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SOUND-INSULATION RATINGS AND THE NEW ASTM SOUND-TRANSMISSION CLASS

BY

T. D. NORTHWOOD

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Sound-Insulation Ratings and the New ASTM Sound-Transmission Class

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A survey is made of past and present systems for rating the sound-insulation value of building walls and floors. It is observed that in most countries ratings based on "average" transmission losses have been replaced by systems that compare transmission-loss characteristics with a standard contour. An example of this approach is the new sound-transmission class contained in ASTM E90-61T. This is discussed from various theoretical and practical viewpoints, and it is concluded that the sound-transmission class is a useful rating system for common architectural problems.

THE sound-insulation requirement for a partition depends on the occupancies it separates; more explicitly, it depends on the magnitude and frequency distribution of the noise produced on one side of the partition and the amount of intruding noise that will be tolerated on the other. In rare instances, the character of the noise may be predictable and constant, and the tolerance level of transmitted noise may be accurately specified. Then it may be possible to specify in a straightforward way the detailed transmission-loss requirements as a function of frequency. But more typical is the problem of designing an apartment or office building, where the required sound insulation varies widely with the individual occupants and their activities of the moment. Here the architect and his client need a simple figure of merit that will help them provide enough sound insulation to satisfy most of the building occupants most of the time.

It is the purpose of this paper to examine the problem of providing such a figure of merit, and in particular to describe the recently developed *Sound Transmission Class*, which appears in the revised standard ASTM E90-61T.[1]

The sound transmission class was designed primarily for assessing the sound-insulation value of walls and floors for use between dwelling units in apartment buildings and similar structures. It also has application in hotels, hospitals, schools, and other situations where the requirements are similar in character, though not necessarily in degree, to those encountered between dwellings. For partitions between offices it is usual to require only that transmitted speech be unintelligible. This suggests an approach slightly different from the dwelling problem, but the sound transmission class is again found to be a useful rating system.

The new classification system is an intermediate stage between the physical measurement of sound-transmission loss and the specification of minimum requirements for separating various occupancies. It might be noted that similar criteria are used in Britain and several European countries for specifying minimum requirements for dwelling separations. In Britain they constitute a *recommended* standard but in most other cases they are mandatory provisions of building codes. Actual minimum requirements are beyond the scope of the present paper and of ASTM E90-61T. Nevertheless, it is hoped that this discussion of the theoretical and practical bases of sound-insulation requirements will lead first to the general use of the sound transmission class as a rating system and ultimately to its use as the basis of minimum standards.

EMPIRICAL APPROACHES

For many years, both here and in Europe, the commonly used rating was the arithmetic average of the transmission losses in decibels measured at a specified series of test frequencies. On this continent the standard method of test, described in ASTM E90-55 and its counterpart American Standard Z24.19-1957, used the arithmetic average of the transmission losses measured at the nine frequencies 125, 175, 250, 350, 500, 700, 1000, 2000, and 4000 cps. Two objections have been raised to the use of such an average as a figure of merit: (1) it gives equal weight to all test frequencies regardless of their importance in sound-insulation problems (although by including the half-octaves below 1000 cps the U. S. nine-frequency average gives extra weight to the low-frequency range); (2) it gives equal weight to both high and low transmission losses, as if superlatively high values at some frequencies could compensate for deficiencies at other frequencies.

Attempts to meet the first objection have led to the introduction of several other "averages," obtained by altering the selection of frequencies included in the average. There is sometimes good reason for concentrating on a special frequency range but unfortunately it is rarely made clear, especially in trade literature, when or why a nonstandard average is being employed. As one step in producing an orderly presentation of information ASTM E90-61T now requires that only the "average" reported be the nine-frequency average, and that it be so labeled.

The second objection is based on the premise that a partition is no better than its lowest transmission loss. It led on this continent to the development of the "energy average,"[2] obtained by averaging the trans-

[1] ASTM E90-61T, "Tentative recommended practice for laboratory measurement of airborne sound transmission loss of building walls and floors" (American Society for Testing and Materials, 1916 Race Street, Philadelphia, 1961).

[2] R. V. Waterhouse, J. Acoust. Soc. Am. 29, 544 (1957).

mission coefficients corresponding to the transmission losses and then taking the decibel equivalent of the average transmission coefficient. Such an average is dominated by the lowest values of transmission loss. Unfortunately, the lowest values are almost always at the lowest test frequencies, which are usually the least important in the evaluation of partition performance. Moreover, even in the laboratory it is difficult to make precise measurements of sound-transmission loss at the lowest test frequencies; thus, the energy average is usually based on the least reliable measurements.

Clearly, no simple average, or even a complicated one such as the energy average, can properly rate the performance of a partition unless it takes into account the variation of transmission loss with frequency. The usefulness of simple averages in the past may be attributed to the fact that the massive structures that predominated had rather simple transmission-loss curves, all rising in a similar way with frequency. But the present use of lightweight structures has resulted in both lower and more irregular transmission-loss curves, and necessitates a criterion that is more closely related to actual performance requirements.

Subjective Reactions and Standard Contours

In at least three countries, Holland, Sweden, and Britain, the dwelling separation requirement was investigated directly by canvassing the tenants of apartment buildings and row dwellings.[3–5] Each of the surveys was conducted without knowledge of the others, and it is of interest to examine the points of agreement and disagreement among their conclusions.

The British and Dutch surveys showed that noise from the floor above constituted the greatest disturbance, apparently because of the special importance of impact sounds such as footsteps and children playing. The Swedish survey also showed the importance of transmission through floors, but did not indicate that impact noise was as serious a problem as airborne sound. Nevertheless, current British and European standards, including the Swedish one, deal with both impact and airborne sound. On this continent there is as yet no standard test method for impact (although one is now being considered by ASTM Committee E-6). Hence this paper deals only with the airborne-sound problem, despite the evident importance of impact transmission.

The Swedish sample included similar structures located on noisy thoroughfares and on quiet residential streets. As might be expected these showed an inverse relationship between disturbance from traffic and disturbance from adjacent dwellings; the more tenants were disturbed by traffic noise, the less they were disturbed by noise from their neighbors.

Correlation of tenant disturbance and airborne-sound insulation was in general very complex. For example, it is difficult to distinguish between reactions to airborne and impact sounds; tenants dissatisfied with one aspect of their dwellings tend to express dissatisfaction with other aspects; a tenant's past experience with very inferior housing may cause him to comment favorably on a slightly less inadequate environment; and of course there is the complicating effect of traffic noise, discussed in the foregoing. Nevertheless, both the British and the Swedish surveys showed a definite reduction in complaints for increased airborne-sound insulation. The Netherlands study, which involved seven different types of structure, yielded little correlation between tenant reactions and sound insulation.

The British survey included two main types of floor structure for which the transmission-loss characteristics were similar, with averages of 49 and 44 db.[6] In the 49-db structures, 22% of the tenants complained about noise problems, and noise was about equivalent to other sources of complaint. In the 44-db structures, 36% of the tenants complained about noise, and noise was the major complaint. These two transmission-loss characteristics, somewhat idealized, form the bases of the grade I and grade II curves shown in Fig. 1. They constitute recommended minimum values for party walls and floors in certain classes of apartments.[7]

The sound-insulation data from the three surveys are shown in Fig. 2, in which the abscissa is the ASTM sound-transmission class, which is described later; for the moment, it can be taken as roughly equivalent to average transmission loss. The results serve mainly to indicate the order of sound insulation required for acceptable dwelling separation. The one anomalous point in the British results was for a new block of apartments whose tenants were mostly refugees from a condemned-housing area; they are therefore not a representative sample. Some information was gleaned from the Dutch results by discarding two structural types for which impact insulation was exceptionally low, and by separating the rest into two groups with high and low insulation. Despite these cautionary remarks, the

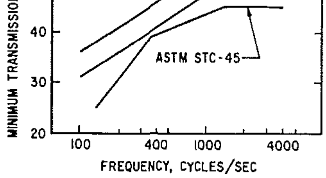

FIG. 1. British recommended minimum requirements for airborne-sound insulation between apartment dwellings. (A sound transmission class contour is shown for comparison.)

[3] C. Bitter and P. Van Weeren. "Sound nuisance and sound insulation in blocks of dwellings I," Rept. No. 24, Research Institute for Public Health Engineering T.N.O. (1955).
[4] O. Brandt and I. Dalén. Byggmästaren **31**, 145 (1952).
[5] P. G. Gray, A. Cartwright, and P. H. Parkin, "Noise in three groups of flats with different floor constructions," National Building Studies Research Paper No. 27, H.M.S.O. (1958).

[6] The standard European average is based on measurements at third-octave intervals from 100 to 3200 cps.
[7] *British Standard Code of Practice*, Chap. III: "Sound insulation and noise reduction," British Standards Institution (1960).

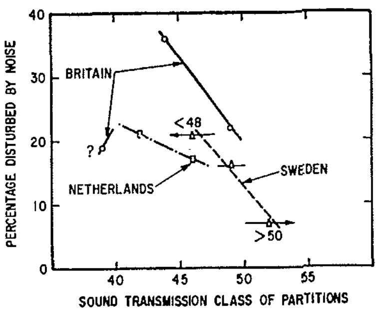

FIG. 2. Results of three surveys to determine the acceptability of existing sound insulation between apartment dwellings.

results suggest that a sound transmission class 45 is borderline for reasonably satisfactory sound insulation, and that a sound transmission class 55 represents about the maximum value that is worth attempting for ordinary housing.

A similar set of rating curves (Fig. 3) was incorporated in the German standard DIN 52211.[8] The same shape was subsequently adopted also by the Scandinavian countries as the basis of sound-insulation requirements for row-dwelling and apartment buildings.[9,10] The DIN curves, also based on the characteristics of actual walls, differ from the British curves in requiring slightly greater transmission loss in the middle frequencies (300 to 1000 cps) and slightly less at lower frequencies. It is to be noted that the standard requires a slightly higher value (2 db) for a laboratory test than for a field test. The difference is an allowance mainly for flanking transmission.

The use of a standard curve rather than a simple arithmetic average is based on the hypothesis that the transmission-loss requirement varies in a certain way with frequency and must therefore be specified for each frequency band. The direct evidence concerning the contribution of each band is rather sketchy although there are theoretical reasons for supporting this view. In a survey of occupants of row dwellings, the British were able to compare a 9-in. solid-brick wall with an 11-in. cavity wall; they found little superiority for the latter despite the fact that its average transmission loss was 5 db better. It was concluded that the lower and middle frequencies, for which there was little difference between the walls, were more critical than the high frequencies for which the superior transmission loss of the 11-in. wall is most evident. The transmission loss is presumably high enough at high frequencies in either case. Both walls just meet the British grade I requirement.

More extensive information is provided by the experiments of Rademacher,[11] who simulated wall-transmission characteristics electrically and had 20 subjects determine the subjective reduction in loudness provided by various transmission characteristics. For noise sources he used samples of music and speech (garbled to eliminate meaning) and several spectra of filtered white noise. His principal noise samples, including speech, music, and one sample of white noise, each had a broad maximum in the frequency range 200 to 800 cps.

Starting with the German DIN curve, he investigated the effect of decreasing the attenuation by 10 db in one octave band, as compared to a uniform attenuation over five octaves. He found that the 10-db decrease in one octave was equivalent to 1 to 4 db over five octaves, the greatest effect being, as might be expected, in the range of highest source power. In another series of tests, he compared four attenuation curves of different shapes, each corresponding to an average transmission loss of 48 db. One characteristic corresponded to the DIN curve, the second increased at 3 db per octave, the third increased at 6 db per octave, and the fourth had a plateau characteristic extending to 800 cycles and then a sharp increase in attenuation. The first three were rated subjectively at about 48 db (when tested with speech or music), but the fourth was rated at only 37 db. This result might be anticipated since only the fourth wall differed substantially in the range of maximum source power. Rademacher dismissed this fourth characteristic as physically unreal and concluded that a simple arithmetic average is adequate for rating most structures. Actually it is similar to many lightweight partitions, and it is to protect against transmission curves of this type that the standard curves were introduced.

Although the British and European standards emphasize the importance of the shape of the transmission-loss curve, they compromise somewhat in their interpretation of actual transmission characteristics. Generally, an average deficiency of 1 db (in some cases 2 db) is allowed relative to the prescribed curve. In both cases, the deficiency might conceivably take the form of a large deviation in a limited frequency band. It is commented[8] that this averaging arrangement is adopted in the absence of sufficient information about the contribution of individual narrow bands. In any case,

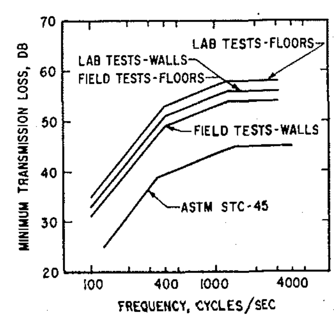

FIG. 3. German minimum requirements for airborne-sound insulation between apartment dwellings. (A sound-transmission class contour is shown for comparison.)

[8] "Bauakustiches Prufungen Schalldammzahl and Normtrittschallpegel," Deutschen Normenausschusses DIN 52211 (1953).

[9] F. Ingerslev and J. Kristensen, "Lydisolation I Boligbyggeri" (Sound insulation of dwellings) with English summary, Statensbyggeforskningsinstitut, Rapport 39, København (1960).

[10] "Anvisningar till byggnadsstadgan," BABS Stockholm (1960).

[11] H. J. Rademacher, Acustica 5, 19 (1955).

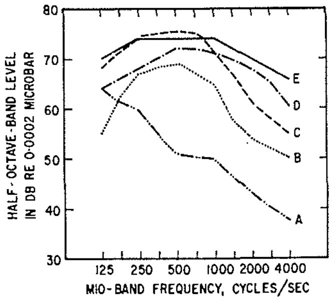

FIG. 4. Half-octave-band levels of typical household noises. Curve A—room air-conditioner, Curve B—vacuum cleaner, Curve C—normal speech (levels exceeded by 1% of speech peaks), Curve D—radio, television (peak levels, speech and music), Curve E—assumed "standard-household noise."

since excesses above the curve are disregarded, the allowable deficiency is actually rather limited.

Summarizing field experience and experimental evidence to date, the consensus is that a simple arithmetic average is not adequate, especially for rating lightweight structures which frequently have serious deficiencies in the most critical frequency range. Several countries are now using standard transmission-loss contours to represent minimum requirements for dwelling separations. Ideally, the transmission loss of a given partition should at no frequency fall below the standard contour; in practice, a limited amount of trading between frequency bands is permitted, although the consequences of this procedure are not yet fully understood.

THEORETICAL CONSIDERATIONS

The British and European standards were developed largely by informed interpretation of the comments of occupants of actual buildings. It is of interest to examine also various theoretical approaches, utilizing information on typical noises and various subjective criteria relating to loudness, noise, or annoyance. These provide some insight into the importance of various frequency bands and assist in selecting an optimum shape of transmission-loss characteristic.

Figure 4 shows half-octave band spectra for a few typical domestic noises. The trend in domestic appliances is toward control of the high-frequency components of noise, so that low- and medium-frequency components predominate in the residual noise. Speech, radio, and television noises are broadly peaked in the middle-frequency range. Speech intelligibility, as distinct from power, involves a slightly higher frequency range extending well beyond 4000 cycles, but this is irrelevant for dwelling separation since the transmission loss should be substantially greater than the amount required merely to reduce intelligibility. Musical instruments and high-fidelity record players will extend the range, especially toward the lower frequencies. Noting from the surveys the special importance of radio, television, and speech noises, it appears that one might consider a "standard household noise" spectrum flat from 250 to 1000 cps and diminishing by 4 to 6 db per octave below and above this frequency (Fig. 4). It should be noted that the curves of Fig. 4 are derived from several sources and are not strictly comparable; they are intended to illustrate spectrum shapes, rather than absolute levels. Several important noises, particularly airborne noise resulting from footsteps and doors slamming, have been omitted for lack of information.

It is assumed that the optimum shape of a rating curve will not vary much with level in the range of application of the rating system, and that a family of parallel curves can be adopted. This is analogous to assuming that equal loudness contours are approximately parallel in the range 20 to 60 phons.

On the listening side, the most obvious procedure is to consider the loudness of the transmitted noise. The work of Stevens,[12] Quietzsch,[13] and Beranek[14] provides a good basis for such a criterion, although their results are more directly applicable to office and industrial problems than to dwelling separation. Stevens devised a method of calculating the loudness of complex sounds that, particularly in its latest form, agrees well with the subjective ratings obtained by Quietzsch for a wide variety of complex noises. Beranek used these data, supplemented by office-noise surveys, to develop the well-known noise criterion (NC) curves, which take into account both loudness and speech-interference levels approximately as they affect the acceptability of office noise. These criteria are used in later sections.

Assuming that the subjective reaction to noise is related to loudness, it is appropriate to determine the transmission-loss characteristic that reduces each band of "standard household noise" (Fig. 4) to a particular equal-loudness contour. For purposes of this paper the 0.5 sone contour, corresponding to a loudness level of 46 phons, is used. (Judging by tenant surveys, this is probably of the right order.) The transmission-loss characteristic that accomplishes this is shown as curve (a) in Fig. 5 (solid circles). This is the most efficient partition for achieving this transmitted loudness since all bands of transmitted sound are reduced to the point where they are equally important in determining over-all loudness.

Kryter[15] recently devised a slightly different series of "equal noisiness" curves, leading to "perceived noise levels" instead of loudness levels. The calculation is essentially the same as Stevens' except that Kryter provides greater weighting for high-pitched components of noise. Kryter claims for his curves only that they correlate better than loudness with subjective judgments of acceptability for certain high-pitched noises such as are produced by jet aircraft. It appears that the high-frequency components may be especially important when a noise is intrinsically obnoxious or alarming. Reviewing the most troublesome sources of dwelling noises, it seems likely that some of them fall into the intrinsically obnoxious category, and it might therefore be more plausible to use Kryter's criterion.

[12] S. S. Stevens, J. Acoust. Soc. Am. **33**, 1577 (1961).
[13] G. Quietzsch. Acustica **5**, 49 (1955).
[14] L. L. Beranek, J. Acoust. Soc. Am. **28**, 833 (1956).
[15] K. D. Kryter, J. Acoust. Soc. Am. **31**, 1415 (1959).

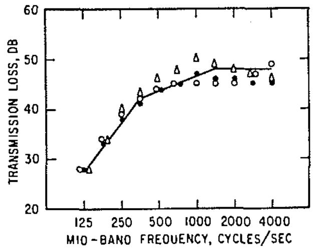

FIG. 5. Theoretically derived transmission-loss curves. Transmission loss required to reduce standard-household noise to: (a) 0.5 sone equal-loudness contour (solid circles), (b) 0.5 Noy equal-noisiness contour (open circles), (c) NC-25 contour (triangles). The solid line is the contour of sound transmission class 48.

Proceeding as before, one arrives at the required transmission loss defined by curve (b) of Fig. 5 (open circles).

The transmitted loudness or perceived noise level, *per se*, is not necessarily a good index of satisfactory sound insulation. More important is the degree to which the transmitted sound is masked by ambient noise existing on the listening side of a partition. For complete masking, a good approximation for complex noises is to require that the transmitted noise be no greater than this ambient level in any half-octave band.[16] Curves (a) and (b) could, on this basis, be regarded as possible spectra of ambient noise. Since Beranek's noise criteria are frequently used for similar purposes, a third transmission-loss characteristic, which reduces standard household noise to NC-25 contour, has also been shown as curve (c) in Fig. 5 (triangles).

Comparing these curves with the DIN curve, it is seen that the latter is reasonably similar in shape. Following these considerations, and with an eye to international standardization, it was decided to adopt the shape of the DIN curves as the basis for the ASTM sound transmission class contours (Fig. 3). Plotted on conventional semilog paper the STC contours consist of a horizontal segment from 1400 to 4000 cps, at a level corresponding to the sound transmission class; a middle segment that decreases 6 db from 1400 to 350 cps; and a low-frequency segment that decreases 14 db from 350 to 125 cps.

Equating the over-all loudnesses of transmitted noise and ambient noise would not result in complete masking if the loudness level of the transmitted sound were particularly high in a narrow band. But the distinction between the equal-loudness and masking criteria is not as great as might be anticipated, since the over-all loudness level of a complex sound depends markedly on the level in the loudest band. For example in Stevens' calculation for half-octave bands the loudest band is weighted five times as much as the other bands. On either basis, it appears reasonably precise to require that a given transmission-loss requirement be met in each band, rather than just on the average.

For dwelling separation, however, where noise sources are highly variable, another approach is to consider the probability that noise will occur in a given frequency band. Both noisy and quiet conditions may fluctuate in the manner indicated in Fig. 4. A review of the spectra of the more troublesome noises suggests that high noise levels are more probable in the mid-frequency range than at high or low frequencies; hence this region should be given special attention. For this reason, in applying the proposed new rating, the following procedure is used: there shall be no deficiencies below the middle segment of the STC curve, but deficiencies averaging 1 db are allowed below the outer segments of the curve.

OFFICE PARTITIONS AND SPEECH PRIVACY

In the foregoing section, the sound transmission class was discussed primarily from the viewpoint of dwelling separation. It is of interest also to consider its applicability to the problem of office separation. This is the second large-scale problem confronting the designer, and differs in several ways from the dwelling separation problem.

The primary requirement for sound insulation between offices is to prevent the transmission of intelligible speech. This is so both for the speaker, who may wish to speak privately, and for the listener, since the distracting quality of speech noise is intensified when it begins to be intelligible. The most comprehensive recent study of factors affecting speech intelligibility was that of French and Steinberg,[17] who developed a straightforward method of calculating speech intelligibility from the properties of each link in a communication system. They first showed that speech intelligibility can be expressed rather precisely in terms of the available dynamic range in each of 20 equally important "critical" frequency bands. A maximum range of about 30 db (above either threshold of audibility or masking level set by noise) is required in each critical band to get the full contribution of the band. To a good approximation the contributions of the individual bands are independent of each other, although there are secondary effects due to masking by adjacent bands. The contribution of each critical band is expressed in terms of an "articulation index," and the average articulation index for the twenty critical bands provides a quantity that is related in a known way to the other common measures of speech intelligibility.

Beranek, in his earlier approach to the problem of specifying minimum noise requirements within spaces such as offices and conference rooms, concluded that ease of speech communication provided a good criterion.

[16] H. Fletcher, M. R. French and J. C. Steinberg, E. Zwicker, and others have demonsrated that calculations of loudness, masking, articulation index, and similar quantities involving perception of complex sounds are most precise when "critical bands" are used. Nevertheless, it is common practice to use data in octave, half-octave, or one-third octave bands. The approximation is valid if the spectra are reasonably smooth and continuous.

[17] M. R. French and J. C. Steinberg, J. Acoust. Soc. Am. **19**, 90 (1947).

Hence, he used the work of French and Steinberg to develop the criteria known as speech-interference levels,[18] obtained by considering speech levels relative to noise in the three octaves most important to intelligibility (300 to 2400 cps). Later, however, he found that acceptability of office noise is more closely related to loudness. This led to the NC curves mentioned earlier.[14]

The speech-privacy problem is the inverse of that considered by French and Steinberg and by Beranek, being concerned with the marginal condition in which speech is not quite intelligible. In this region, the simple linear approximation that works so well when intelligibility is high is no longer strictly applicable. Nevertheless, a linear approximation has been used successfully in office-separation problems by Hardy[19] and more completely by Cavanaugh *et al.*[20] The latter is probably the most useful method available when the problem is well defined: for example, when the room configuration is known and the ambient noise level known or specified. For low-intelligibility conditions, the effect of their linear approximation is to obtain articulation index values that are somewhat larger than those obtained by the French and Steinberg method. Since they deduce from office surveys a maximum acceptable value of this index, calculated by the same method, the discrepancy is perhaps safely canceled out again; but it should be noted that their results are not comparable with those presented below.

For the usual office-building design problem, a rating that ensures a reasonable probability of general satisfaction is again necessary. The uses and limitations of the sound-transmission class for this purpose are considered below, with the help of the French and Steinberg study and their nonlinear treatment for conditions of low intelligibility. Following Beranek's example,[18] the critical bands of French and Steinberg are replaced by bands of equal-frequency ratio, in this case by half-octave bands. The conversion is accomplished by weighting each half-octave by a factor proportional to the number of critical bands it contains.[16] The weighting factors are derived from composite studies of both male and female voices. The idealized speech spectrum of French and Steinberg (Fig. 4) is assumed to exist in a source room separated from a listening room by a partition having a transmission loss defined by an STC contour. The transmitted-speech level in the listening room will depend on the room absorptions and the partition area; room absorptions of 100 sabins each and a partition area of 100 sq ft will be assumed. It will further be assumed that the ambient level in the listening room is defined by an NC curve. Then the signal-to-noise ratio in each band is dependent on the sum of the STC and NC values (assuming that the NC curves of interest are all parallel to NC-30). The articulation index in each band is determined by the speech level (exceeded by 1% of peaks) relative to noise level; for level differences less than 12 db, the band-articulation index is shown in Table I, and for level differences greater than 12 db, the value is $W=(E-6)/30$, where E is the level difference. This procedure applies when the ambient level is moderately above the threshold of audibility, but not so high that nonlinear effects become significant.

The relationship between articulation index and the sum of STC and NC numbers is shown in Fig. 6. It is seen that for an articulation index of 0.03 and for $S/(A_1A_2)=0.01$, STC plus NC should equal 68. For example, assuming an ambient level corresponding to NC-35, the transmission loss should then be equal to or greater than STC-33.

Now, consider the variables affecting this result. Differences between individual speakers may affect the speech level by up to ± 10 db; differences in voice usage between a small office and a large conference room might introduce a similar change of ± 10 db, although the two effects are probably not cumulative (i.e., to some extent a loud talker is one who habitually declaims). Differences in room absorption and partition size from the assumed values will affect the transmitted level by changing the factor $10\log[S/(A_1A_2)]$, but, in any case, this factor, derived from reverberant-room theory, is a crude approximation in modern offices with absorbent ceilings.

TABLE I. Band-articulation index for small differences between the level exceeded by 1% of speech peaks and the ambient level. (Adapted from reference 17.)

Level diff	30W[a]	Level diff	30W
1	0.2	7	2.4
2	0.4	8	3.0
3	0.7	9	3.6
4	1.1	10	4.4
5	1.5	11	5.1
6	1.9	12	6.0

[a] 30W rather than W is tabulated for convenience in calculations.

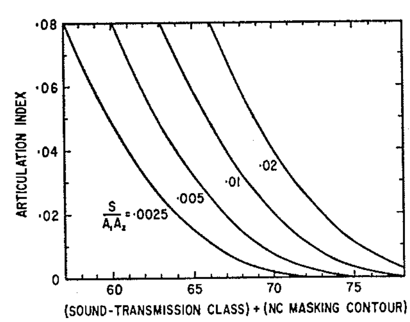

FIG. 6. Combined effect of idealized partition (conforming to a given sound transmission class contour) and a given ambient-noise level (conforming to modified NC contour) on articulation index of transmitted speech. (S—Area of partition; A_1 and A_2 are absorptions of source and receiving rooms.)

[18] L. L. Beranek, Proc. Inst. Radio Engrs. **35**, 881 (1947).
[19] H. C. Hardy and J. E. Ancell, Noise Control **4**, 9 (1958).
[20] W. J. Cavanaugh, W. R. Farrell, P. W. Hirtle, B. G. Watters, "Speech privacy in buildings," J. Acoust. Soc. Am. **34**, 475 (1962).

TABLE II. Analysis of four walls.

Wall	Sound transmission class	Equivalent sound transmission class Test 1 Equal loudness	Test 2 Equal masking by ambient noise	Test 3 Equal artic. index	"Averages" 9-Freq. arithmetic	11-Freq. arithmetic	Energy
A	47	51	49	50	46	48	40
B	36	37	35	39	32	34	26
C	30	36	31	32	33	36	27
D	20	27	23	25	21	22	21

Deviations of the ambient-noise spectrum from the assumed NC-curve will also affect the result. In the calculation leading to Fig. 6 it was found that the articulation index depends on the bands from 350 to 1000 cycles, with a lesser contribution from the 250- and 1400-cycle bands; hence the NC-curve should be matched to the noise in this range unless the noise is concentrated in other bands.

Finally, there is the error introduced by the method of matching a transmission-loss curve to the STC contours. Typically, an actual curve will fall on the STC curve at one or two frequencies in the middle range and be above at the other 3 or 4 frequencies. Consequently, a partition with a sharp mid-frequency dip will provide a lower articulation index than its STC rating would indicate. In a few cases calculated for actual partitions the standard matching procedure was too conservative by 0 to 6 db. This seems small enough for a general rating of this type in view of the other variables in the calculation. Moreover, it is suspected that although speech intelligibility is a primary consideration in office separation, loudness is probably a secondary but significant one. This is illustrated, for example, by experiments of Cavanaugh *et al.*,[20] who used narrow-band transmission in a study similar to those of Rademacher, but with speech privacy as a criterion. It was found that a narrow-transmission band in the region of maximum speech power had an annoying effect out of proportion to the intelligibility it carried.

The average error due to matching curves can be minimized by relaxing the requirement slightly; it is therefore suggested that STC plus NC values should total 66 for room conditions corresponding to $S/(A_1A_2)=0.01$. More-precise values can be determined for other values of $S/(A_1A_2)$ by referring to the appropriate curves of Fig. 6.

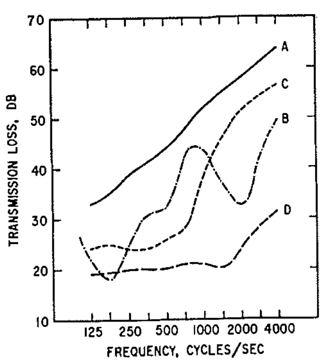

FIG. 7. Transmission losses of four typical walls. Curve A—3 in. concrete wall, Curve B—2×4 in. stud wall (Reference 20, Fig. 16), Curves C and D—Office partitions.

RATINGS OF ACTUAL WALLS

To illustrate the use of the ratings, a detailed analysis is made of the performance of the partitions whose transmission characteristics are shown in Fig. 7. Wall A is a solid concrete wall 3 in. thick. The coincidence frequency for this wall is below the test range and it therefore has a smooth, steeply rising characteristic. Wall B is a 2- by 4-in. stud and plaster wall. Such walls have a characteristic high-frequency dip and a low-frequency dip that varies in detail from sample to sample; this particular curve was taken from reference 20, Fig. 16. Walls C and D are two office partitions that have pronounced deficiencies in the middle range.

The sound-transmission class, determined as prescribed in ASTM E90-61T, is given in the second column of Table II. The reliability of the class rating was tested in three ways described in the following. Since the standard test frequencies form a half-octave series, the analysis was made on a half-octave basis throughout. A sample set of calculations is given in Appendix A.

Test 1

Loudness levels were calculated using the method (Mark VI) given by Stevens[12] for the fraction of standard-household noise (Fig. 3) transmitted by each wall. Similar calculations were made for a range of sound-transmission class contours in order to obtain the curve of Fig. 8. From this it was possible to determine

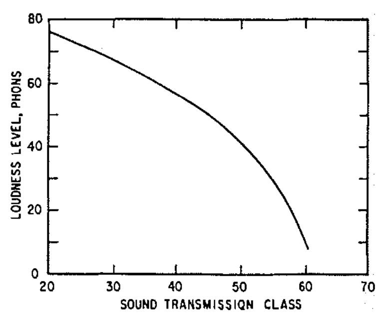

FIG. 8. Loudness levels of standard-household noise transmitted by partitions conforming to STC contours.

the STC contour that would transmit the same loudness as each wall. This "equivalent sound-transmission class" is given in the third column of Table II. This is a test of the system on the assumption that the absolute loudness of transmitted sound is an index of wall performance. (A similar calculation, using perceived-noise levels instead of loudness levels, produced almost identical results.)

Test 2

A better criterion is to require that transmitted noise be low enough to be masked by ambient noise. This condition would be approximately attained if peak levels of transmitted noise were not greater than the ambient level in any half-octave band.[16] Assuming an NC contour of ambient noise (modified for half-octaves) the NC curve that just-masked transmitted noise was determined for each wall. Then the STC contour just masked by the same NC curve was also determined. This is given in the fourth column of Table II.

Test 3

Articulation indices were calculated for each wall, on the assumption that ambient noise corresponding to an appropriate NC curve was present. (The NC curve was chosen so that the STC rating of the wall plus the NC value totalled 66, corresponding to the speech-privacy requirement discussed earlier, but the exact criterion used is not important in the calculation.) The actual articulation index obtained was used to deduce from Fig. 6 the equivalent sound-transmission class for speech, i.e., an actual STC contour that would combine with the assumed NC curve to give the observed articulation index.

The three equivalent sound-transmission classes, based on the three criteria described above, are shown in Table II. Since the masking criterion (test 2) depends on the highest band of noise, relative to the NC curves, it agrees closely with the actual sound-transmission class, which is determined in a similar way. This is the safest criterion, since it is a measure of the probability that the transmitted noise will be masked by ambient noise and thus unnoticed. As might be expected the other two, since they tend to average out peaks, fall slightly above the sound-transmission classes found by the standard procedure. But, apart from a slight shift in scale, the sound-transmission class accurately rates partitions in comparison with any of the three tests considered here.

For comparison, three "averages," the 9-frequency average, an 11-frequency average (including data for 1400 and 2800 cps), and the energy average are shown in the last three columns. These serve to illustrate the inconsistencies that can arise with simple averages. All three show considerable scatter relative to the sound-transmission class or to any of the three tests; none of the three gives the proper ranking for walls B and C; the energy average, unduly influenced by low-frequency transmission losses, grossly under-rates walls A and B.

SUMMARY

Evidence has been presented showing that a simple average is an unreliable index of the sound-insulation value of a partition. It is noted that in many other countries the simple average has been replaced by a standard contour that defines transmission loss as a function of frequency. The significance of such contours has been examined theoretically from the viewpoint of dwelling and office separation, and it is shown that the sound-transmission class now incorporated in ASTM E90-61T provides a simple and accurate rating system.

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APPENDIX A. SAMPLE CALCULATIONS OF WALL PERFORMANCE

The calculations made in preparing Table II were quite straightforward, but it might stimulate additional studies if the details are set down here. Actual calculations are given in Table III.

Transmitted-Noise Levels

The standard household noise (Fig. 4) is taken to be the level in a source room containing 100 sabins of absorption. The receiving-room correction is zero for receiving-room absorption of 100 sabins and a transmitting-wall area of 100 sq ft. Hence the receiving-room level is obtained simply by subtracting the wall transmission losses from the band levels of the standard noise. This is the first step in tests 1 and 2. A similar procedure is used in test 3, after first adapting French and Steinberg's idealized-speech curve (level exceeded by 1% of speech peaks) for half-octave band levels in the source room.

Loudness Calculations

Stevens' procedure was followed exactly, using the formula $S_t = S_m + 0.2(\Sigma S_i - S_m)$, where S is total loudness in sones, S_m is the loudness in the loudest half-octave band and $(\Sigma S_i - S_m)$ is the sum of the loudnesses in the other bands.

Masking by Ambient Noise

An NC curve was found that just equaled or exceeded the transmitted standard noise in each half-octave

TABLE III. Sample calculations for wall A.

	Half-octave band (center frequency) 125	175	250	350	500	700	1000	1400	2000	2800	4000
1. Standard household noise ($L_1=L_2+TL$)	70	72	74	74	74	74	74	72	70	68	66
2. TL, wall A	33	35	39	41	44	48	52	55	58	61	64
3. Transmitted-noise level	37	37	35	33	30	26	22	17	12	7	2
Test 1—Loudness											
4. Loudness index	0.23	0.40	0.45	0.50	0.50	0.37	0.26	0.12	0.05	0.02	0.00
5. Total loudness,	$S_t=0.50+0.2(2.40)=0.98$. Loudness level = 40 phons. Equivalent sound-transmission class = 51 (from Fig. 8).										
Test 2—Masking											
6. Modified NC-28[a]	44	40	37	33	31	28	27	25	24	23	22
	(This just exceeds transmitted noise in all bands.) Equivalent sound-transmission class $=77-28=49$.										
Test 3—Speech intelligibility											
7. Speech noise: $L_1=L_2+TL$	68	71	74	75	75	75	71	67	61	58	55
				(Level exceeded by 1% of peaks)							
8. Receiving-room level (subtract line 2)	35	36	35	34	31	27	19	12	2	...	...
9. Subtract ambient level NC-19[a] ($=66-$STC 47)	...	5	8	10	10	8	1	...	...	...	...
10. 30W (per critical band)	...	1.5	3.0	4.4	4.4	3.0	0.2	...	...	...	...
11. Band-weighting factor (10 times no. of critical bands per half-octave)	0	0	4	10	13	16	20	26	32	33	26
12. 6000 A=165. A=0.028	...	...	12	44	57	48	4	...	...	...	...
	From Fig. 6, STC+NC=69; hence, equivalent STC=50.										

[a] NC curves are modified for ½ octaves and made parallel to NC-30.

band. This was taken to be the ambient level in the receiving-room that would just mask the transmitted noise. The equivalent sound transmission class is the STC contour that attenuates the standard noise sufficiently for it to be just masked by the same NC contour. This calculation is facilitated by the fact that both STC and modified NC contours are families of parallel curves (the latter are taken to be parallel to NC-30). Then the masking condition is expressed simply by the formula STC+NC=77; for example, in the sample calculation of Table III the standard household noise attenuated by STC-49 is just masked by NC-28.

Articulation Index

The method outlined in an earlier section is illustrated in Table III, lines 7 to 12.