flanking paths. Also, in the field there are usually other conditions—pipe penetrations of the construction system, air-conditioning duct penetrations—that are not present in the basic partition or floor/ceiling system tested in the laboratory. Thus, as would be expected, the sound isolation between rooms in an actual building is often somewhat less than that which can be realized in an idealized laboratory situation. Notwithstanding the complexity of the real-world situation, however, there is a need to measure and to classify the sound isolation capabilities of construction systems under typical field conditions. In fact, field performance is the ultimate interest of building professionals, as well as of the occupants themselves.

Field Sound Transmission Class

The current field test standard (i.e., ASTM E336) provides recommended methods for measuring sound insulation in buildings for nearly all cases likely to be encountered in the field. If the field situation is such that flanking of sound around the partition system being measured can be shown to be insignificant, meaningful field sound transmission loss values can be determined and the test data rated to yield a field sound transmission class (FSTC) value. The classification procedures discussed earlier for rating laboratory-derived sound transmission loss data are also used, but the added letter designation F indicates that the rating value is based on field-derived rather than laboratory test data.

Noise Isolation Class

In many complex field installations, the absence of significant flanking paths by the procedures of ASTM E 336 cannot be demonstrated. In such cases, the standard provides for simply measuring the noise reduction between the rooms in question without taking into account appropriate corrections for partition or floor/ceiling receiving room absorption and so forth. Thus the test provides only a measurement of the overall noise reduction achieved by the construction in situ and includes the effects of flanking paths between rooms in the particular environment. The noise reduction data can be rated in accordance with the procedures of ASTM 413 to yield a single-number noise isolation class (NIC) value. However, this value represents the sound isolation performance of the construction only in the particular environment tested. An NIC value attained at one building may not apply to an installation in another building where the acoustical environment is significantly different.

Therefore, several different field test procedures are standardized in ASTM E 336 to cover the various field conditions encountered. Naturally, the complexity in different measurement conditions and the various ratings appropriate for these different conditions lead to some confusion and even misuse of the data. Suffice to say that when field measurements are involved, the users of the resulting test data must understand just what was measured and all pertinent details of the field test conditions. Finally, and above all, the ratings derived from field tests (FSTC or NIC) are neither interchangeable nor directly comparable with laboratory-derived ratings (STC).

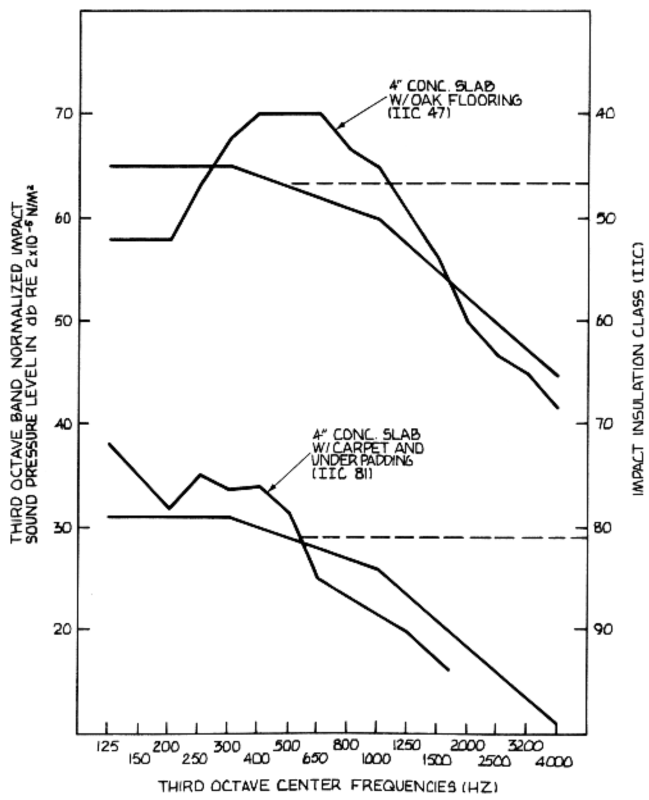

Figure 1.25 Impact insulation for a reinforced concrete floor slab with and without carpeting. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction,* 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

Control of Direct Structure-Borne Sound

When sound energy is directly induced into a structure (by the impact of footsteps, falling objects, hammering, or by rigidly attached vibrating mechanical equipment, etc.), the energy will travel relatively easily throughout the structure and reradiate as airborne sound in adjacent spaces. This type of direct structure-borne sound can be controlled at the source by resilient mounting of mechanical equipment, by the use of resilient or cushioning materials at the point of impact (with flooring materials such as carpeting), and by special isolated constructions.

Impact Insulation Class

Direct impact sound of footsteps and falling objects may be a concern with many building types (apartments, offices, etc.) where occupied spaces occur over one another. Acoustical testing of the ability of a floor/ceiling assembly to reduce direct impact sound transmission is similar to that for airborne sound transmission loss testing. A test specimen construction is placed in a floor opening between two test rooms, and microphones are positioned in the lower test room to record the sound levels transmitted with a standard taping machine operating on the test specimen. The complete details of the test procedure and method of reporting the test results are included in the current standard method of test (ASTM E 492).

Figure 1.25 shows typical laboratory test results for a reinforced concrete floor slab with and without floor carpeting. The impact insulation class (IIC) increases significantly (IIC 47 vs. IIC 81), indicating that the transmitted impact sound levels due to the carpeting are considerably reduced. The improvement with a cushioning material such as carpeting at the point of impact is enormous—as any apartment dweller who has experienced this situation with neighbors overhead can attest.

Chapter 2 includes a performance table of IIC values for a number of common floor/ceiling assemblies. Also shown, for comparison, are the corresponding airborne STC values for the constructions. Wherever there is a potential for disturbance from both airborne and direct impact sounds, both the STC and IIC ratings of the separating floor/ceiling construction should be considered.

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The ability of a construction to effectively isolate direct impact sounds (i.e., higher IIC values) depends largely on the "softness" of the floor surface and/or the degree to which the directly impacted floor surface is decoupled from the radiating surfaces below. Unlike the case of airborne sound transmission, the mass of the structure plays a secondary role in a structure's ability to isolate direct impact sound except at low frequencies. Heavy concrete slab constructions are only slightly more efficient in isolating impacts than much lighter wood constructions over a significant range of audible frequencies. Soft, cushionlike flooring surfaces, however, significantly improve the IIC values for both light and more massive floor/ceiling assemblies. The low-frequency boominess of transmitted impact sounds associated with lightweight wood frame floors even with carpeting can be improved by carefully detailed and constructed measures, such as resiliently supported or independent gypsum board ceilings below the floor surface structure.

As with airborne sound transmission, the adequate performance of impact-isolating structures in the field is the ultimate objective. In actual buildings, there are numerous flanking paths for impact sound transmission, as well as many instances in which a system that was effectively decoupled in the laboratory test specimen becomes seriously short-circuited in the real building context. Again, detailing of the construction and field supervision are essential to be sure that special impact-isolating features of a particular assembly are retained in the actual installation. This becomes increasingly important as higher acoustical performance values are sought for both airborne and structure-borne sound transmission.

Isolation of Mechanical/Electrical Equipment

Most building services (heating, ventilation, and air-conditioning [HVAC] systems, electrical power generators or transformers, elevators, automatic delivery systems, etc.) involve rotating, reciprocating, or otherwise vibrating equipment. When such sources are located near critical occupied spaces and are directly attached to the supporting structure, serious problems can arise from both airborne and direct structure-borne sound transmission. The complete treatment of mechanical/electrical equipment noise and vibration control is beyond the scope of this general review. However, some fundamental principles are common to nearly all types of mechanical/electrical equipment sources. Obviously, the larger the machine capacity and its electrical power consumption, the greater the potential for noise and vibration output. A first guideline, then, is to select and specify (in quantitative terms if possible) the quietest available equipment for the task at hand. Second, the major noise sources should be located as far from critical areas as possible (e.g., basement mechanical equipment rooms rather than upper level). Third, the vibrating equipment must be effectively decoupled from the building structure (i.e., vibration isolation mounts and bases, resilient connections at connecting ducts and pipes, etc.). Fourth, the enclosing mechanical room structure (floors, walls, and ceilings) must reduce airborne and structure-borne sound to adequately low levels in adjacent spaces. The latter includes careful attention to all possible flanking paths for airborne and structure-borne sound that might short-circuit the designed noise and vibration control system. Figure 1.26 illustrates the general approaches to noise and vibration control measures for a typical building mechanical equipment installation. Chapter 3 addresses this and other common building noise control applications as well. In addition, excellent guidance in the selection of design criteria, as well as in the analysis of HVAC system noise and vibration control measures, is available in technical society guide books (e.g., chapters on sound and vibration control in the current edition of the *American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Guide*).

1.3 DESIGN CRITERIA

Architectural and engineering applications of the basic concepts of sound control in buildings require establishment of reasonable design criteria guidelines and standards. A typical building may contain literally hundreds of kinds of spaces intended to house a tremendously wide variety of activities. Many of the spaces are multiuse in that they must accommodate more than one type of activity, occasionally simultaneously. The optimum acoustical environment for one activity may be impossible for another. Even some apparently unitary-use rooms, such as a music recital hall, may need an adjustable acoustical environment to handle the needs of various sizes and types of performing groups, as well as variations in the acoustical environment for the music of different periods (classical or romantic versus contemporary, etc.).

Criteria have been or can be developed for every source-path-receiver situation in and around buildings. Criteria for acceptable background sound levels in various kinds of rooms, as well as criteria for acceptable degrees of sound isolation from exterior sources and from sources within a building, have become part of the building

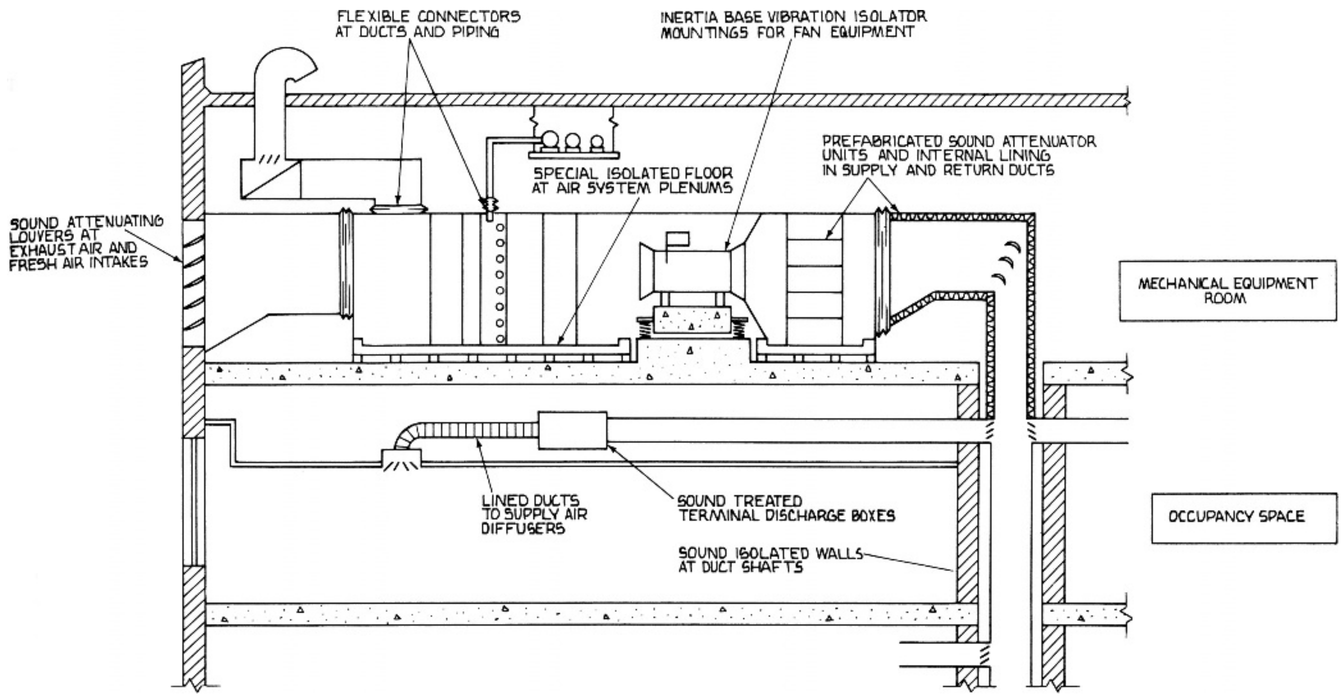

Figure 1.26 Typical mechanical equipment noise and vibration control measures. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

technology literature. With time, many of the developing criteria form the basis for standards and codes. Keep in mind that in most building situations, people are the ultimate receptors of the sounds in question. The somewhat variable and often confusing responses observed in various situations should not be too surprising when the end result is so often a largely subjective one. In other words, one man's music can be another's noise. However, criteria that have withstood the test of time, and the intelligent application thereof, can minimize the risks in the engineering design decisions involved. The building designer's task is more comfortable, of course, when the criteria have found their way into hard-and-fast standard values that must be met in a particular building code. The responsibility then may be shifted to the later stage of the building project, where those responsible for the field execution of a specified acoustical construction provide the assurance that code requirements have been satisfied.

This chapter briefly reviews some of the available state-of-the-art criteria for building acoustics applications, and Chapter 3 addresses certain applications in more detail. As with most aspects of building technologies, new criteria and standards are continually being developed, and there will be new and modified criteria to meet changing societal needs. Fortunately, the fundamental laws governing the behavior of sound do not change, and an understanding of the basic principles and concepts of sound control in buildings should permit the building professional to intelligently deal with new and modified criteria.

Criteria for Background Sound Levels

The general background or ambient sound levels in a space are an extremely important element of the acoustical environment of that space. They form the "noise floor," so to speak, against which the occupants hear the desired sounds or undesired sounds (noise) in the space. Continuous background sound can cover up or mask the minor intrusive sounds within a space or those transmitted from an adjacent space. Just as there is a wide variety of kinds of spaces in buildings, there is an equally wide range of acceptable background sound levels. For critical spaces, such as radio broadcast or recording studios, very low background sound levels must be assured to be able to pick up the faintest desired musical speech sounds. In contrast, excessively low levels in a typical office environment might be deafening, in that practically all of the everyday normal activity sounds would become objectionable. A higher level of bland, unobtrusive background sound in such spaces becomes more comfortable for the occupants. The general objective is *quiet*, that is, a comfortable level of background sound

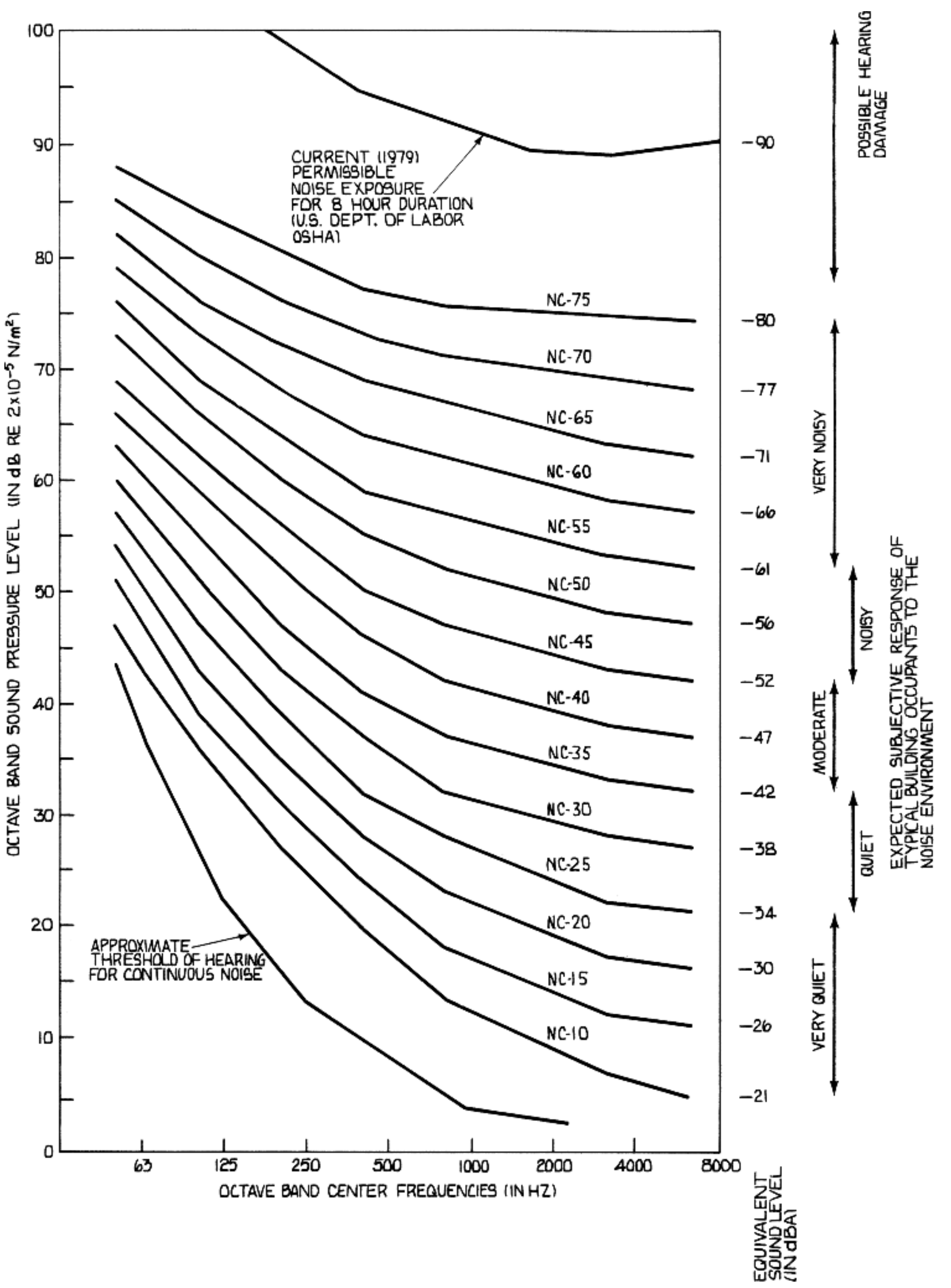

Figure 1.27 Background noise criteria curves. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

appropriate for the particular space involved. The objective is not silence, the virtual absence of sound, as might be desired in very critical recording studios or acoustical laboratory testing chambers.

Noise criteria (NC) curves that have been extensively used for engineering design and specification of building noise control elements are shown in Figure 1.27. These criteria curves specify allowable sound pressure levels in octave bands of frequency over the full audible range. The numerical value assigned (i.e., the NC number) is the arithmetic average of the levels in the 1000-, 2000-, and 4000-Hz bands (the frequency range most important to the understanding of speech). Each criterion curve generally permits higher levels of low-frequency sound compared to middle and upper frequencies, and follows the general pattern of how people respond to sound over the audible range. Low-frequency sounds are generally less annoying than high-frequency sounds within the limits expressed by the various NC curves.

Note: Since NC curves were first introduced in the late 1950s, they have found wide application in building noise control. In the 1980s and 1990s, further refinements and

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TABLE 1.2 Recommended Criteria for Steady Background Sound in Typical Building Spaces

TYPE OF SPACE OR ACTIVITY	CRITERIA: RECOMMENDED NC CURVE	CRITERIA: SOUND LEVEL, dBA
Workspaces in which continuous speech communication and telephone use are not required	60–70	65–75
Shops, garages, contract equipment rooms	45–60	52–65
Kitchens, laundries	45–60	52–65
Light maintenance shops, computer rooms	45–55	52–61
Drafting rooms, shop classrooms	40–50	47–56
General business and secretarial offices	40–50	47–56
Laboratories, clinics, patient waiting spaces	40–50	47–56
Public lobbies, corridors, circulation spaces	40–50	47–56
Retail shops, stores, restaurants, cafeterias	35–45	42–52
Large offices, secretarial, relaxation areas	35–45	42–52
Residential living, dining rooms	30–40	38–47
General classrooms, libraries	30–40	38–47
Private, semiprivate offices	30–40	38–47
Bedrooms, hotels, apartments with air conditioning	30–40	38–47
Bedrooms, private residences, hospitals	25–35	34–42
Executive offices, conference spaces	25–35	34–42
Small general-purpose auditoriums (less than about 500 seats), conference rooms, function rooms	30 (max)	40 (max)
Small churches and synagogues	25 (max)	35 (max)
Radio, TV, recording studios (close microphone pickup)	25 (max)	35 (max)
Churches, synagogues (for serious liturgical music)	20 (max)	30 (max)
Large auditoriums for unamplified music and drama	20 (max)	30 (max)
Radio, recording studios (remote microphone pickup)	15 (max)	25 (max)
Opera performance halls	15 (max)	25 (max)
Music performance and recital halls	15 (max)	25 (max)

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improvements to account for how people respond to the frequency content of HVAC system sounds have evolved. Two such examples are room criteria (RC) and balanced noise criteria (NCB) methods. These newer methods are discussed further in Chapter 3 and may be found in current ANSI Standard S12.2-1995, "Criteria for Evaluating Room Noise."

Also indicated in Figure 1.27 is the equivalent single-number A-scale frequency-weighted equivalent values in dBA for the individual NC curves. For example, a background sound environment that just matched the NC 35 curve would measure 42 dBA with a simple sound level meter. For many building applications, the more detailed octave-band analysis is necessary for engineering design or specification. However, the use of simple A-weighted sound levels for analysis and evaluation of final field results may be appropriate. Figure 1.27 also shows the general subjective judgment a typical building occupant might express relative to the background sound environment represented by the various NC curves and their equivalent dBA values.

Table 1.2 lists recommended criteria ranges for background sound levels in typical building spaces in terms of both NC curves and dBA values. Design criteria from the table may be selected for design purposes in developing HVAC system noise control measures and in specifying system components such as air-conditioning diffusers, fluorescent light ballasts, and the like. Note that the

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TABLE 1.3 Nature of Speech Communication Possible in Various Background Sound Levels

BACKGROUND SOUND LEVEL, dBA	VOICE EFFORT REQUIRED AND DISTANCE	NATURE OF COMMUNICATION POSSIBLE	TELEPHONE USE
55	Normal voice at 10 ft	Relaxed communication	Satisfactory
65	Normal voice at 3 ft Raised voice at 6 ft Very loud voice at 12 ft	Continuous communication	Satisfactory
75	Raised voice at 2 ft Very loud voice at 12 ft Shouting at 8 ft	Intermittent communication	Marginal
85	Very loud voice at 1 ft Shouting at 2–3 ft	Minimal communication (restricted prearranged vocabulary desirable)	Impossible

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10-dB recommended design criteria range (e.g., classrooms, NC 30–40) indicates the wide range of acceptability found among typical building occupants. Generally, the middle of the recommended design range is chosen (e.g., NC 35 for classrooms). However, often a building owner may indicate a desire that a conservatively low design criterion be used because, for example, the building must accommodate hearing-impaired occupants (e.g., NC 25 for classrooms). The lower the design criteria's value, the more costly the noise control measures are likely to be to meet that design criterion, so selection is an extremely important part of the building planning decision process in the context of the overall building budget. Spaces for some activities, such as music performance or recording, can rarely be too quiet. For the latter, a recommended maximum limit rather than a design range is desirable, as can be seen in Table 1.2. The background sound level criteria and the extent to which they are realized in a finished building have important implications for other related acoustical design aspects in particular situations (e.g., those involving acoustical privacy within and between rooms).

Criteria for High Noise Level Areas

In most industrial plants, building mechanical service areas, and other such areas, the production process or system equipment noise cannot be controlled to reasonably low levels for optimal acoustical comfort from a practical standpoint. In these spaces, it often is a matter of simply providing the best possible environment for speech communication or telephone usage. Or, if very high noise levels are likely, it may be a matter of protection of the exposed workers' hearing.

Table 1.3 indicates the nature of speech reception possible in various noise environments, as well as a person's ability to carry on telephone communications in that environment.

Table 1.4 indicates the current Occupational Safety and Health Administration (OSHA) permissible noise exposures for various exposure durations. Note that these are upper-limit criteria for exposure and are not recommended design values. Even if an industrial noise environment falls below these limits (say, a typical worker's exposure is less than 90 dBA for an 8-hour work day), there is still a potential hearing damage hazard. Currently, legislative efforts are in progress toward lowering the exposure limit to 85 dBA from 90 dBA for 8-hour exposure, with corresponding reductions for shorter exposure durations. A building professional may well be involved in critical decisions concerning an industrial building design, as the building or equipment enclosures can influence the

TABLE 1.4 Permissible Noise Exposure in Industrial Environments

DURATION PER DAY, HR	PERMISSIBLE SOUND LEVEL, SLOW METER RESPONSE, dBA
0.25 or less	115
0.5	110
1	105
1.5	102
2	100
3	97
4	95
6	92
8	90

From Paragraph 1910.95, Occupational Safety and Health Act, U.S. Department of Labor (1979).

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mechanical equipment room noise to which personnel are exposed.

Sound Isolation between Dwelling Units

The Federal Housing Administration (FHA) of the U.S. Department of Housing and Urban Development (HUD) recommends criteria for all federally subsidized housing to ensure that both airborne and impact sound transmission between dwelling units will be controlled. Constructions that meet the criteria and are properly installed in the field will provide good sound insulation between dwelling units and should satisfy most occupants. Because the level of background sound varies in different building site environments, three criteria grades are established:

> *Grade I*. Generally "quiet" suburban and peripheral suburban areas where the nighttime exterior background noise levels might be about 35 to 40 dBA or lower. In addition, Grade I is applicable to dwelling units in high-rise buildings above about the eighth-floor level and to apartment buildings desiring maximum sound insulation regardless of location.
>
> *Grade II*. Generally "average" suburban and urban residential areas where the nighttime exterior background noise levels fall in the 40- to 45-dBA range.
>
> *Grade III*. Generally "noisy" suburban or urban areas where the nighttime exterior background noise levels exceed 55 dBA. This category is considered as minimum desired sound isolation between dwelling units.

Figure 1.28 and Table 1.5 indicate key FHA recommendations for airborne and impact sound isolation criteria in terms of minimum STC and IIC values for each of the three grades. Table 1.6 indicates key criteria for airborne sound isolation within a dwelling unit. As expected, FHA interior criteria are less demanding than those for neighboring occupancies. Also, no criteria for impact sound are suggested, as it is assumed that activities within a dwelling unit may be controlled by the occupants themselves. It is usually a neighbor who makes noise, not one's own family!

Criteria for Mechanical Systems

The major building air-handling and electrical power systems, for example, must be located for efficient distribution and service to various parts of the building. Most often, especially in high-rise structures, not all of the mechanical equipment spaces can be located in remote basement areas. Above-grade locations at intermediate levels and at the upper floors of a building are almost always necessary for fans, pumps, cooling towers, emergency generators, and the like. Accordingly, these spaces must be adequately isolated from occupied spaces above and below. This involves the specification and detailing of adequate floor/ceiling and enclosing wall systems to reduce airborne sound transmission. As is apparent from the FHA criteria of Table 1.5, in apartment buildings, generally high orders of sound isolation are required where sensitive occupants are immediately adjacent to major mechanical/electrical noise sources. When the noise emission levels for the various potential sources are known or can be estimated, it is relatively easy to determine the required isolation to meet a specified background noise level in an adjacent occupied area. Suitable constructions can then be designed and specified.

A special problem with such noise sources is the possible direct excitation of the building structures by the vibrating mechanical equipment, through the many ducts, pipes, or electrical conduit that must also be connected to the equipment. Decoupling of all sources of vibration from the building structure is axiomatic. This is accomplished by means of special resiliently supported isolation bases and mounts, resilient hangers, flexible couplings, and so forth, all intended to avoid direct contact of the sources of vibration with the structure that would otherwise reradiate the sound energy in other spaces throughout the building. Chapter 3 addresses in more detail the criteria and selection guidelines for typical mechanical equipment installations in buildings.

Criteria for Rooms for Listening and Performance

Auditoria, music and drama performance halls, conference rooms, sports stadia, classrooms and, for that matter, all spaces large and small where audiences listen to some desired sound source or sources must satisfy certain fundamental acoustical requirements if they are to supply satisfactory listening conditions. Chapters 4, 5, and 6 address in great detail the acoustical design issues surrounding spaces of all types and capacities for listening and performance. However, there are some design criteria common to all listening rooms, large or small. The basic objectives for any are simply stated in terms of two aspects of the basic building design: (1) the control of all undesired sounds from exterior sources, adjacent spaces within the building, the HVAC systems serving the space, and so forth; and (2) the control of all desired sounds the audience has

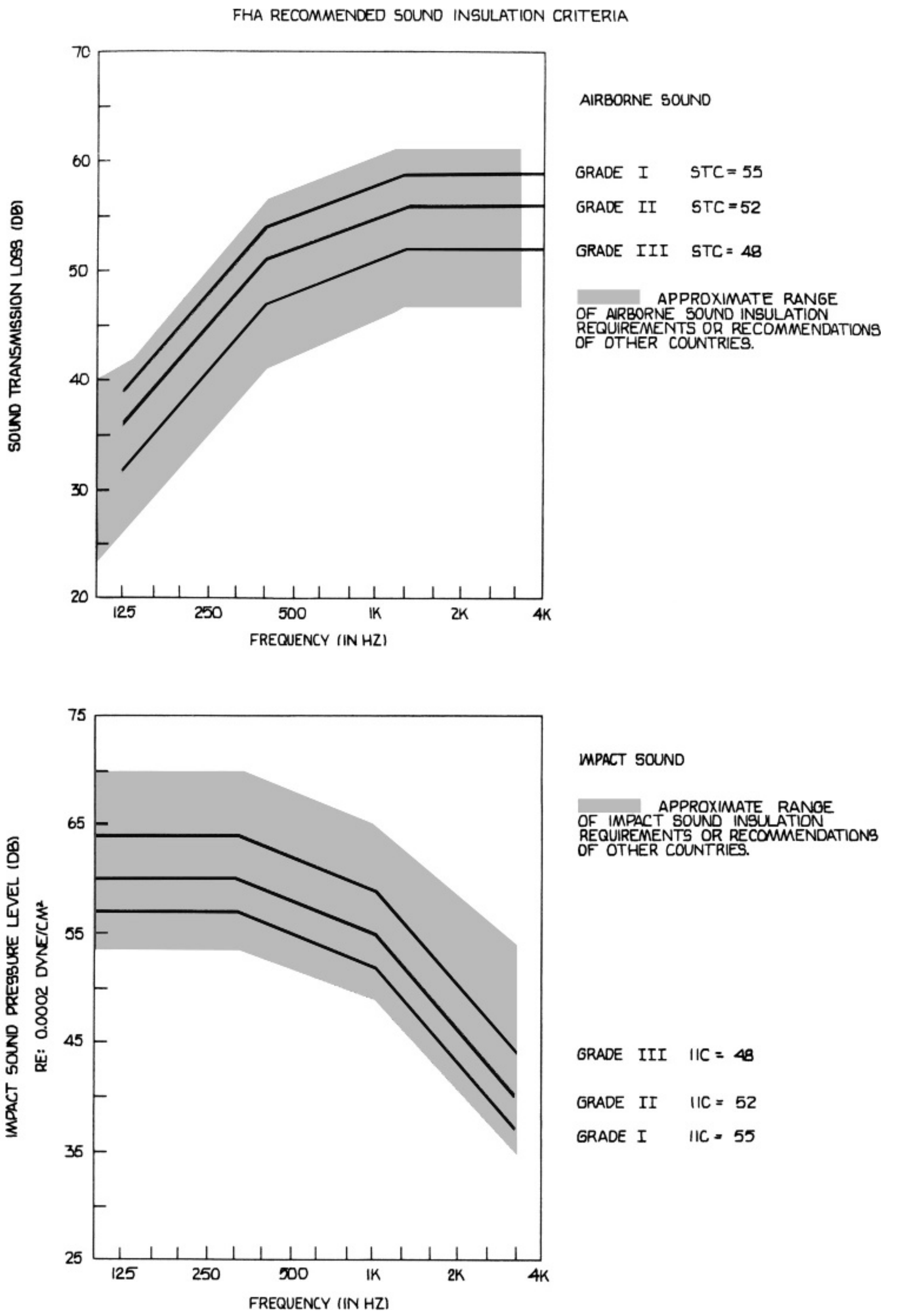

Figure 1.28 FHA-recommended criteria for sound isolation between dwelling units. (From W. J. Cavanaugh, *Building Construction: Materials and Types of Construction*, 5th ed., ed. Whitney Huntington and Robert Mickadeit. Copyright © 1981 John Wiley & Sons. Reprinted by permission of John Wiley & Sons.)

come to hear, so that they are adequately loud and properly distributed without echo or distortion throughout the space.

The first is rather obvious. However, often serious oversights, such as inadequate control of HVAC system noise, can mask significant parts of the desired speech or music program. The poor acoustics of a church or school auditorium can often be corrected by simply turning off the air-conditioning fans. Such situations should not occur. Properly chosen background sound levels (refer to Table 1.2) and then the design of sound-attenuating constructions to exclude all potential intrusive sounds will satisfy this extremely important first requirement. Table 1.2 also suggests the range of acceptable background sound levels for various types of auditoria spaces, depending on their size and type of program material. Small conference

TABLE 1.5 FHA Criteria for Sound Insulation between Dwelling Units

	QUALITY AND LOCATION GRADE		
	GRADE I	GRADE II	GRADE III
Party walls	STC 55	STC 52	STC 48
Party floor/ceilings	STC 55 IIC 55	STC 52 IIC 52	STC 48 IIC 48
Mechanical equipment room to dwelling unit	STC 65[a]	STC 62[a]	STC 58[a]
Commercial space to dwelling unit	STC 60 IIC 65	STC 58 IIC 63	STC 56 IIC 61

[a] Special vibration isolation of all mechanical equipment is required.
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rooms or classrooms, where speaker-to-listener distances are small, are less demanding than larger performance auditoria with critical program material.

The control of the desired sounds is a much more complex matter, because in most spaces the full range of sources (speech through music) must be accommodated and the audience itself is dispersed over a major part of the enclosing volume of the room. With systematic study of typical source-to-receiver paths, the complexities can be overcome in most rooms, especially with today's readily available computer-aided design and analysis procedures.

To begin with, the source must be made adequately loud at all possible listener locations. This is accomplished by taking advantage of the natural reinforcement of the major room surfaces that can direct reflected sound in mirrorlike fashion from the source to the listener (see Chapter 4). In larger rooms, or for some sources that are weak to begin with, electronic reinforcement systems must supplement the natural loudness of the desired sounds (see Chapter 5). The coordination and integration of sound amplification system equipment with the basic room acoustics design is often an important part of the overall acoustical design. In very large auditoria and sports arenas, electronic amplification systems, as described in Chapter 5, do the entire job of providing adequate loudness.

Another corollary requirement associated with the loudness requirement is that the desired sound must be distributed uniformly throughout the listening space without long-delayed discrete reflections (echoes), focused reflections, repetitive reflections (flutter echoes), or other undesirable colorations of the original source. These detailed design considerations are important but rarely amenable to simple criteria. Simplified ray diagram analyses for the various principal source locations can reveal the general pattern of sound distribution throughout the space and the presence of possible deleterious reflections. In general, reflected signals that arrive within about 40 milliseconds (msec) after the direct sound has arrived (i.e., a path difference of 40 feet or less between the direct and reflected sound) contribute to the apparent loudness of the sound. Reflected sounds of sufficient level arriving after about 60 msec may be distinguished as discrete separate signals (or echoes). Intermediate delays between about 40 and 60 msec may simply result in fuzziness of the sound received, with no real contribution to its loudness or intelligibility.

A final requirement for good listening conditions is adequate reverberation control. Excessive reverberation can destroy speech intelligibility, yet inadequate persistence of sound can make music sound dead and lifeless. In most rooms, the selection of criteria for reverberation is largely a matter of judgment and, in some cases, compromise between the ideal for either extreme, music or speech uses. Chapter 4 includes design criteria for reverberation time (RT), early decay time (EDT), clarity (C), early-to-total energy ratio (D), loudness (L), and other factors that are crucial in the analysis and design of new buildings for the performing arts, as well as for understanding the acoustical environments in existing facilities. The past several decades have seen extensive research in the acoustics of listening spaces and in the psychoacoustical responses of typical listeners themselves, as discussed in Chapter 6, all of which contributes to better spaces for listening and performance and ultimately evolves into acoustical design criteria and design guidelines for all spaces in which people are to hear and enjoy desired music or speech sounds.

TABLE 1.6 FHA Criteria for Sound Insulation within Dwelling Units

	QUALITY AND LOCATION GRADE		
	GRADE I	GRADE II	GRADE III
Bedroom to bedroom	STC 48	STC 44	STC 40
Living room to bedroom	STC 50	STC 46	STC 42
Bathroom to bedroom	STC 52	STC 48	STC 45
Kitchen to bedroom	STC 52	STC 48	STC 45
Bathroom to living room	STC 52	STC 48	STC 45

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1.4 SELECTED STANDARDS IN BUILDING ACOUSTICS

There are literally hundreds of standards promulgated by national and international standards bodies, industrial and trade organizations, and technical and scientific societies concerned with acoustics. The following list of selected standards includes those most likely to be of interest in building construction.

- *American National Standards Institute (ANSI)*
  Standards Secretariat for Acoustical Standards
  Acoustical Society of America
  asa@aip.org/

  ANSI S1.1-1994 (R 2004) American National Standard Acoustical Terminology

  ANSI S1.4-1994 (R 2004) American National Standard

  ANSI S1.6-1984 (R 2006) American National Standard Preferred Frequencies, Frequency Levels, and Band Numbers for Acoustical Measurements

  ANSI S1.8-1989 (R 2006) American National Standard Reference Quantities for Acoustical Levels

  ANSI S1.11-2004 American National Standard Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters

  ANSI S1.13-2005 American National Standard Measurement of Sound Pressure Levels in Air

  ANSI S1.42-2001 (R2006) American National Standard Design Response of Weighting Networks for Acoustical Measurements

- *American Society for Testing and Materials (ASTM)*
  www.astm.org/

  ASTM C423-07a Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method

  ASTM C634-02 Terminology Relating to Building and Environmental Acoustics

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

  ASTM E336-05 Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings

  ASTM E413-04 Classification for Rating Sound Insulation

  ASTM E492-04 Test Method for Laboratory Measurement of Impact Sound Transmission through Floor-Ceiling Assemblies Using the Tapping Machine

  ASTM E1414-06a Test Method for Measuring Airborne Sound Attenuation between Rooms Sharing a Common Ceiling Plenum

- *International Standardization Organization (ISO)*
  www.iso.org/iso/home.htm

  ISO 140-1 to -18 Acoustics—Measurement of sound insulation in buildings and of building elements

  ISO 717-1 and -2 Acoustics—Rating of sound insulation in buildings and of building elements

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CASE STUDY

FOGG ART MUSEUM LECTURE HALL, HARVARD UNIVERSITY (1895–1973)

The Beginnings of Modern Architectural Acoustics

Ewart A. Wetherill, AIA, RAIC, FASA

In recent decades, the use of advanced investigative methods has led to the rediscovery of previously unavailable information from ruins and forgotten records of demolished buildings. One significant recent example is the auditory simulation of a room that by a remarkable combination of circumstances became the vehicle by which the science of room acoustics was founded.

It is seldom that a building gains significance for all the wrong reasons. The original Fogg Art Museum at Harvard University, opened in 1894 as a memorial to William Hayes Fogg, had all the natural advantages—a prime location, a wealth of fine art and endowments, and an eminent scholar as its star—yet its place in history may ultimately be as the vehicle for the founding of a new science.

SOLVING AN AGE-OLD PROBLEM

In 1895, the original Fogg Art Museum Lecture Hall was dedicated as a memorial to William Hayes Fogg. The bequest had apparently been regarded by Harvard University as something of a mixed blessing, and the architectural design by William Morris Hunt was fairly controversial from the outset. It was soon discovered that the acoustics of the main lecture hall were so bad that the space had to be abandoned as unusable, and Harvard's president, Charles W. Eliot, turned to Wallace Clement Sabine, a 27-year-old assistant professor of physics, for help in resolving the difficulty. Sabine undertook the study of a problem that had never been resolved, despite the discouragement of his senior faculty colleagues who considered it beyond solution.

The acoustical difficulties of the lecture hall are best described in Sabine's own words: "The rate of absorption was so small that a word spoken in an ordinary tone of voice was audible for five and a half seconds afterwards. During this time even a very deliberate speaker would have uttered the twelve or fifteen successive syllables. Thus the successive enunciations blended into a loud sound, through which and above which it was necessary to hear the orderly progression of the speech. Across the room this could not be done. . . ."[1]

This situation could most likely have been partially resolved within a few months to make the room at least usable enough for lectures. However, it evolved into a much deeper study that lasted three years, incurring the displeasure of President Eliot, who was anxious to restore the reputation of the notorious new building. Sabine first reviewed every available reference on building acoustics but found little guidance. After observing that acoustical conditions for speech were worst in the empty lecture hall and noticeably better when it was full of people, he then explored ways of defining the properties of sound in the room.

Several possible techniques to analyze the behavior of a sound were tried and ultimately rejected in favor of measuring the length of time for a sound to decay to inaudibility. Sabine's next challenge was to develop a source of sound that could be repeated quickly and very accurately. Finally deciding upon an organ pipe mounted on a wind chest as a sound source that could be repeated many times, he would excite the room at the mid frequency tone of 512 Hertz (cycles per second) and measure the time for its decay to inaudibility, using only his ears and a stopwatch. In the absence of any electronic measurement capabilities, he minimized variations by taking many samples and calculating the mean value of each set of measurements.

Sabine found that easily removable seat cushions from the nearby Sanders Theatre could be used as a consistent standard for making incremental changes to the amount of sound absorption in the lecture hall. However, they were only available at night and had to be returned in time for classes each day. Sabine also discovered that the only time the hall was consistently quiet enough for his measurements was between 2:00 a.m. and 6:00 a.m. when the Harvard Square streetcars were not running. He developed a routine of concentrating only on his classes and the late-night experiments, sleeping little and avoiding other activities as much as possible.

Part of the experiment required establishing what he termed the sound-absorbing power of a variety of building materials and furnishings. To compare a material to his seat cushion standard, he had to carry out the laborious process of measurements twice. He eventually eliminated the need for repetition by selecting the sound-absorbing power of an open window as his permanent reference. A unit area of open window remains the standard for complete absorption of incident sound energy and is internationally known as a *sabin* in recognition of his scientific achievement.

His analysis of the Fogg lecture room and a series of other spaces in the Boston area concluded with confirmation that the physical properties of any room were directly related to the time required for a sound to decay to inaudibility, which he named its "reverberation time." The Fogg lecture hall study was officially closed in September 1898, when corrective treatment consisting of hair felt was installed at the upper part of the rear wall and in the recesses in the domed ceiling, with the result that "the room was rendered not excellent, but entirely serviceable . . . without serious complaint."[2]

Having derived a universal method for calculating the duration of sound, thus allowing the reverberation time of

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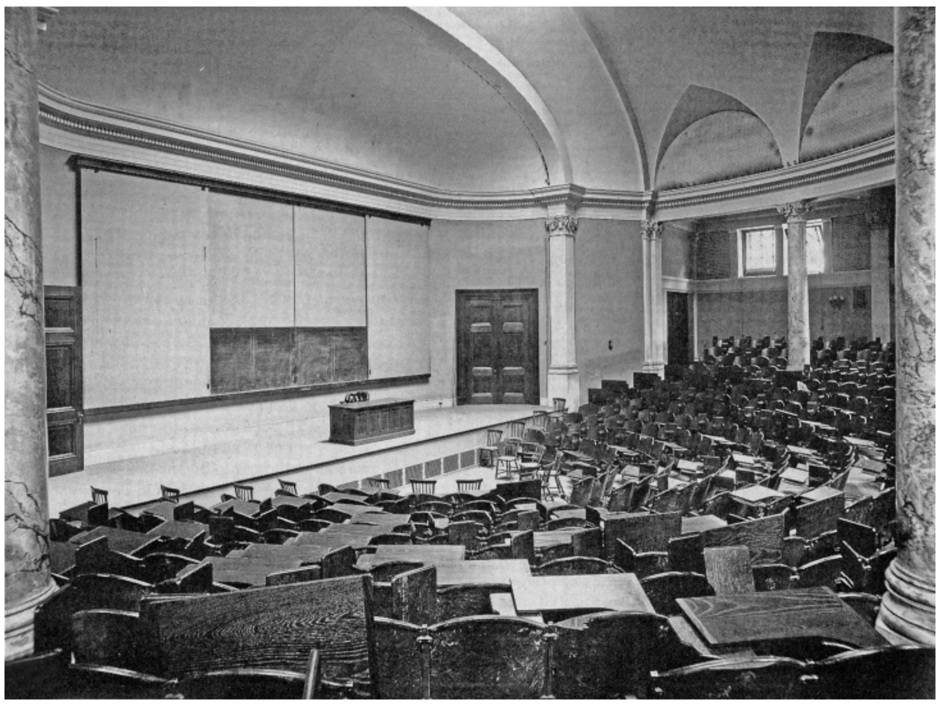


Figure 1.29 Fogg Art Museum, original lecture hall ca. 1898. (Photograph ca. 1910 courtesy of the Fogg Art Museum, Harvard University Art Museums, and E. A. Wetherill, AIA, FASA.)

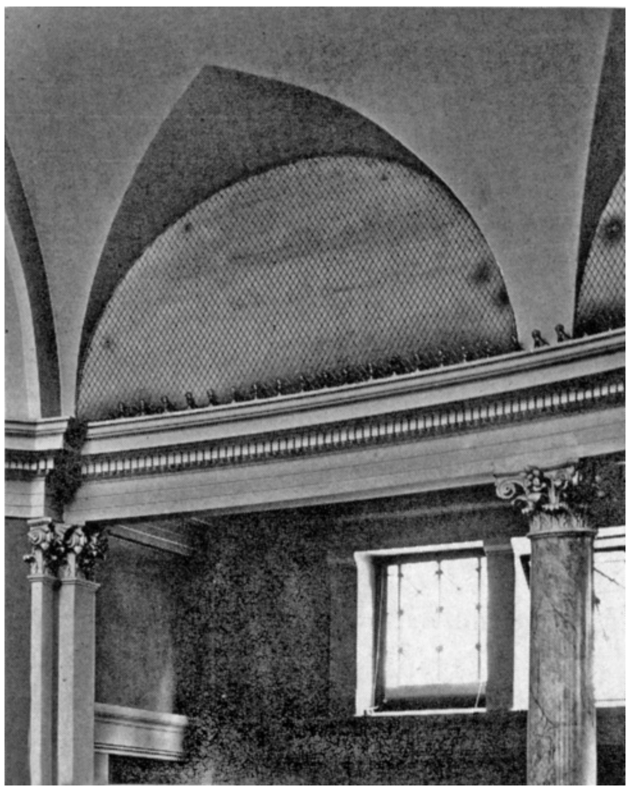


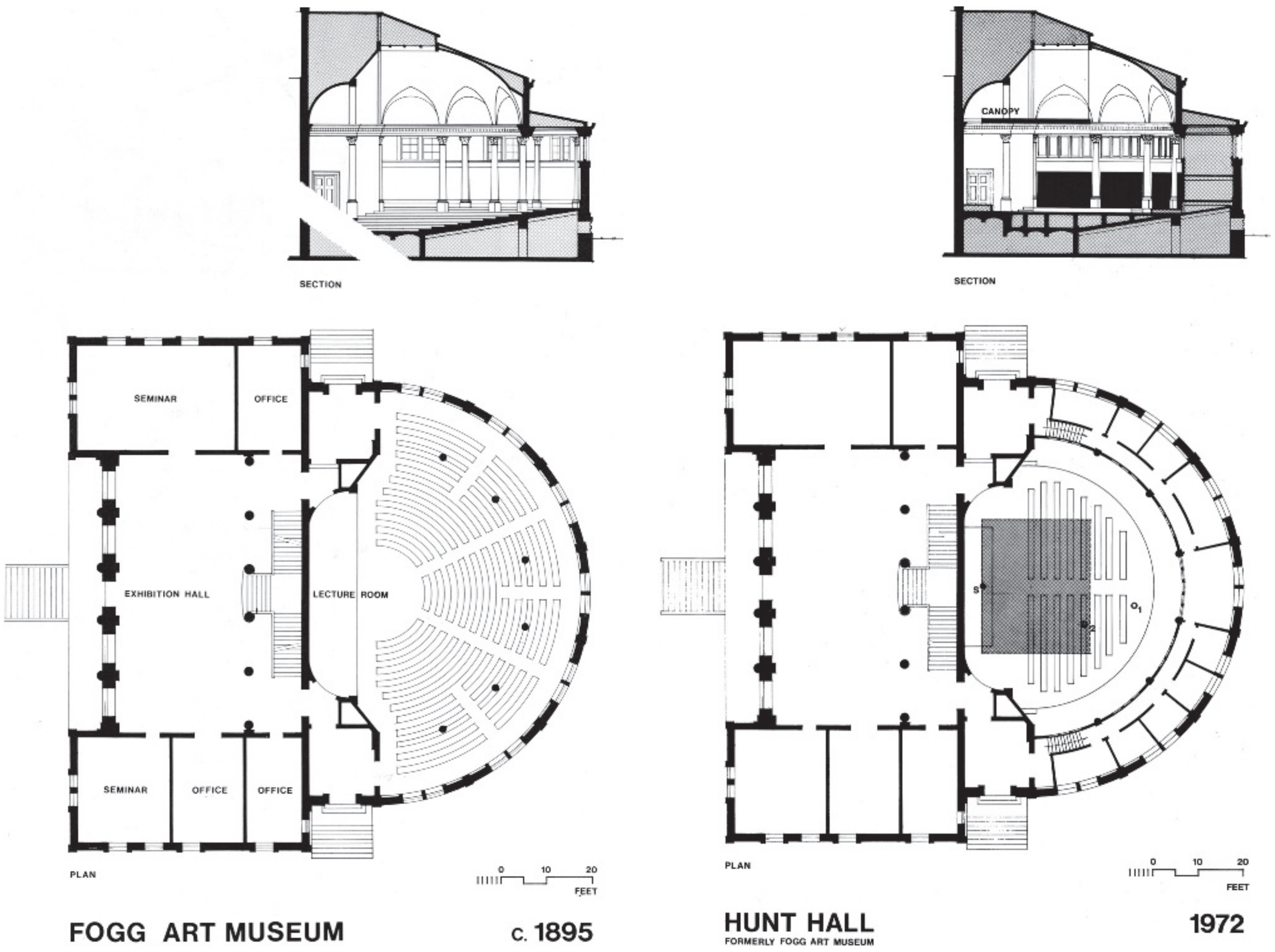
Figure 1.30 Fogg Lecture Hall, showing locations of acoustical treatment recommended by Sabine; seven semicircular recesses in the domed upper wall and eight panels between the lower rear wall. (Courtesy of E. A. Wetherill, AIA, FASA.)

a room to be predicted in advance of construction, Sabine took on a significantly larger challenge in the design of a new concert hall. Boston's Symphony Hall, completed in 1900, still ranks as one of the world's finest orchestral halls. Inevitably, Sabine's research drew him further into exploration of the acoustics of buildings and refinement of methods for the derivation of sound-absorbing properties of materials. This resulted in the use of several organ pipes to derive the sound absorption coefficient (as a percentage of a sabin) for the three octaves above and below 512 Hertz. This method of classifying absorption of materials, used together with the simple equation that Sabine derived for calculating reverberation, remains the universal standard.

SUBSEQUENT HISTORY OF FOGG ART MUSEUM

Aside from the problems of the lecture hall, the design of the museum as a teaching facility had evidently long been a source of unhappiness to its users, so it is likely that by the time Sabine concluded his study the museum director, Edward Forbes, was already laying plans for a new building better suited to his own vision of what a teaching museum should be. Why Sabine's opinion of acoustical improvement of the hall was not shared by others is not known, but in 1911 to 1912 the lecture room size was reduced from more than 400 seats to around 200 by the addition of a new inner wall following the semi-circular arc of the columns. In Forbes's words, "We hope for a . . . roof that does not leak [and] a

FOGG ART MUSEUM LECTURE HALL, HARVARD UNIVERSITY (1895–1973)



(a) (b)

Figure 1.31 Fogg Art Museum with the original 400-seat lecture-hall configuration (left) and final 1972 configuration as Hunt Hall with the 200-seat lecture hall (right). The building was demolished in 1973. (Courtesy of E. A. Wetherill, AIA, FASA.)

medium-sized lecture hall instead of a large one in which you cannot hear."[3]

Sometime in 1913, Forbes proposed the addition of two new wings, creating a symmetrical complex with the original building as the center. However, because this was never funded, the director and supporters turned their attention entirely to the design of a new building. This was opened in 1927 as the new Fogg Art Museum and the old building became an annex to the school of architecture. Few records have been found so far on the lecture room from its 1911–1912 remodeling to 1927. A recent historical study included photographs of the old museum facilities taken in 1926 prior to the move to the new museum. However, no photographs of the lecture hall were included.[4]

In 1935, the year that the Faculty of Design was established, the building was renamed Hunt Hall in honor of its architect. Around this time, a layer of hair felt covered by a perforated asbestos board was installed on the lower two-thirds of the inner wall. Little additional information prior to 1965, when the room was first carpeted, could be elicited either from available documents or former occupants. In 1972, the old museum was returned to the Fine Arts faculty and some inexpensive changes were made to the lecture room. On the recommendation of Professor Robert Newman, a flat canopy was added over the raised lecturer's platform and an eight-foot-high band of highly absorptive material was added around the semicircular inner wall, covering the perforated asbestos board.[5]

A report written in 1973 by one of Newman's students described the acoustical changes in the following manner: Before remodeling, focused reflections from walls and ceiling created locations at which "the sound was reinforced

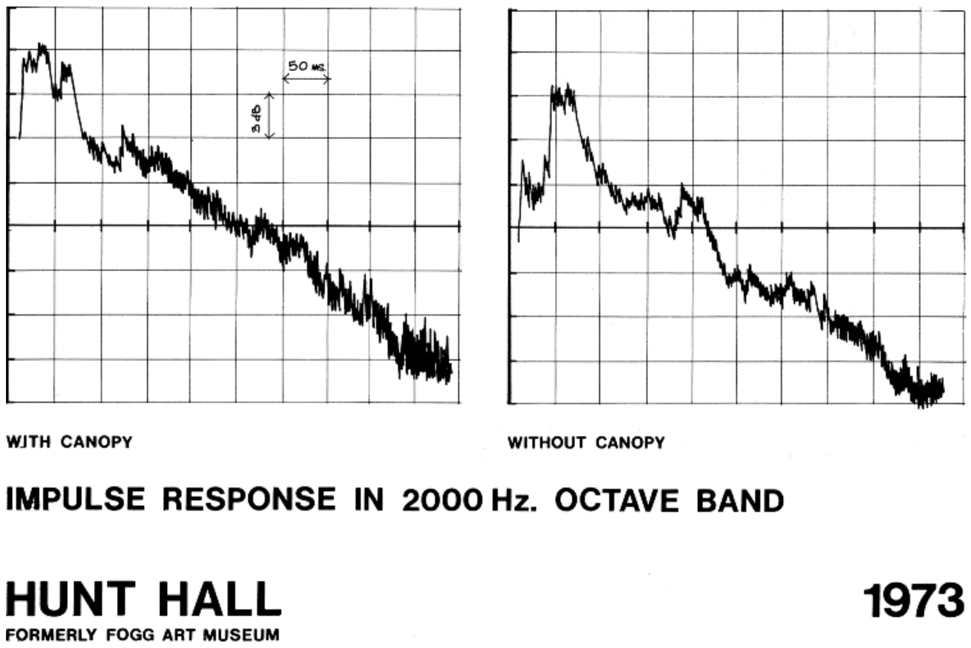


Figure 1.32 Acoustical impulse measurements of Hunt Hall, formerly Fogg Lecture Hall, prior to demolition in 1973. The impulse response with the ceiling canopy in place (left) clearly shows the significant reflected sound energy arriving at a listener's seat during the first 50 milliseconds of the delay, compared to the impulse response without the canopy (right). Note that each vertical division on the graphs represents 3 decibels. (Courtesy of E. A. Wetherill, AIA, FASA.)

making hearing very easy (assuming the speaker did not move). Conversely there were dead spots where hearing was often extremely difficult." After the remodeling, the student report concluded that "Having attended two classes a week since these corrections were made, I can say that the hearing conditions . . . have been drastically improved. A speaker anywhere to the front of the room can be heard clearly throughout the hall."[6] The building was demolished in 1973 to make way for a student dormitory. So, for at least its final year, speech intelligibility in the room was relatively acceptable.

FINAL MEASUREMENTS IN HALL, INVESTIGATION OF AVAILABLE RECORDS, AND COMPUTER STUDY

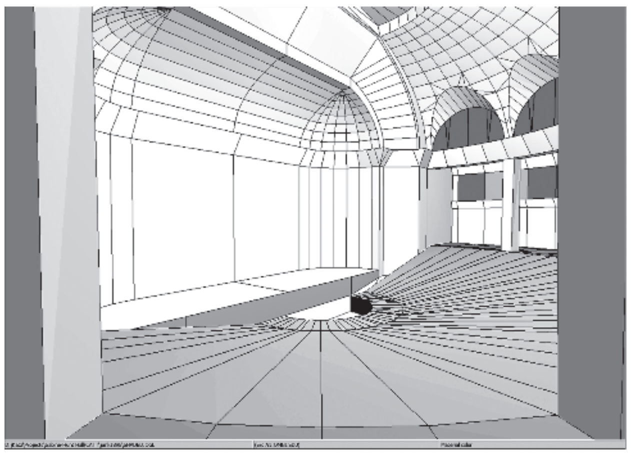
The decision to make some final acoustical measurements in the lecture hall was prompted by a brief news announcement that demolition of the building was planned for the middle of June 1973. In the two-week period between the end of academic occupancy and the start of demolition, two series of acoustical measurements were made, first with the Newman canopy in place and second without it. Samples of sound decay, impulse response, and sound distribution for both conditions were tape-recorded for laboratory analysis. A simple experiment, in which the level of sound from a continuous source at the lecturer's position was plotted from a grid of microphone positions, confirmed the selective focusing of sound reflections from wall and ceiling surfaces.

The accompanying plan and longitudinal section of the lecture room defining the remodeling of 1911–1912 were compiled from tracings of a single blueprint discovered in the Cambridge city hall archives. These drawings and a summary of the final acoustical measurements were compiled in a paper that was presented at the November 1973 meeting of the Acoustical Society of America.

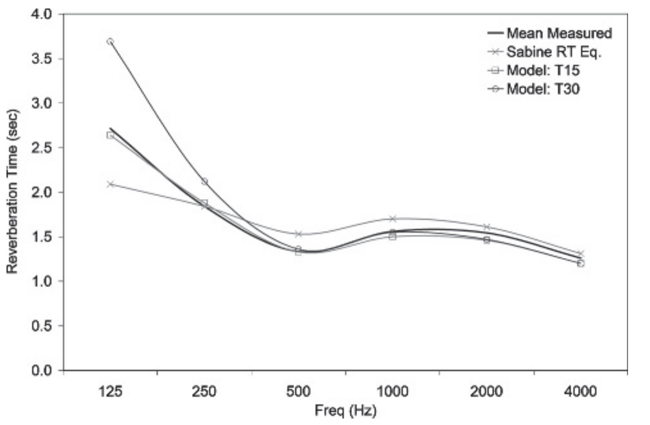
Further information on the lecture hall, including the location of architectural drawings published prior to construction, was received from correspondents who had received a copy of the 1973 paper. These additions were reported in a second presentation at the November 1976 meeting of the Acoustical Society. Little further investigation was undertaken prior to a symposium held in conjunction with the spring 1994 meeting of the Acoustical Society to commemorate the 100th anniversary of Sabine's initial study.

RECENT COMPUTER MODEL OF LECTURE HALL

The use of a computer model of the lecture room for auralization studies received little consideration until early 2005, when it was made the subject of a paper presented at *Forum Acusticum 2005*.[7] This study entailed a detailed analysis of available architectural, photographic, and acoustical information defining the physical properties of the lecture hall. The accuracy of dimensions required to complete the computer model brought to light some discrepancies between available drawings and what could be deduced from photographs, resulting in the final model being based on a combination of dimensions from drawings of various sources. The geometrical model was created using circular and ellipse equations selected for best fit to the architectural drawings, with an estimated surface approximating the fixed seating and original sloped floor.



(a)



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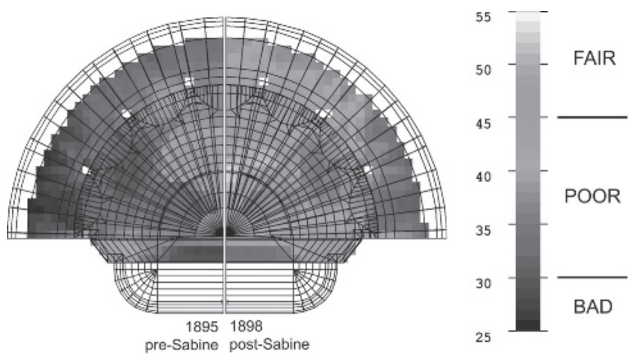

(c)

Figure 1.33 Results from computer studies— a (top) computer image of the original Fogg Lecture Hall; b (lower left) comparison of measured and computer-simulated reverberation times; c (lower right) plan showing speech intelligibility before and after Sabine's corrections. (Courtesy of E. A. Wetherill and B. F. G. Katz.)

Starting with the reduced room size that existed in 1972, the inner wall was then removed to reestablish the original room configuration. A perspective view, created from the same position as the camera in the pre-1911 photograph, shows only minor differences from the original. The shaded wall surfaces are those on which Sabine installed acoustic treatment in 1898. A final comparison of interest shows a difference in room volume, the model volume being approximately 4% smaller than Sabine's estimate.

Sound source and microphone positions used in the final measurements of reverberation were replicated to obtain a comparison with the model values. Some minor adjustments were made to initial assumptions for sound absorption coefficients. The final state of the model, using ray tracing techniques and the traditional Sabine reverberation time calculation, compares closely with measurements made in 1973 in the actual space, as shown in Figure 1.33b. Having calibrated the model against actual measurements, it was then possible to move backwards in time through the series of modifications occurring from 1910 to 1973, finally arriving at the room as Sabine found it in 1895.

The computer model is difficult to interpret in the absence of color printing, so more detailed studies should be continued by referring to the article published in the July 2007 issue of *Acoustics Today,* which, in addition to listing further sources, also presents a clear graphic comparison of speech intelligibility in the original and final room configurations. This is also consistent with the focusing effects noted during the final measurements, confirming the inherent acoustic deficiency of the original lecture hall, which was cited as the major fault of the lecture hall.

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CONCLUSIONS AND POTENTIAL FOR FURTHER INVESTIGATION

The close correlation between actual and computer-simulated results is consistent with the initial thesis, but further comparisons between still-existing spaces and computer models are needed to confirm that this method is appropriate for spaces of all shapes and sizes. It is the hope of the authors that the information made available in *Acoustics Today* will facilitate such studies.

Despite the efforts expended to date, it is tempting to believe that further useful information on the lecture hall still exists in some forgotten archive. For example, it is difficult to believe that someone conversant with the experimental possibilities of photography would not leave a visual record of his unique work. Sabine's biography confirms that in the years following the completion of his study, his increased academic commitments to Harvard University, his own continuing work in acoustics, and, finally, war-related research in the years prior to his untimely death in 1919 left him little time or opportunity to reexamine his seminal study. The hope persists, however, that vastly improved capability for research and communication resulting from computer technology will lead to the eventual discovery of more information.

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4. K. Brush, *Vastly More than Brick & Mortar* (New Haven, Conn.: Yale, 2003).
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6. Ibid., quoting student report, 1973.
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A TIMELINE OF SOME SIGNIFICANT EVENTS IN ARCHITECTURAL ACOUSTICS SINCE SABINE'S PIONEERING WORK AT THE FOGG MUSEUM LECTURE HALL

This timeline is adapted from a commemorative book, *ASA at 75,*[1] prepared in connection with the seventy-fifth anniversary of the founding of the Acoustical Society of America at its 2004 spring meeting in New York City. The idea for forming a society specifically devoted to acoustics had its beginnings on July 30, 1928, when Floyd R. Watson (1873–1974), Vern O. Knudsen (1893–1974), and Wallace Waterfall (1890–1974) met at a Santa Monica beach club near Los Angeles, California. They originally envisioned an organization for engineers working primarily in architectural acoustics. In the fall of 1928 they sent letters to men who were involved in acoustics, proposing the formation of an "American Society of Acoustical Engineers." A second letter was sent on December 10, 1928, to 16 individuals, mostly at universities, asking the recipients and their colleagues to attend an organizational meeting to be held at the Bell Telephone Laboratories at 463 West Street in New York City, where Harvey Fletcher was director of the now-famous Bell Acoustics Research Department. Forty men attended, principally from Bell Labs and commercial organizations in the Greater New York City area. Upon a motion by Floyd Watson, the group voted the official name of the society as "The Acoustical Society of America" and immediately began planning its first technical meeting the following spring in May 1929. Architectural acoustics has from the beginning been a growing and vibrant technical activity of the society, which has become an international organization of more than 7,500 scientists, engineers, architects, materials researchers, and others concerned with all aspects of sound and vibration. Although there is a great deal of overlap, most members have primary or secondary interest in one or more of the society's 13 technical disciplines: Acoustical Oceanography, Animal Bioacoustics, Architectural Acoustics, Biomedical Ultrasound/Bioresponse to Vibration, Engineering Acoustics, Musical Acoustics, Noise, Physical Acoustics, Psychological and Physiological Acoustics, Signal Processing in Acoustics, Speech Communication, Structural Acoustics and Vibration, and Underwater Acoustics.

1900 Opening of Boston Symphony Hall, the world's first hall to be designed using scientifically based architectural acoustics design principles; it is still considered to be one of the world's greatest halls. Wallace Clement Sabine, the acoustical consultant, based his recommendations on his pioneering acoustics research. He is often credited with transforming the understanding of acoustics from a mysterious art to a respected discipline, and is considered by many to be the "father of modern architectural acoustics."

1919 Opening of Riverbank Acoustical Laboratory, Geneva, Illinois, the first commercial laboratory for testing acoustical properties of building materials. Riverbank was designed by Wallace Sabine, who unfortunately died before the laboratory was completed. Riverbank was subsequently directed for several decades by Wallace's cousin, Paul Sabine, and Paul's son, Hale Sabine.

1927 World's first talking movie, *The Jazz Singer*. The advent of "talkies" created the need for proper microphones, sound stages, recording and playback systems, and production and presentation facilities.

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1929 Founding of the Acoustical Society of America, which provided a forum for professionals working in acoustics, including a large and growing contingent in architectural acoustics. Subsequent professional societies included the Audio Engineering Society (founded 1948), the National Council of Acoustical Consultants (founded 1962), and the Institute of Noise Control Engineering (founded 1970).

1941–1945 World War II necessitated solutions for communications, noise control, underwater sound propagation and detection, and many military applications, which mobilized a tremendous pool of talent and eventually led to countless post-WWII applications of acoustical technology.

1948 Founding of Bolt Beranek and Newman, Inc. (BBN), the first acoustical research and consulting firm, initially in response to a variety of acoustical concerns for the new United Nations Headquarters in New York City. The roots of many acoustical consulting firms, research activities of all types, and even computer communication systems can be traced back to BBN.

1957 Establishment of the Wallace C. Sabine Silver Medal, to be awarded by the ASA for outstanding contributions to the science of architectural acoustics.

1960 Formal establishment of the Technical Committee on Architectural Acoustics of the Acoustical Society of America.

1962 Publication of *Music Acoustics and Architecture* (John Wiley & Sons), by Leo L. Beranek. The culmination of extensive research, Beranek's book included a detailed study of 55 concert and opera halls throughout the world, which widely influenced the architectural acoustics community. This book remains a fundamental resource for study and reference and was later updated in two books by Dr. Beranek in 1996 and in 2004.

1982 Publication of *Halls for Music Performance: Two Decades of Experience 1962–1982* (Acoustical Society of America), which pioneered a series of books, based on poster sessions at ASA meetings, featuring particular building types.

1989 Opening of McDermott Concert Hall, Dallas, Texas. Ranking among the world's greatest modern halls, McDermott Hall combined classical shoebox design (similar to Boston Symphony Hall) with modern innovations, such as acoustical variability provided by large reverberation chambers and movable stage-ceiling canopies.

1994 Wallace Sabine Centennial Symposium, held at MIT in conjunction with the 127th annual meeting of the ASA.

2002 Approval of ANSI Standard S12.60-2002, the "classroom acoustics standard," which provides criteria for proper listening conditions. The standard was developed by the TCAA Classroom Acoustics Working Group, based on decades of research and experience on speech intelligibility, absorption of materials, sound isolation, and HVAC and environmental noise control.

2004– Contemporary advances often result from computer-aided modeling and auralization. Though firmly founded on the past century's experience, new developments promise almost unimaginable potential for future development, research, and technology.

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