3j. Architectural Acoustics

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3j-1. Sound-absorptive Materials. When sound waves strike a surface, the energy may be divided into three portions: the incident, reflected, and absorbed energy. Suppose plane waves are incident on a surface of infinite extent. For this case, the absorption coefficient α of the surface may be defined as

$$\alpha = \frac{\int_s \mathbf{I}_p \cdot \mathbf{ds}}{\int_s \mathbf{I}_A \cdot \mathbf{ds}} \tag{3j-1}$$

where I_p is the time average of the intensity vector of the sound field at the absorptive surface, *ds* is the vector surface element—the positive direction being into the material from the incident side, and I_A is the time average of the intensity vector which would exist at the surface element if the surface were removed. The absorption coefficient defined above is a function of angle of incidence and frequency.

For acoustical designing in architecture, it is convenient to employ an absorption coefficient α (at a given sound frequency) which represents an average over all angles of incidence. But α depends also on the area of the absorbent surface; the larger the area of a sound absorber on a wall, floor, or ceiling of a room, the smaller is its sound absorption coefficient. The data for α presented in this section are for measurements made on areas of about 72 sq ft, but we assume these are valid for all areas. A surface of S ft^2 is said to have an absorption of αS sabins. Thus the *sabin* (sometimes called a square-foot unit of absorption) is the absorption equivalent of 1 ft^2 of material having an absorption coefficient of unity.

A quantity which describes the acoustical properties of a material that is more fundamental than absorption coefficient is its *acoustic impedance*, defined as the complex ratio of sound pressure to the corresponding particle velocity at the surface of the material. Because of the complexities involved in the solutions to problems of room acoustics by boundary-value theory in terms of boundary impedances, the simpler concept of absorption coefficient is usually employed in calculating the acoustical properties of rooms, as indicated in the following section.

Most manufactured acoustical materials depend largely on their porosity for their acoustic absorption, the sound waves being converted into heat as they are propagated into the interstices of the material and also by vibration of the small fibers of the material. Another important mechanism of absorption is panel vibration; when sound waves force a panel into motion, the resulting flexural vibration converts a fraction of the incident sound energy into heat.

The average value of absorption coefficient of a material varies with frequency. Tables usually list the values of α at 125, 250, 500, 1,000, 2,000, and 4,000 Hz, or at

128, 256, 512, 1,024, 2,048, and 4,096 Hz, which for practical purposes are identical. In comparing materials which are used for noise-reduction purposes in offices, banks, corridors, etc., it is sometimes useful to employ a single figure called the noise-reduction coefficient (abbreviated NRC) of the material which is the average of the absorption coefficients at 250, 500, 1,000, and 2,000 Hz, to the nearest multiple of 0.05.

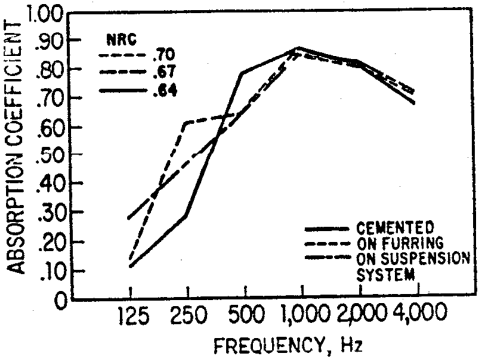

FIG. 3j-1. The absorption vs. frequency characteristic for regularly perforated cellulose fiber acoustical tile. These data represent average values for $\frac{3}{4}$-in.-thick tile, mounted in the same way but of different manufacture. (*After H. J. Sabine, chap.* 18 *in "Handbook of Noise Control," C. M. Harris, ed., McGraw-Hill Book Company, New York,* 1957.)

Figures 3j-1 through 3j-3 give the absorption coefficient vs. frequency for several types of acoustical material.[1] The absorption-frequency characteristics of regularly perforated cellulose fiber tile $\frac{3}{4}$ in. thick is shown in Fig. 3j-1. These curves represent average coefficients for materials of the same type, thickness, and method of mounting but of different manufacture. Similar data are shown in Fig. 3j-2 for fissured mineral tile $\frac{13}{16}$ in. thick. Values of noise-reduction coefficient are shown to the right of the graph. Values of absorption coefficient for various types of building materials are given in Table 3j-1.[1] The equivalent absorption of individuals and seats, expressed in sabins, is given in Table 3j-2. More complete data and data for other types of material are given in the literature.[1,2]

Sound-absorptive materials and structures may be classified in the following way: (1) prefabricated units, including acoustical tile, tile boards, and certain mechanically perforated units backed with absorptive material; (2) acoustical plasters; (3) acoustical blankets, consisting of mineral wool, glass fibers, hair felt, or wood fibers held together in blanket form by a suitable binder; (4) panel absorbers, including panels of plywood, paperboard, and pressed-wood fiber; (5) membrane absorbers consisting of a membrane of negligible stiffness backed by an enclosed air space; (6) resonator absorbers of the Helmholtz type; and (7) special types.

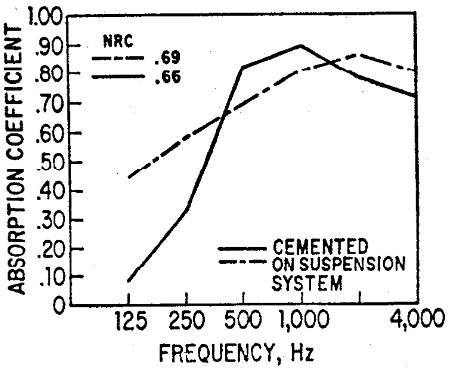

FIG. 3j-2. The absorption vs. frequency characteristic for fissured mineral tile. These data represent average values for $\frac{13}{16}$-in.-thick tile, mounted in the same way but of different manufacture. (*After H. J. Sabine, chap.* 18 *in "Handbook of Noise Control," C. M. Harris, ed., McGraw-Hill Book Company, New York,* 1957.)

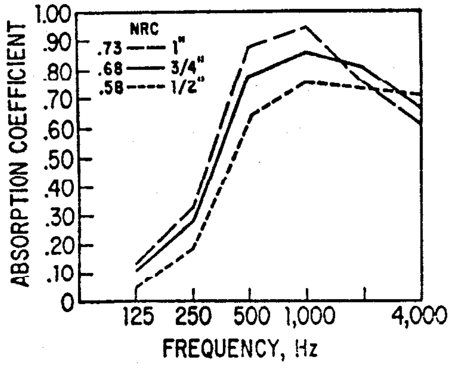

FIG. 3j-3. The absorption vs. frequency characteristic for regularly perforated cellulose fiber acoustical tile which has been spot-cemented to a rigid surface. These data represent the average value for tiles of different manufacture, mounted in the same way and having different thicknesses. (*After H. J. Sabine, chap.* 18 *in "Handbook of Noise Control," C. M. Harris, ed., McGraw-Hill Book Company, New York,* 1957.)

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[1] *Acoust. Materials Assoc., Bull.* XXIX, New York, 1969.

[2] For example, see V. O. Knudsen and C. M. Harris, "Acoustical Designing in Architecture," John Wiley & Sons, Inc., New York, 1950.

Table 3j-1. Absorption Coefficients for Building Materials*

Materials	Frequency, Hz					
	125	250	500	1,000	2,000	4,000
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03
Carpet, heavy, on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Same, on 40-oz hairfelt or foam rubber	0.08	0.24	0.57	0.69	0.71	0.73
Same, with impermeable latex backing on 40-oz hairfelt or foam rubber	0.08	0.27	0.39	0.34	0.48	0.63
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Fabrics:						
Light velour, 10 oz/yd^2 hung straight, in contact with wall	0.03	0.04	0.11	0.17	0.24	0.35
Medium velour, 14 oz/yd^2, draped to half area	0.07	0.31	0.49	0.75	0.70	0.60
Heavy velour, 18 oz/yd^2, draped to half area	0.14	0.35	0.55	0.72	0.70	0.65
Floors:						
Concrete or terrazzo	0.01	0.01	0.015	0.02	0.02	0.02
Linoleum, asphalt, rubber, or cork tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Wood	0.15	0.11	0.10	0.07	0.06	0.07
Wood parquet in asphalt on concrete	0.04	0.04	0.07	0.06	0.06	0.07
Glass:						
Large panes of heavy plate glass	0.18	0.06	0.04	0.03	0.02	0.02
Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04
Gypsum board, $\frac{1}{2}$ in. nailed to 2 × 4's 16 in. o.c	0.29	0.10	0.05	0.04	0.07	0.09
Marble or glazed tile	0.01	0.01	0.01	0.01	0.02	0.02
Openings:						
Stage, depending on furnishings	0.25–0.75					
Deep balcony, upholstered seats	0.50–1.00					
Grills, ventilating	0.15–0.50					
Plaster, gypsum or lime, smooth finish on tile or brick	0.013	0.015	0.02	0.03	0.04	0.05
Plaster, gypsum, or lime, rough finish on lath	0.02	0.03	0.04	0.05	0.04	0.03
Same, with smooth finish	0.02	0.02	0.03	0.04	0.04	0.03
Plywood paneling, $\frac{3}{8}$ in. thick	0.28	0.22	0.17	0.09	0.10	0.11
Water surface, as in a swimming pool	0.008	0.008	0.013	0.015	0.020	0.025

* From *Acoust. Materials Assoc. Bull.* XXIX, New York, 1969.

Some tables list the "ceiling attenuation factor" of acoustical materials designed for use in suspended ceilings. This factor is a measure of the reduction of sound level between two contiguous rooms when the transmission path of the sound is through the two suspended ceilings and the plenum common to both.

3j-2. Reverberation-time Calculations. After sound has been produced in or enters an enclosed space, it will be reflected by the boundaries of the enclosure.

Although some energy is lost at each reflection, several seconds may elapse before the sound decays to inaudibility. This prolongation of sound after the original source has stopped is called *reverberation*, a certain amount of which is found to add a pleasing characteristic to the acoustical qualities of a room. On the other hand, excessive reverberation can ruin the acoustical properties of an otherwise well-designed room.

TABLE 3j-2. ABSORPTION OF SEATS AND AUDIENCE*
(In sabins per person or unit of seating)

	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz
Audience, seated in upholstered seats...	3.3	4.1	4.8	5.3	5.1	4.7
Unoccupied seats, cloth-covered, upholstered..........................	2.7	3.6	4.4	4.8	4.5	3.9
Unoccupied seats, leather-covered, upholstered..........................	2.4	3.0	3.3	3.4	3.2	2.6
Wooden pews, occupied...............	3.1	3.4	4.1	4.7	5.0	4.7
Chairs, metal or wood seats...........	0.15	0.19	0.22	0.39	0.38	0.30

* Based on values given in *Acoust. Materials Assoc. Bull.* XXIX, New York, 1969, modified by author. Materials and methods of fabrication can greatly influence the above values.

Because of the importance of the proper control of reverberation in rooms, a standard of measure called *reverberation time* (abbreviated t_{60}) has been established. It is one of the important parameters in architectural acoustics. This is the time required for a specified sound to die away to one-thousandth of its initial pressure, a drop in sound pressure level of 60 dB. It is given by the following equation:

$$t_{60} = \frac{0.049V}{S\bar{\alpha} + 4mV} \quad \text{sec} \tag{3j-2}$$

where V = volume of the room, ft^3
S = total surface area, ft^2
$\bar{\alpha}$ = average absorption coefficient given by

$$\bar{\alpha} = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \cdots}{S_1 + S_2 + S_3 + \cdots} = \frac{a}{S} \tag{3j-3}$$

α_1 = absorption coefficient of area S_1, etc.
a = total absorption in the room, sabins

The quantity m is the attenuation coefficient for air given by Fig. 3d-6. For relatively small auditoriums and frequencies below 2,000 Hz, the mV term can usually be neglected so that Eq. (3j-2) reduces to

$$t_{60} = \frac{0.049V}{S\bar{\alpha}} \quad \text{sec} \tag{3j-4}$$

3j-3. Optimum Reverberation Time. A certain amount of reverberation in a room adds a pleasing quality to music. Since the reverberation time one would consider to be optimum is a matter of personal preference, it is not a quantity that can be calculated from a formula. On the other hand, useful engineering-design data can be obtained from a critical evaluation of empirical data based upon the preference evaluations of large groups of individuals. The results of such information from all available sources considered reliable, in this country and abroad, have been carefully evaluated by Knudsen and Harris,[1] who have published the curves for optimum

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[1] *Ibid.*

reverberation time shown in Figs. 3j-4 and 3j-5. The data in Fig. 3j-4 give the optimum reverberation times at 500 Hz as a function of volume for rooms and auditoriums that are used for different purposes. Since the optimum reverberation time for music depends on the type of music, it is represented by a broad band. The optimum reverberation time for a room used primarily for speech is considerably shorter; a reverberation time longer than those shown results in a decrease in speech intelligibility.

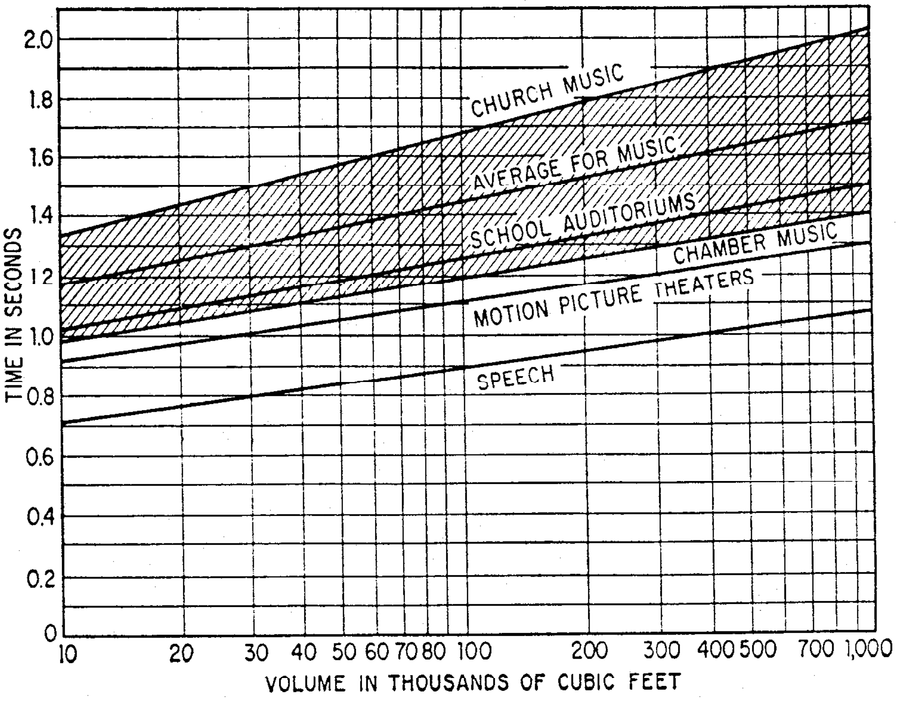

FIG. 3j-4. Optimum reverberation time at 500 Hz for different types of rooms as a function of room volume. This figure should be used in conjunction with Fig. 3j-5 to obtain optimum reverberation time as a function of frequency. (*After V. O. Knudsen and C. M. Harris, "Acoustical Designing in Architecture," John Wiley & Sons, Inc., New York,* 1950.)

The optimum reverberation times at frequencies other than 500 Hz are obtained by multiplying the values given in Fig. 3j-4 by the ratio R from Fig. 3j-5 for the desired frequency. These data indicate that below 500 Hz the optimum reverberation time may fall anywhere in a wide range shown by the crosshatched band; smaller rooms usually have preferred ratios that are in the lower part of the band.

3j-4. Structure-borne Sound Transmission. Noise in a building may originate from sources in air, it may be generated by impacts against the building structure, or it may result from mechanical vibration imparted to the building structure. The transmission path from one location in the building to another may be by either one, or a combination, of the following mechanisms: (1) sound may be transmitted along a direct air path, for example through a ventilation duct from one room to the next; (2) mechanical energy may be imparted to the structure; such energy then travels through the structure (usually with relatively little attenuation) to surfaces elsewhere in the building which it sets into vibration, thereby radiating noise; or (3) sound may force a partition into vibration, thereby transmitting acoustic energy into an adjacent room.

Sound also may be transmitted from one room to an adjacent room by a path other than through the common intervening partition, for example, along other walls or along the floor or ceiling. Such indirect transmission of sound is called *flanking transmission.*

Structures that provide good isolation against airborne noise do not necessarily provide good isolation against structure-borne noise. In general, structure-borne sound insulation techniques are designed to prevent vibratory energy from entering the building structure, for example, by the use of resilient flooring, carpeting, or "floating floor" constructions.

Data giving the structure-borne noise insulation values of many types of floor and ceiling constructions are given by Berendt[1] et al.

3j-5. Air-borne Sound Transmission through Partitions. The fraction of incident sound energy transmitted through a partition is called its transmission coefficient τ.

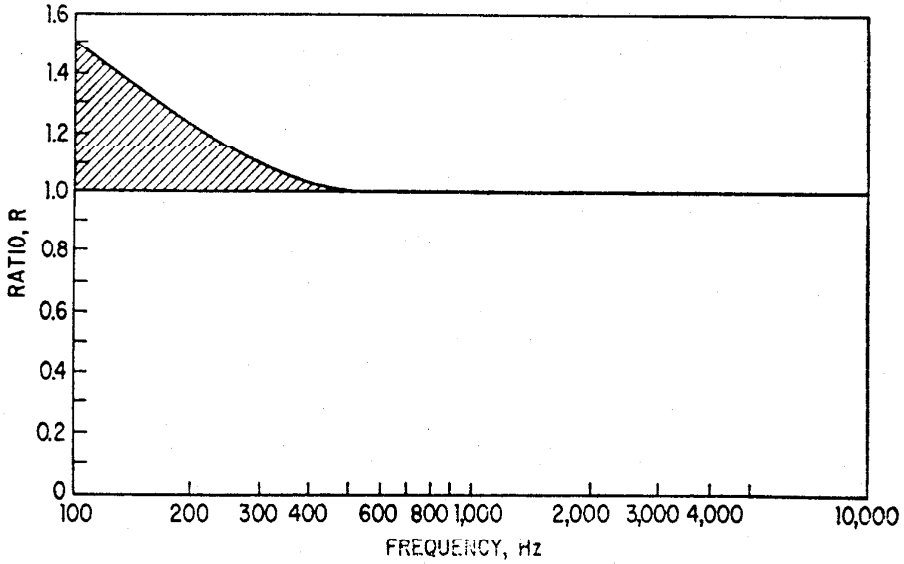

FIG. 3j-5. Chart for computing optimum reverberation time as a function of frequency. The time at any frequency is given in terms of a ratio R which should be multiplied by the optimum time at 500 Hz (from Fig. 3j-4) to obtain the optimum time at that frequency. (*After V. O. Knudsen and C. M. Harris, "Acoustical Designing in Architecture." John Wiley & Sons, Inc., New York,* 1950.)

In rating the noise-insulating value of partitions, windows, and doors, it is generally convenient to employ a logarithmic quantity, transmission loss T.L., which is equal to the number of decibels by which sound energy that is incident on a partition is reduced in transmission through it. The two quantities are related by the equation

$$\text{T.L.} = 10 \log \frac{1}{\tau} \quad \text{dB} \qquad (3j\text{-}5)$$

Air-borne sound is transmitted through a so-called "rigid" partition, such as a wall of concrete or brick, by forcing it into vibration; then the vibrating partition becomes a secondary source, radiating sound to the side opposite the original source. Over a large portion of the audible range, such a partition, on the average, approximates a mass-controlled system so that its transmission loss should increase 6 dB each time the weight of the partition is doubled. In most actual partitions the increase is usually less, say 4 to 5 dB for the average frequency range between 125 and 2,000 Hz. This is illustrated by Fig. 3j-6, which gives the transmission loss (averaged over

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[1] R. D. Berendt, G. E. Winzer, and C. B. Burroughs, "A Guide to Airborne, Impact, and Structure Borne Noise-Control in Multifamily Dwellings," U.S. Department of Housing and Urban Development, Washington, D.C., September, 1967.

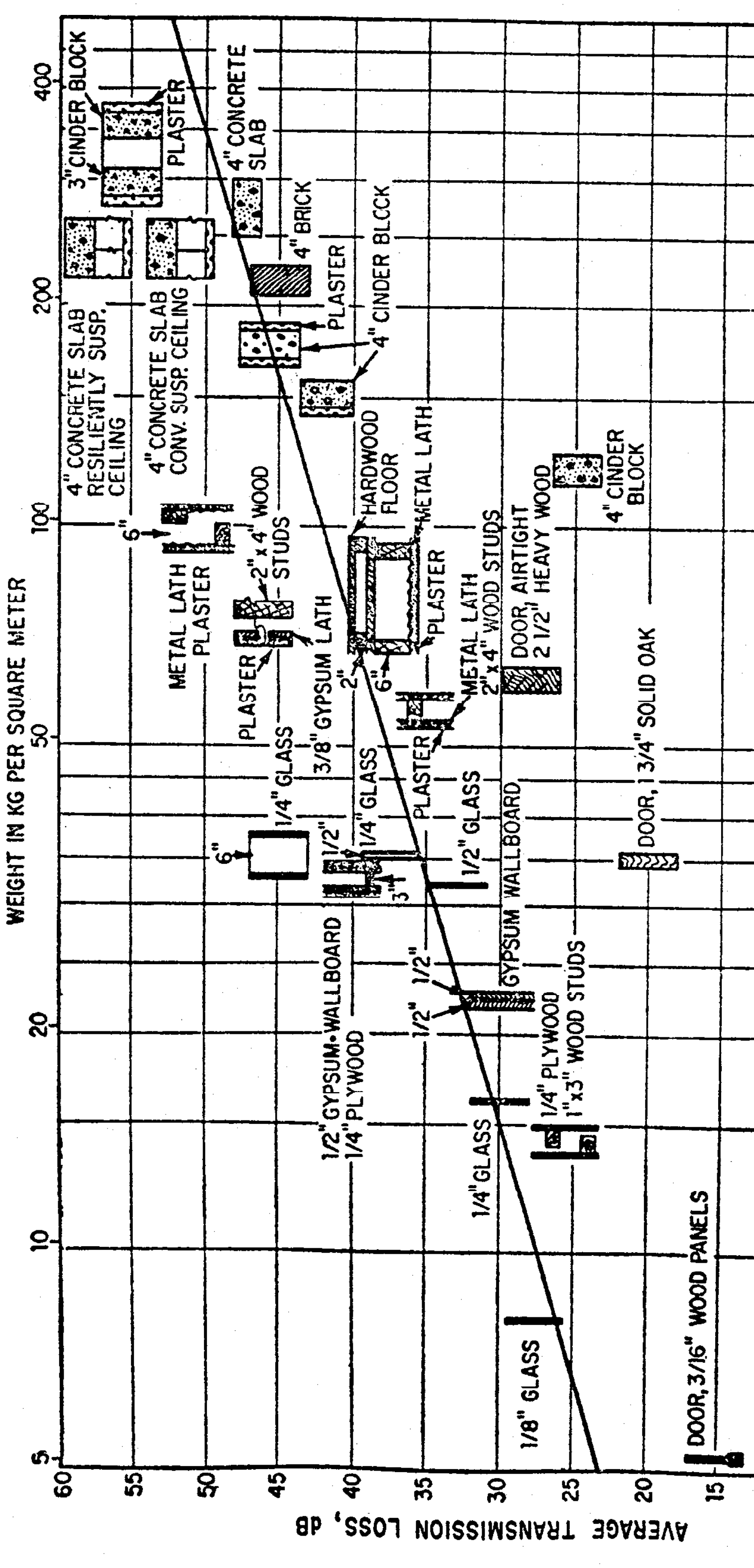

FIG. 3j-6. The mass-law relation between average sound transmission loss and mass per unit area of a homogeneous partition. The transmission loss, expressed in decibels, is averaged over the frequency range from 125 to 4,000 Hz. (*R. K. Cook and P. Chrzanowski, from C. M. Harris, ed., "Handbook of Noise Control," chap. 20, McGraw-Hill Book Company, New York,* 1957.)

frequency in the range from 125 to 4,000 Hz) as a function of weight of the partition in pounds per square foot of surface area. The straight line represents an average of the experimental data showing that the average transmission loss increases approximately 4.4 dB for each doubling of mass per unit area of a homogeneous partition. The transmission loss for a partition is not constant with frequency, increasing usually 3 to 6 dB/octave.

A single number which represents the sound transmission loss of a partition averaged over frequency may correlate rather poorly with the subjective assessment of the insulation value of the partition. Therefore another rating is frequently employed to represent the sound insulation value of a partition by a single number: "sound transmission class" (STC). The STC value of a partition is determined by comparing the curve of transmission loss vs. frequency for the partition with a set of standardized transmission loss vs. frequency contours.[1]

Sound insulation values for various types of walls and floors employed in ordinary building construction are given in Table 3j-3. Note that a compound-wall construction can yield relatively high sound insulation with relatively low mass per unit wall area. The double-wall construction is one such example. It is important that the separation between the walls be as complete as possible—structural ties will greatly reduce the effectiveness of such a structure.

3j-6. Noise Level within a Room. The sound level of noise which is transmitted into a room from the outside depends on (1) the noise-insulating properties of its bounding surfaces, (2) the total absorption in the room, and (3) the characteristics of the noise source. The following formula gives a rating of the overall noise reduction provided by the enclosure. It represents, approximately, the difference between the noise level outside a room and the noise level inside a room.

$$\text{Level difference} = 10 \log \frac{a}{T} \quad \text{dB} \tag{3j-6}$$

where a represents the total absorption in the room in sabins defined by Eq. (3j-4), and T represents the total transmittance of the enclosure given by

$$T = \tau_1 S_1 + \tau_2 S_2 + \tau_3 S_3 + \cdots \tag{3j-7}$$

where τ_1 is equal to the transmission coefficient of area S_1, etc.

If a source of noise is within a room, then at distances near to the source the sound pressure decreases inversely with increasing distance from the source: there is a decrease in sound pressure level of 6 dB for each doubling of the distance from the source, just as if the source were in the open air. However, at every point in the room there will be an additional contribution to the total pressure as a result of reflections from the walls. As one recedes from the source, the reflected contributions become more and more important until direct sound from the source becomes negligible by comparison.

Then if the sound field is diffuse (perfect diffusion is said to exist if the sound pressure everywhere in the room is the same, and it is equally probable that the waves are traveling in every direction), the sound pressure level in the room will be given approximately by

$$L_p = 10 \log \frac{W}{a} + 136.4 \quad \text{dB} \tag{3j-8}$$

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[1] R. D. Berendt, G. E. Winzer, and C. B. Burroughs, "A Guide to Airborne, Impact, and Structure Borne Noise-Control in Multifamily Dwellings," U.S. Department of Housing and Urban Development, Washington, D.C., September, 1967. See also *ASTM Rept.* E90-66T, Tentative Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions.

TABLE 3j-3. INSULATION VALUES FOR VARIOUS TYPES OF WALL AND FLOOR CONSTRUCTION*

Type of construction	Weight, lb/ft²	STC rating, dB	Transmission Loss, dB								
			125 Hz	175 Hz	250 Hz	350 Hz	500 Hz	700 Hz	1,000 Hz	2,000 Hz	4,000 Hz
Solid concrete, 3 in. thick	30	47	35	37	40	41	44	49	52	59	64
Solid concrete, 6 in. thick, both sides plastered	80	53	39	42	42	47	50	55	58	64	
Hollow concrete block, 6 in. thick	34	43	32	33	33	37	40	43	47	51	48
Same as above except painted	34	45	37	35	36	39	42	47	49	55	58
Hollow gypsum block, 3 in. thick, one side plastered, other side plaster on resilient clips	27	45	48	43	41	43	47	48	44	55	62
Double brick wall, 6 in. cavity. Overall thickness 18 in.	120	62	48	54	54	56	56	60	64	69	
Wood stud, gypsum wallboard	6	38	20	21	27	33	37	38	43	48	43
Wood stud, gypsum lath and plaster	15	46	32	34	37	40	42	46	48	48	63
Same as above but with perforated lath	14	44	42	34	32	38	42	47	49	50	62
Staggered wood stud, gypsum board and insulation	14	46	39	38	40	41	42	44	48	56	51
Wood stud, plastered gypsum lath on resilient clips	13	52	46	44	46	53	54	56	57	50	62
Metal channel stud, gypsum board	5	39	20	24	30	33	37	43	47	48	44
Metal channel stud, 2 layers of gypsum board	9	47	31	35	38	41	45	51	53	54	54

* Values based on data taken from R. D. Berendt, G. E. Winzer, and C. B. Burroughs, "A Guide to Airborne, Impact, and Structure Borne Noise-Control in Multifamily Dwellings," U.S. Department of Housing and Urban Development, Washington, D.C., September, 1967. For average values for other types of construction including doors and windowpane materials, see Fig. 3j-6. For the definition of STC used to obtain the ratings (above), see *ASTM Rept.* E90-66T, Tentative Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Walls and Floors.

if a value of $\rho c = 40.8$ rayls is assumed for air; W = power of the sound source in watts, and a = total absorption of the room in sabins. A consideration of the above formula shows that, if the acoustic-power output of the noise source remains constant, and if the total absorption in the room is increased from a_1 to a_2, the reduction in noise level is given by

$$\text{Noise reduction} = 10 \log \frac{a_2}{a_1} \quad \text{dB} \qquad (3j\text{-}9)$$

According to this equation, which should be regarded as an engineering approximation to actual conditions, if the absorption in a room is increased by a factor of 4, the noise reduction will be 6 dB. It shows that the addition of absorption in a room will provide substantial noise reduction in average level in a room that is relatively bare but little decrease in level in a highly damped room. The reduction will be different at different frequencies since the total absorption is a function of frequency. However, it is sometimes convenient to employ the noise-reduction coefficient of a material to obtain a single noise-reduction figure. Besides reducing the steady-state noise level, the addition of absorptive treatment in a room also provides beneficial effects by reducing the reverberation time in the room and by localizing the source of noise to the area in which it originates—thereby minimizing unexpected noises.

TABLE 3j-4. RECOMMENDED ACCEPTABLE AVERAGE NOISE LEVELS IN UNOCCUPIED ROOMS*

	Decibels†
Radio, recording, and television studios	25–30
Music rooms	30–35
Legitimate theaters	30–35
Hospitals	35–40
Motion-picture theaters, auditoriums	35–40
Churches	35–40
Apartments, hotels, homes	35–45
Classrooms, lecture rooms	35–40
Conference rooms, small offices	40–45
Courtrooms	40–45
Private offices	40–45
Libraries	40–45
Large public offices, banks, stores, etc	45–55
Restaurants	50–55

* V. O. Knudsen and C. M. Harris, "Acoustical Designing in Architecture," John Wiley & Sons, Inc., New York, 1950.

† The levels given in this table are "weighted"; i.e., they are the levels measured with a standard sound-level meter employing the "A" (40-dB) frequency-weighting network.

3j-7. Acceptable Noise Levels for Various Types of Room. Table 3j-4 gives values of recommended acceptable average noise levels for unoccupied rooms with the ventilation system in operation. These values often are used for design purposes, for example, in computing the amount of overall noise insulation that should be provided for a room. Although even lower noise levels than those which are listed may provide some advantage under certain circumstances and may be desirable if cost is not a factor, this table gives values which represent a combination of acceptability and economic practicality. For certain types of room the values which are recommended are lower than those which are commonly found.

The single numbers given in Table 3j-4 represent "weighted" sound pressure levels. In another system for rating noise conditions in a room a single number is obtained by comparing the octave-band spectrum of the room noise with a set of octave-band level curves called "noise criterion" or "NC" curves. In many cases, description by a single number will not suffice. Then the noise spectra must be expressed in terms of octave-band levels.