N-96-01
II-A-906

DRAFT

TABLE OF CONTENTS

Noise Criteria for Dwellings: A Critical Review

by

Simon L. Yaner and Daniel R. Flynn

National Bureau of Standards
Washington, D.C. 20234

FIGURES

TABLES

1. INTRODUCTION

In spite of the considerable amount of effort expended by the acoustical community over the last 40 years or so, noise indoors remains a major aspect of the noise problem. The present report was undertaken:

(1) to explore why at a time of broad architectural achievement in the sphere of building construction, inferior buildings (from an acoustical viewpoint) are still being produced;

(2) to provide a conceptual framework for selecting and improving noise criteria for buildings. Although the problem of noise pollution indoors is acute in almost all types of buildings, the present report focuses primarily upon dwellings, where most people spend considerable amounts of time.

Scientific attention to noise isolation between dwelling units dates back to Sabine's work near the turn of the century. By the late 1930's national building codes, primarily in Europe, began to incorporate requirements for the sound insulation of dwellings. In these codes, the approach has usually been to specify the acoustical properties which various building elements must achieve in order to be acceptable. The emphasis has been primarily on interior elements such as party walls and floor-ceiling assemblies. Section 2 of this report summarizes the origins of, and evaluates, rating procedures used to describe noise insulation properties of building elements.

The most serious problem with an approach based upon specification of the sound transmission loss of building elements is that reliance is placed on an element regardless of how it may be built and installed and irrespective of other sound transmission paths. In actual constructions serious performance degradation can occur due to either poor workmanship or to "flanking" sound transmission. As a result, it is often difficult to predict actual use performance from laboratory data.

To illustrate this point, consider that the greatest collection of acoustic data available to building designers comes from laboratory tests of single components (e.g., walls, doors, etc.) In actual buildings many paths can exist for noise to travel. Some of these may be properly designed to minimize sound transmission but others may not. As a result it is often found that even though a particular set of building elements has achieved an excellent rating in the laboratory, in actual use the finished product (e.g., a dwelling) is poor [1,2,3] For this reason, in recent years there has been increased recognition of the need to shift the emphasis in building codes from sound transmission loss of building elements to the noise isolation, or level difference, between rooms. A critical review of these proposals is contained in Section 3 of this report.

Human response to noise is partially dependent upon three parameters of the noise: its amplitude, its frequency spectrum and the variations of both of these quantities with time. To provide a practical description of the noise environment it is necessary to combine these three parameters into some single-figure rating in order

*Figures in square brackets indicate the literature references at the end of this report.

that the noise environment can be described in a meaningful way without resorting to a three-dimensional matrix which would be both cumbersome and difficult to comprehend. This rating scheme defines a psychophysical scale and computational procedure which can be used to relate the important noise parameters to the subjective response. The function which is actually used in developing the psychophysical scale depends upon which aspects of the human response, and the noise, are considered to be most important for a particular problem (e.g., loudness, noisiness, interference with speech communication, interference with sleep, etc....). Since this selection is made on the basis of judgment, it is not surprising that there exist numerous scales, each reflecting the particular idiosyncrasies of the researcher responsible for its development. Section 4 of this report summarizes some of the schemes currently available for predicting human response to various noise environments.

Before noise exposure or noise isolation standards can be developed and incorporated into building codes, it is important to establish quantitatively the relationship between the various noise environments and the average response of building occupants so that a point along the scale describing this dose-response relationship can be chosen above which the noise is judged undesirable or unacceptable. It is generally agreed that there exists great variability among individuals with respect to noise tolerance and requirements for quiet. Nonacoustic parameters such as socioeconomic status and age, which contribute to the human response to noise, can best be examined through social surveys rather than laboratory investigations. Individual variability and the influence of non-acoustic parameters can be dealt with by using data taken from large groups of subjects. A review of the results of some of the many social surveys conducted over the years is presented in Section 5.

Finally, in Section 6, the major findings of this report are summarized, gaps in existing knowledge are identified, and a conceptual framework is proposed for future improvements in establishing relevant noise criteria for dwellings.

2. EVALUATION OF BUILDING NOISE CRITERIA BASED ON PROPERTIES OF BUILDING ELEMENTS

By the late 1930's, as the building industry began to move away from traditional constructions, national building codes, primarily in Europe, began to incorporate requirements for noise insulation between dwelling units. These requirements were generally stated in terms of the acoustical properties which interior elements, such as party walls and floor-ceiling assemblies, had to achieve in order to be acceptable.

2.1 Evaluation of Noise Requirements Embodied in Various Standards and in Building Codes

Typically, the transmission loss of a partition at various frequencies is measured according to well-defined and prescribed rules [4,5]. The results are then expressed in a graphical form by plotting the transmission loss as a function of frequency over a range of 16 to 18 one-third octave bands. Detailed data may be useful in engineering design applications but in specifying performance criteria for building codes, a single-figure rating of the overall performance of a partition is more practical.

Originally, requirements for sound insulation were stated in terms of the arithmetic mean of the transmission loss values over the range between approximately 100 and 3000 Hz [6]. This scheme was soon found defective since it allowed for two partitions, one of which had good transmission loss throughout the whole frequency range and the other which had poor transmission loss in one region offset by superior transmission loss in another region, to achieve the same rating. Consequently, since the 1950's the trend has been to state noise insulation requirements in terms of the performance relative to a standard reference curve, sometimes called a grading curve [7]. If the transmission loss of a given partition is found to exceed that of the grading curve at all frequencies, the partition is clearly acceptable. If the transmission loss at all frequencies is found to be poorer than that specified in the grading curve, the partition is clearly unacceptable. In reality, however, most partitions are neither all "good" nor all "bad". Rather, at some frequencies the transmission loss may be better than that embodied in the grading curve while falling below the requirements at some other frequencies. It soon became apparent that rules had to be devised for making the comparisons between a measured transmission loss curve and the grading curve in order that only a "reasonable" amount of unfavorable deviations be allowed.

In Germany, where the scheme was first proposed in 1953, the performance of a partition with respect to acoustical insulation is expressed in terms of the number of dB by which the grading curve must be either lowered or raised in order that the mean unfavorable deviation not exceed 2 dB. In addition, the number is accompanied by a positive or negative sign indicating whether the grading curve must be moved upward or downward [8]. In England, the mean deviations (below a different grading curve) cannot exceed 1 dB [9]. In either case, only the deviations that fall below the grading curve are used in the computations of the mean unfavorable deviation.

Similar developments have occurred in various countries. Although details do vary among countries, the approach has been similar enough to enable the International Organization for Standardization (ISO) to arrive at a recommended method for assessing the relative performance of partitions with respect to their ability to act as sound barriers [10].

In the United States a standard method for assessing partition performance has also been adopted [11]. This method, developed by the American Society for Testing and Materials (ASTM), is quite similar to the ISO standard. According to the ASTM procedure, the sound transmission loss of a partition is measured according to precisely defined rules at 16 one-third octave frequency bands centered at the frequencies from 125 to 4000 Hz. The results are then plotted as a function of frequency. The graph thus obtained is then compared to a reference curve which is adjusted until two criteria are met. First, the mean unfavorable deviation, computed by dividing the sum of all unfavorable deviations by the number of such unfavorable third-octave bands, cannot exceed 2 dB. Second, no unfavorable deviation at any frequency can exceed 8 dB. The partition reading is given by the value of the rating curve at 500 Hz when these two criteria are met.

Implicit in the American Sound Transmission Class, or the similar international procedure, are two critical assumptions:

(1) that it is known, from a human response viewpoint, what constitutes an adequate amount or protection against intrusive noise;

(2) that it is known what constitutes an insignificant and negligible amount of deviation from the norm.

With these assumptions in mind, it is interesting to look at the evidence supporting current practices.

2.2 Evidence Behind the Grading Curve Embodied in the ISO and ASTM Standards

A review of the origin of the curve used to judge partitions indicates that the data base upon which it rests is not entirely satisfactory.

2.2.1. Origin of the Grading Curve

Historically, tenant complaints came about at the time when the building industry was departing from traditional masonry constructions and moving towards the use of lightweight, prefabricated structures. In older constructions, where the rate of tenant complaints was low, dwelling units were often separated by a 25 cm plastered brick wall intended primarily to serve as a fire wall. The smooth transmission loss curve of this brick wall was taken as the criterion against which other structures should be judged. It was only after this decision was more or less agreed upon that a number of investigations were carried out to provide the backup data.

2.2.2. Evidence from Social Surveys

To provide the needed backup data, the chief approach taken by numerous investigators, has been to identify those structures which were deemed acceptable by the majority of building occupants through social surveys. Subsequently sound transmission loss measurements are taken on these structures either in the field or in the laboratory. Such surveys were conducted in England [12,13], Holland [14], Sweden [15,16] and France [17].

a. *Evaluation of the Results of the British Surveys*

Two surveys [12,13] were conducted in England, primarily to provide the necessary data to validate an already chosen scheme. In the first survey, 250 pairs of semi-detached houses were studied. The houses were similar except that the walls were of two types: (1) the traditional plastered brick wall, and (2) a two-layer brick wall separated by an air cavity. The average transmission losses (averaged arithmetically over the frequency range 100 to 3150 Hz) provided by the two wall types were similar but the cavity wall had higher transmission loss at high frequencies while having poorer performance at low frequencies. Inhabitants of these dwelling units were questioned about the general noise conditions in their dwellings and whether they felt that the walls were providing adequate sound insulation.

The results of this study appeared to indicate that the traditional 25 cm brick wall provided a sufficient amount insulation, since tenants living within such constructions did not complain particularly about noise. In addition, the data indicated that the increased insulation provided by the cavity wall at high frequencies was not perceived subjectively. Finally, it was also found that the way people judged their indoor environment was somewhat conditioned by the way they perceived their outdoor environment. People who lived in "noisy" areas tended to be less disturbed, and more often unaware, of their neighbors' noises than people who lived in "quiet" areas.

Shortly after the completion of the 1953 study a new survey was organized to assess the subjective response of people living in apartment buildings as opposed to townhouses. In this survey three groups of 1500 apartments were studied. The average transmission losses of the walls were similar for all apartments and when averaged over 100 to

3150 Hz were comparable to that of the traditional brick wall. However, for each group of apartments deviations from the average transmission loss for airborne sound provided by floor-ceiling assemblies were as much as 5 dB. This would indicate that the apartments with the best insulation had an average transmission loss 10 dB greater than that provided by the insulation of the worst apartment.

The social survey results indicated that apartment dwellers in general were more annoyed by their neighbors' noises than were people in townhouses. Also, in apartments having an average airborne sound transmission loss of 49 dB, 22% of the people were disturbed by their neighbors' noises but not more so than with other conditions associated with living in apartments. In apartments with an average transmission loss of 44 dB the rate of disturbance increased to 36%. Furthermore, for these people, noise was found to be the biggest single factor leading to complaints. Surprisingly enough, the rate of complaints among people living in apartments having an average transmission loss of only 39 dB dropped to 21 percent. Close scrutiny of the data, however, revealed that people who lived in the apartments with the poorest sound insulation were generally from a very low socioeconomic class, had been waiting for long periods of time before being able to move into their apartments, and had previously been living under much worse conditions. These people did not complain about any aspect of their dwellings even though they usually experienced some overcrowding due to the large size of the families.

The British studies have sometimes been cited in support of the choice of the brick wall as a criterion. In our opinion, however, the data gathered in those studies do not provide the desired backup material for the following reasons:

(1) All the people interviewed in the two British studies were living in subsidized housing. Since these people were generally low on the socioeconomic scale, their standard of living and their expectations may have been different from those of other groups.

(2) At the time when these studies were being conducted, England was only beginning to recover from the effects of World War II and still suffered a significant housing shortage. Under those conditions any housing might have been acceptable.

(3) The samples studied covered only a small range for the transmission loss curves and none studied had a significantly better curve than the classicial brick wall.

(4) In the second study, the differences among the three groups of apartments were only in the sound insulation of the floor-ceiling assemblies. It is therefore unclear if people were in fact responding to airborne noise or to impact noise.

b. Evaluation of the Results of the Swedish Survey

While the British studies were underway, similar but independent efforts were carried out in Sweden [15,16]. The Swedish studies involved a set of 500 apartments divided into three groups on the basis of the sound transmission loss provided by the walls. The physical measurement program was also combined with social surveys.

Basically, the data generated in these studies were in good agreement with those obtained in the British studies. Generally, it was found that an inverse relationship existed between sound insulation and inhabitants' complaints about noise. When the average transmission loss was 45 dB, 21 percent of people complained about their neighbors' noises, while the complaint rate dropped to 16 percent with an increase in the transmission loss to 50 dB, and to 7 percent with a further increase in the transmission loss to 55 dB. However, as in the British studies, other non-acoustical factors were found to contribute to people's judgments of their acoustical environment.

Considering that the standard of living in Sweden at the time of the studies was considerably better than that of postwar England, it is surprising that the results of the British and Swedish studies came out as closely as they did.

c. Evaluation of the Results of the Dutch Survey

Studies similar to those conducted in England and Sweden were carried out in Holland [14]. These studies involved a set of 1200 apartments and 1200 people. The Dutch data failed to reveal a correlation between people's satisfaction and the sound transmission loss of party walls. The reasons for the discrepancy between the data obtained in the Dutch survey and those obtained in the British and Swedish surveys are not totally clear. One possibility is that, in the Dutch survey, most of the differences among apartments were in the sound insulation provided by floor-ceiling assemblies -- thus the difficulty in differentiating between responses due to impact sound and those due to airborne sound arises.

d. Evaluation of the Results of the French Survey

A study similar to those conducted in England, Sweden and Holland was recently performed in France [17]. In the French study, six groups of dwellings were involved with 266 respondents surveyed. The dwellings studied in this investigation were chosen on the basis of their conformance with the French Constructions Standards, which themselves are modeled after the smooth transmission loss curve of the standard brick wall. The results of the French study reveal that despite the fact that all the dwellings meet the French norm, 40 percent of the people interviewed reported hearing their next door neighbor's TV and radio. Similar results were not found regarding conversations. Consequently, it can only be concluded that while the traditional brick wall may once have provided adequate isolation, it may provide insufficient protection from amplified music or televisions and radios (i.e., amplified conversation) or from modern appliances or household equipment.

e. Evaluation of the Results of the Various Social Surveys

The results of the social surveys, as a whole, do seem to indicate, with the exception of those performed in Holland, that tenant satisfaction is related to the degree of sound transmission loss provided by building elements. The data also reveal that people's response to indoor noises is influenced by the environmental noise outdoors as demonstrated by the fact that people who live in "noisy" areas are less aware of their neighbors' noises than people who live in "quiet" areas. Yet, none of the national building codes have included requirements for outdoor-to-indoor isolation. In fact, at the present time, a standardized and agreed upon method for the measurement of outdoor-to-indoor isolation does not even exist.

Although the British and Swedish studies seem to indicate that the selection of the brick wall as a design goal for party walls may have been appropriate, close scrutiny of the data reveals that in fact these studies do not provide conclusive backup data because they included party walls with only a very limited range of transmission loss characteristics, none of which had a significantly higher transmission loss curves than that of the traditional brick wall. In addition, most of the people interviewed came from lower socioeconomic groups and thus may have had different expectations than people from other groups. These conclusions are further supported by the French findings that 40% of the people surveyed (all of whom lived in dwellings meeting building construction standards based on the transmission loss curve of the brick wall) complained about their next door neighbor's TV and radio sounds.

2.2.3. Evaluation of the Evidence Based Upon Loudness and Annoyance

Because of the discrepancy between the Dutch survey data and the British and Swedish survey data, van den Eijk [18], in Holland, developed a new approach to the problem. He first stated that one could not be annoyed by a noise which one could not hear. Consequently, if one could specify the statistical distribution of sound levels for the most annoying noise source, a knowledge of loudness functions should allow for the derivation of the insulation requirements for a zero loudness level in a space adjacent to the noise source room.*

Radio sounds had been found in the British survey to be the predominant source of complaints among apartment dwellers. For this reason, van den Eijk determined the statistical distribution of peak levels of radio programs in each of 8 octave bands having center frequencies from 50 to 6400 Hz. This distribution was derived from data obtained for a radio working continuously through 17 mornings and afternoons. The results

*Actually, van den Eijk's procedure led to the required noise isolation, or level difference between rooms, and not the sound transmission loss, or insulation, of the separating partition.

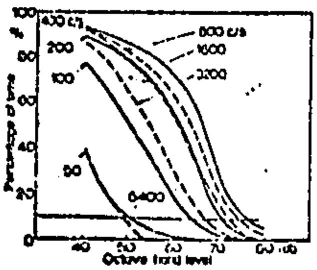


Fig. 1 Statistics of peak levels in radio-programmes. For each of eight octave bands the percentage of the time that certain octave band levels are surpassed is indicated. Based on about 55 hours of mixed radio-programmes.

Figure 1

were presented as a series of curves showing the peak levels exceeded in each frequency band during various percentages of time. These results are reproduced in Figure 1. From the data contained in Figure 1 and using the Fletcher-Munson loudness contours [19], another series of curves was generated. These curves purported to specify the necessary sound transmission loss requirements in each of the 8 octave bands in order that the loudness in an adjacent room would not exceed the 0 phon loudness level for more than 5, 10, 20, 30, 40 or 50 percent of the time. The resulting values can be seen in Figure 2.

Inspection of Figure 2 reveals that the shape of the curve derived on the basis of loudness is quite different from that used in either the British or German building codes as well as that embodied in the ISO and ASTM Standards. Specifically, the curve based on loudness drops sharply below 400 Hz and above 3200 Hz whereas none of the others do. In the range between 400 Hz and 3200 Hz the curve based on loudness is essentially flat while the others are not. Furthermore, the requirements, based upon a 0 phon loudness level are much greater than those of either the German or British Standards. To reduce radio noise to this extent, the sound isolation required could be prohibitively expensive.

For the reason just given, van den Eijk also computed what he thought was the transmission loss that would be required to reduce his radio programs to a loudness level of 20 phons. The results of these computations are shown in Figure 3 together with the requirements embodied in the British and German building codes. As can be seen in Figure 3, if a 20 phon loudness contour is used instead of a 0 phon loudness contour, the discrepancies between the two sets of curves with respect to level are reduced. However, the discrepancies concerning the shape of the curves

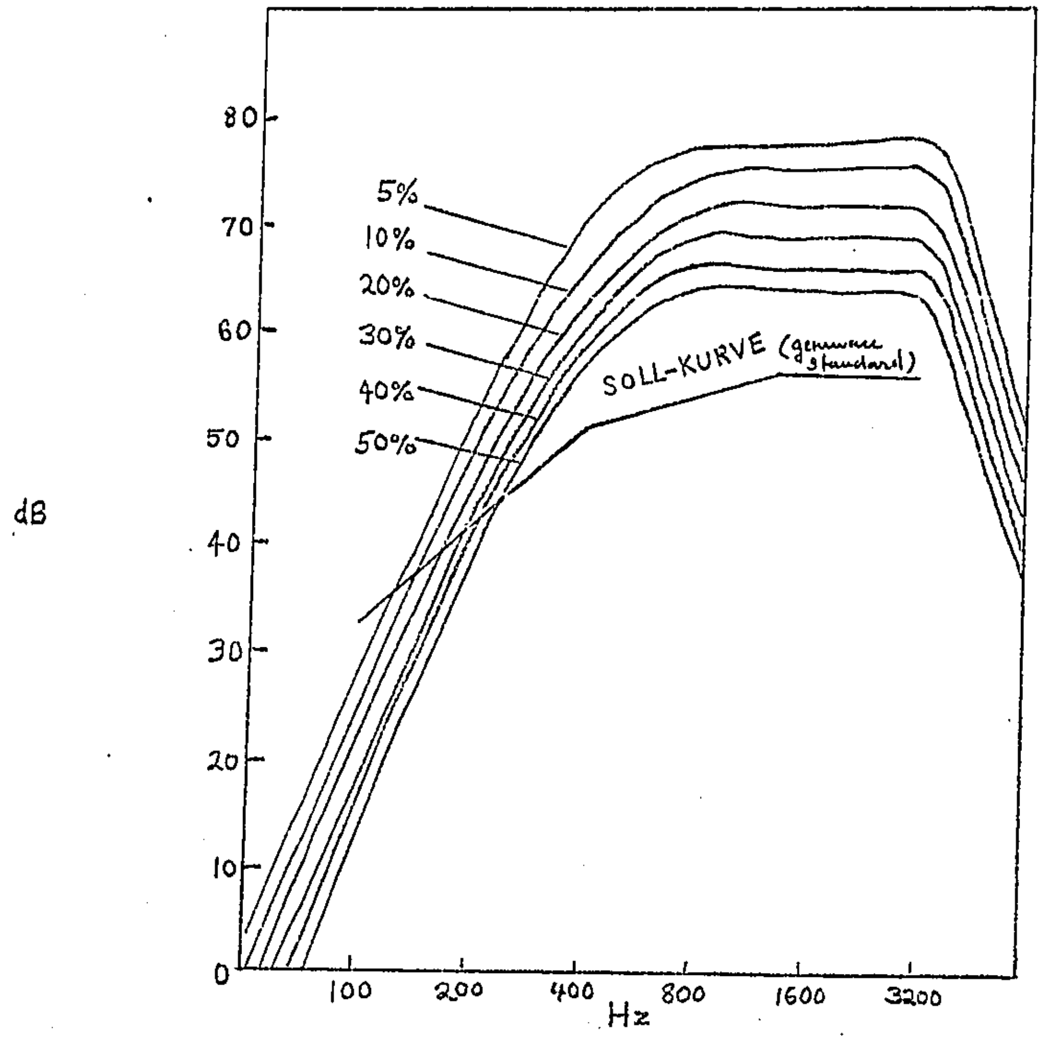


Figure 2 Required Isolation based on radio level surpassing 0 phone in receiving room for various percentages of time

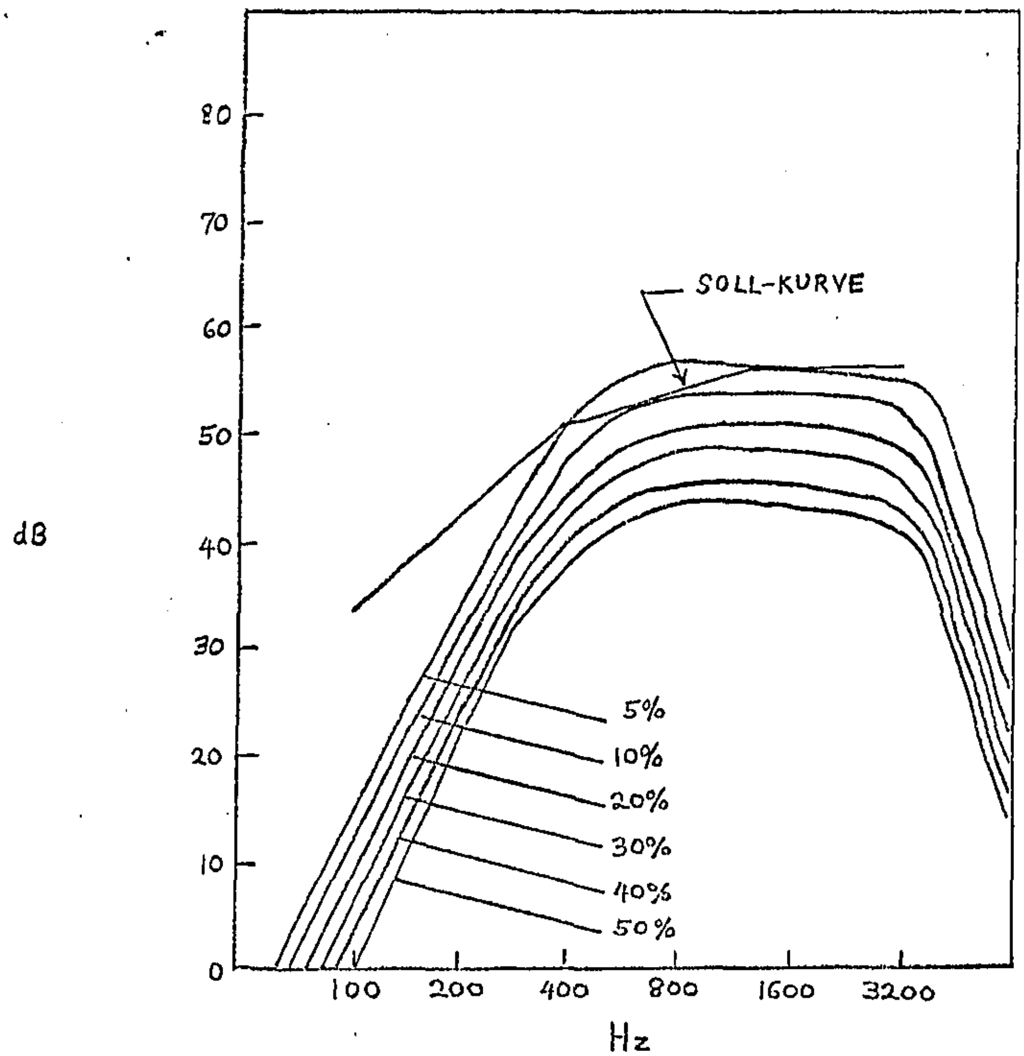


Figure 3. Required Airborne Isolation based on radio programs and a 20 phons contour in receiving room.

are not reduced. Van den Eijk concluded that the critical requirement for airborne sound insulation is in the frequency range from 400 to 800 Hz. He further hypothesized that if the noise is allowed to intrude next door at a low or moderate level (e.g., 20 phon loudness level), it should not be a source of annoyance. The Dutch building code, which specifies the insulation required in each octave band between 250 Hz and 2 kHz is derived partially on the basis of allowing radio sounds to intrude next door at what is thought to be a loudness level of 20 phons for about 10 percent of the time.

There exist a number of problems associated with the work of van den Eijk. First, van den Eijk reports that his transmission loss requirement curve is based upon an intrusion of radio programs for 10 percent of the time at a loudness level of 20 phons -- in fact, that is not the case. It appears that what van den Eijk did was compute the transmission loss requirement in order that each octave band, taken alone, would lie on the 20 phons contour. However, if there are a number of bands, each of which singly produces a loudness level of 20 phons, the overall loudness level in the receiving room will exceed the 20 phons level by an amount which increases with the number of contributing bands.

If each octave band taken alone produces a loudness level of 20 phons, it is reasonable (for example in accordance with loudness summation principles enunciated by Stevens [20]) to assume that each band contributes equally to the loudness level in the receiving room. Accordingly, the incremental loudness level in the receiving room as a function of the number of bands present can be computed using various computational procedures. The results of each computation are shown in Figure 4 for Stevens' Mark VI [20], Stevens' Mark VII [21], and the Fletcher-Munson [22] procedure.

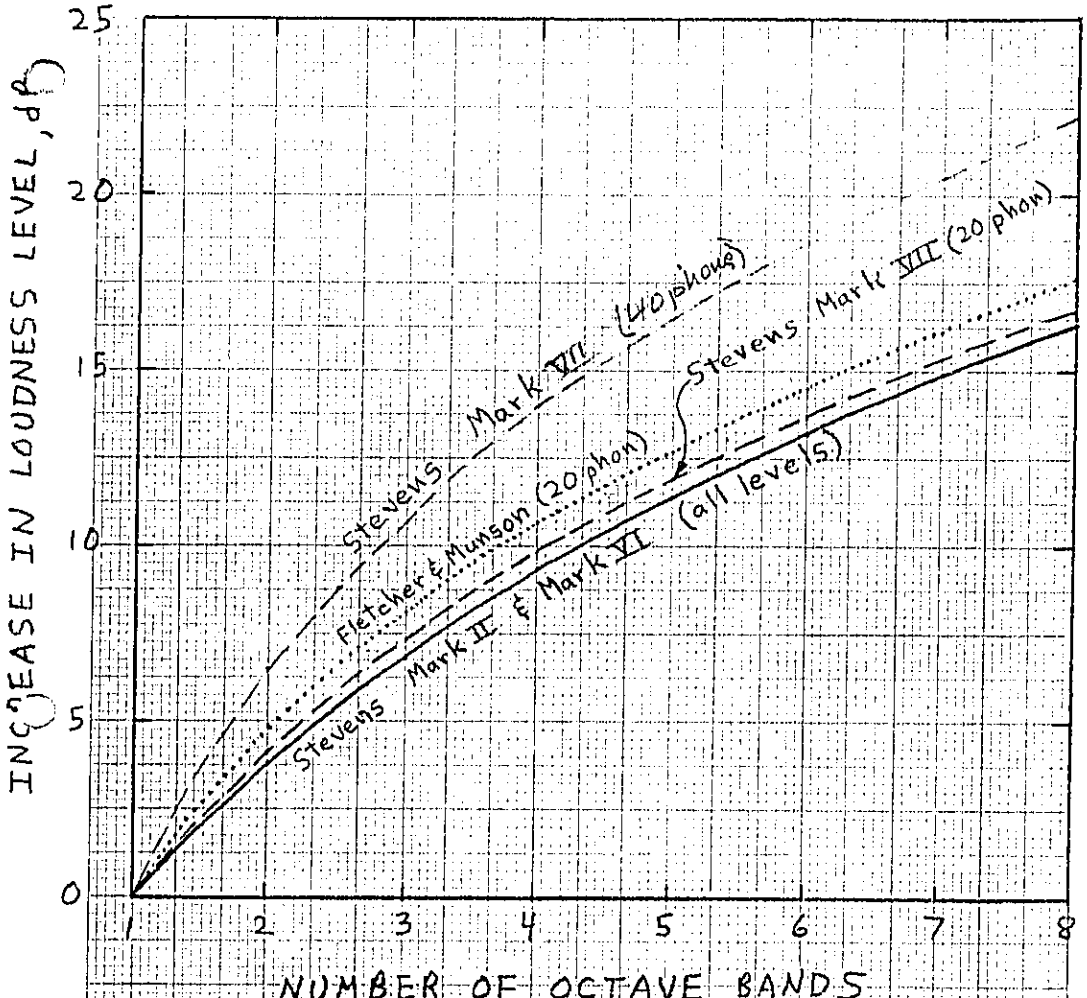


Figure 4. INCREASE IN Loudness Level in Receiving Room as a function of the number of bands present

As can be seen in Figure 4, the overall loudness level for the 8 bands utilized by van den Eijk would be about 16 to 18 dB above that of each individual band, depending upon which computational procedure is used to compute loudness level.*

The practical implication of van den Eijk's failure to sum up the loudness contributions from the several octave bands is that, given his statistical distribution of radio program sound levels and transmission loss such that each octave band individually results in a loudness level of 20 phons, the resulting overall loudness level in the receiving room is 36 to 38 phons depending upon which loudness summation principle is used.

While it is reasonable to assume that one cannot be annoyed by a noise that cannot be heard, it is an entirely different matter to assume that one cannot be annoyed by a noise heard at a low or moderate level (e.g., 36 or 38 phons). Indeed, while loudness is considered to be highly correlated with annoyance, there are other parameters associated with annoyance which do not depend upon loudness [23,26]. Thus, it could be argued that van den Eijk's requirements may have been derived through the use of the wrong parameter. To test this possibility van den Eijk's published data, as well as his rationale, were used in conjunction with the 0.16 noy contour [27] rather than the 20 phon contour. (The reason for choosing the 0.16 noy contour was that it also corresponds to a sound pressure level of 20 dB at 1000 Hz.) The curve derived on the basis of intrusion from next door at a level corresponding to the 0.16 noy contour

*Note that the summation procedure of Fletcher and Munson applies only to pure tones; consequently, in order to estimate the overall loudness level associated with van den Eijk's spectrum each octave band was replaced by a single pure tone located at the band center frequency.

for 10 percent of the time was compared to the curve derived by van den Eijk for the 20 phon loudness contour. The result is presented in Figure 5.

Inspection of Figure 5 suggests that the isolation values required, based upon loudness, differ from those based upon noisiness* both in terms of the frequency range that must be considered and in terms of the actual values required. While the curve based on loudness indicates that in the range between 800 Hz and 1600 Hz the insulation required is independent of frequency, the curve based on noisiness indicates that the requirements in this range increase as a function of frequency. The practical implication of this is that there is a need to specify the isolation requirements up to at least the 3200 Hz band, contrary to van den Eijk's conclusion that insulation requirements need not be specified beyond the 800 Hz band. In addition, Figure 5 reveals that in the range below 400 Hz significantly more insulation is required than is suggested by van den Eijk's curve (e.g., 8 to 14 dB more, depending upon frequency).

Aside from the problem associated with the use of loudness level as a criterion for generating noise insulation requirements, there is another problem. Inherent in van den Eijk's conclusions is the belief that if the noise problem is solved for radio it is also solved for other noise problems. Although van den Eijk [28], in following studies, also examined the isolation required for TV noise, sufficient isolation for TV or radio programs might not be adequate for other noises, particularly those whose spectral shapes differ significantly. The British surveys

*Which in the context of Kryter's work is synonymous with annoyance.

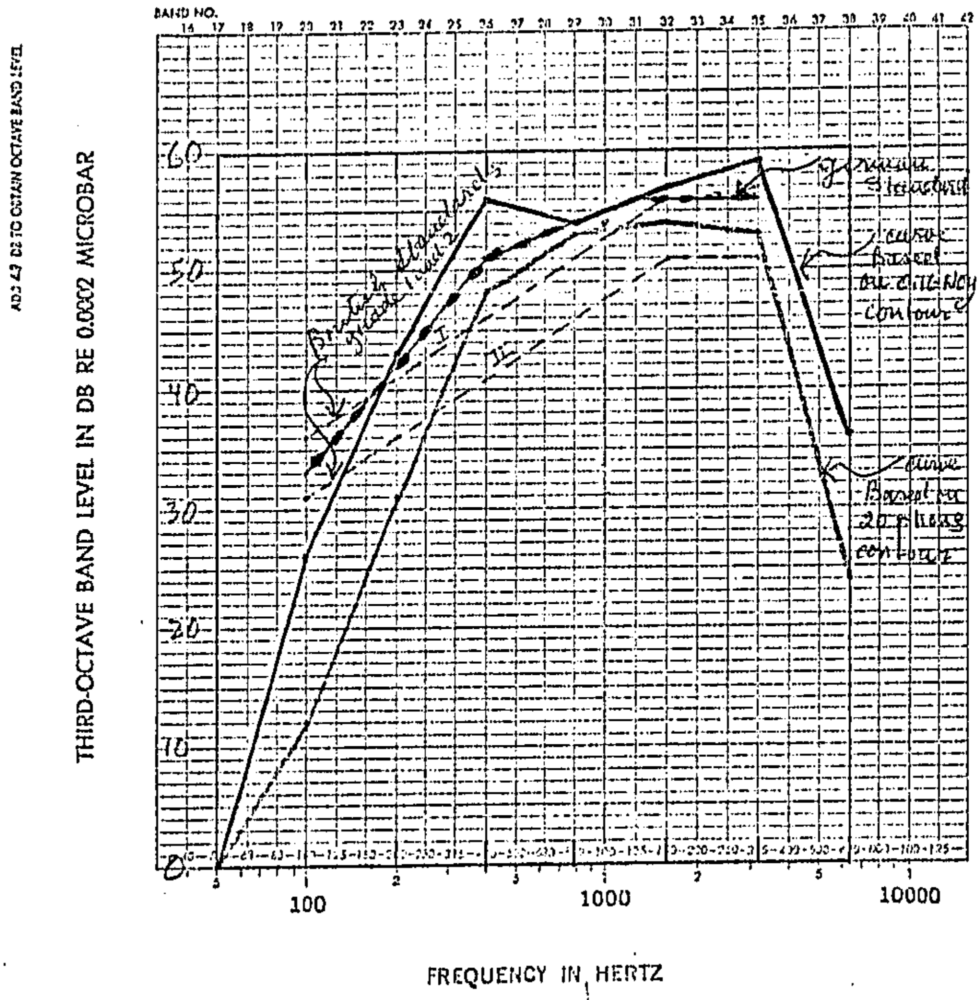


Figure 5. Differences Among curves based on loudness and annoyance

——— F & M 20 phon

——— 0.16 noy

——— German

- - - - British

clearly demonstrate that people in dwellings are disturbed by other types of noises such as musical instruments. These noises may contain energy in regions other than those between 400 Hz and 3200 Hz. Certainly in a country such as the USA where modern stereo systems, household appliances, and home tools are common, requirements founded upon the loudness of a neighbor's radio programs (the frequency response of which is unclear) could be misleading. In addition, there may exist some questions regarding the applicability to the American scene of the radio distribution of peak levels presented by van den Eijk since at the time of the study the Dutch radio did not broadcast commercials. Furthermore, the investigations of van den Eijk did not account for the effects of radio (or TV) size, room acoustics, location of the radio or TV with respect to party wall and the background noise in the receiving room.

Northwood [29] has used an approach somewhat similar to that of van den Eijk in order to arrive at estimates of noise isolation requirements. He included a number of noises commonly found around the home by combining the spectra of TV, radio, speech and domestic appliances. He also pointed out that this "standard household noise" must "compete" on the quiet side of the partition with the existing background noise. In the absence of data on ambient noises in homes, Northwood assumed a background noise with a spectrum similar in shape to the well-known NC-25 contour [30]. Isolation requirements were then derived on the basis of the "standard household noise" intruding next door and being heard above this background noise. A curve of isolation as a function of frequency was thus obtained. This curve is reproduced in Figure 6 where it is compared to the German grading curve. Isolation requirements based on the "standard household noise" are below those of the German curve at all frequencies (e.g., less

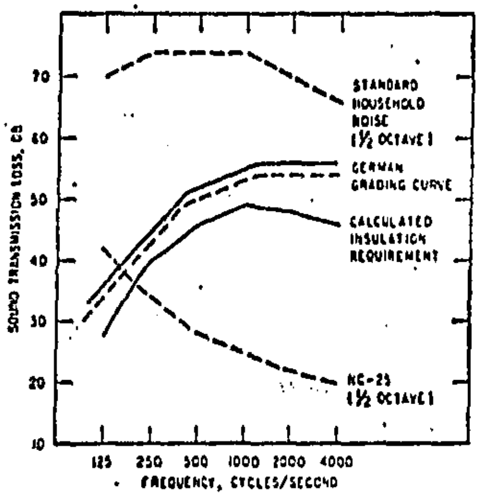


FIG. 6 Derivation of sound insulation required to reduce standard household noise (Fig. 2) to a level corresponding to NC-25.

Figure 6

isolation is required than in the German standard). In addition, the shapes of the two curves are different since isolation requirements in the Northwood curve fall off at frequencies above 1 kHz while those in the German curve do not.

Conceptually, the approach used by Northwood is appealing; however, the noise isolation requirements computed are rather speculative since:

(1) there exist few, if any, data regarding the statistical distribution of indoor noise levels; thus Northwood's standard household noise may or may not be representative of the situation in typical households.

(2) there are no data regarding the relation between the NC-25 contour and ambient household noises; thus, the NC-25 contour may or may not be a reasonable way to define ambient noise in dwellings. It is known that spectra that meet NC contours are judged "hissy", "rumbly", and unnatural [31]. Consequently, it is doubtful that they do indeed represent typical background noises.

In 1969 Clark [32] carried out a series of psychoacoustics studies designed to test the validity, from a human response viewpoint, of the shape of the curve embodied in the ISO and ASTM standards as well as the need for the "8 dB" rule.

In one series of experiments, subjects were presented three different noise sources -- male speech, popular music, and vacuum-cleaner noise. Each source was presented alternately through one of two filters -- one representing the shape of the ASTM rating contour (STC) and the other being a one-third octave or octave band-pass filter. The stimuli were presented in a background noise conforming to the spectrum shape and level of NC-25 contour. Subjects were asked to adjust the level of the band of noise until it was equally annoying to the noise passing through the "STC filter". The results of these experiments showed that when subjects equated the "annoyance" of a one-third octave or an octave band of noise to that of the same noise shaped best obtained equal annoyance contours that closely matched the shape of an inverted STC contour. This finding was interpretated as an indication that the shape of the STC contour is indeed representative of the relative contribution of the various bands of noise to annoyance. In our opinion, however, the study does not solve the problem of the adequacy of the grading curve shape for the following reasons:

(1) Since the subjects were always judging the one-third or octave band of noise against an STC contour the results could have been biased towards an STC due to attentional effects.

(2) Inherent in Clark's experimental design was the assumption, already discussed, that household ambient noise is adequately represented by an NC-25 contour. This may or may not be correct in real life conditions. Yet, there is no question that the annoyance produced by an intruding noise is dependent upon the signal to noise ratio (e.g., ratio of intruding sound to background noise in receiving room); thus the shape of the background noise spectrum may be critical.

(3) The range of sound levels in Clark's study was very limited; thus, generalization to other situations may be questionable.

In a second series of experiments, Clark addressed the question of the importance, from a human response viewpoint, of coincidence dips in a transmission loss curve. The experiment was carried out in a manner similar to the one described previously but the band-pass filter was replaced with a filter corresponding to the noise isolation between two rooms, including simulated coincidence dips, either one-third octave or an octave in width and 0 to 20 dB in depth. Subjects were asked to adjust the attenuation of the noise passing through the STC filter until it was equally annoying to the same noise going through the simulated noise isolation filter. The results of this series of experiments suggest that dips in the noise isolation, corresponding to coincidence dips in the transmission loss of the partition, are not important subjectively and thus the 8 dB rule present in the STC rating scheme may be over-protective and could be abolished. However, here again the results should be interpreted cautiously since some of the same uncertainties described above are applicable to this second set of experiments as well.

2.3. Conclusions

It should be clear from the discussion contained in the previous pages that, although there exist precise and well-defined rules for rating building elements with respect to their ability to provide sound insulation, the foundation, from a human response viewpoint, for these requirements is not entirely satisfactory.

While the social surveys conducted in England and Sweden appeared, at least superficially, to demonstrate that the traditional 25 cm plastered brick wall leads to a minimal rate of complaints among residents, the French survey tends to demonstrate that such walls may not provide sufficient protection. In addition, since all the surveys involved only a very limited range of isolation, and since none considered anything significantly better than the 25 cm brick wall, it is impossible to determine from these surveys how people would respond to walls of different characteristics.

The evidence based upon subjective response (e.g., loudness or annoyance) is even more sketchy and besides highly speculative. It is therefore not surprising that over the years numerous reference curves have been used for rating noise insulation and that these curves exhibit a fair amount of variation with respect to shape, frequency cut-off, and the extent of insulation required (i.e., see Figure ~~6~~ 7). Since there exist practically no data defining subjectively significant changes in household noise intrusions, it is difficult to determine the meaning, if any, of the differences among the curves. Finally, it may be noted that the curves which are based upon loudness (or annoyance) suggest that the ISO and ASTM curves may be too stringent at low and high frequencies. While good transmission loss is easily achieved at high frequencies (provided no large coincidence dip exists), it is both difficult and expensieve to achieve good isolation against low frequency sounds. Therefore, it would be "good" if isolation requirements could be reduced at low frequencies, as suggested by curves derived on the basis of loudness; however, such generalizations may be premature since the data base is extremely limited and restricted to very few noises.

To conclude, it appears fair to state that although there exist an international and a national standard curve against which partitions can be judged, there still exist unresolved questions regarding the shape of curve, the frequency region of concern, the significance of deviations from the grading curve, the importance of coincidence dips, and, most importantly what the standard curve means in terms of human requirments. On the basis of current knowledge, answers to these unresolved questions cannot be given. In addition, when one considers the difficulty of predicting use performance from laboratory data, due to degradation as a

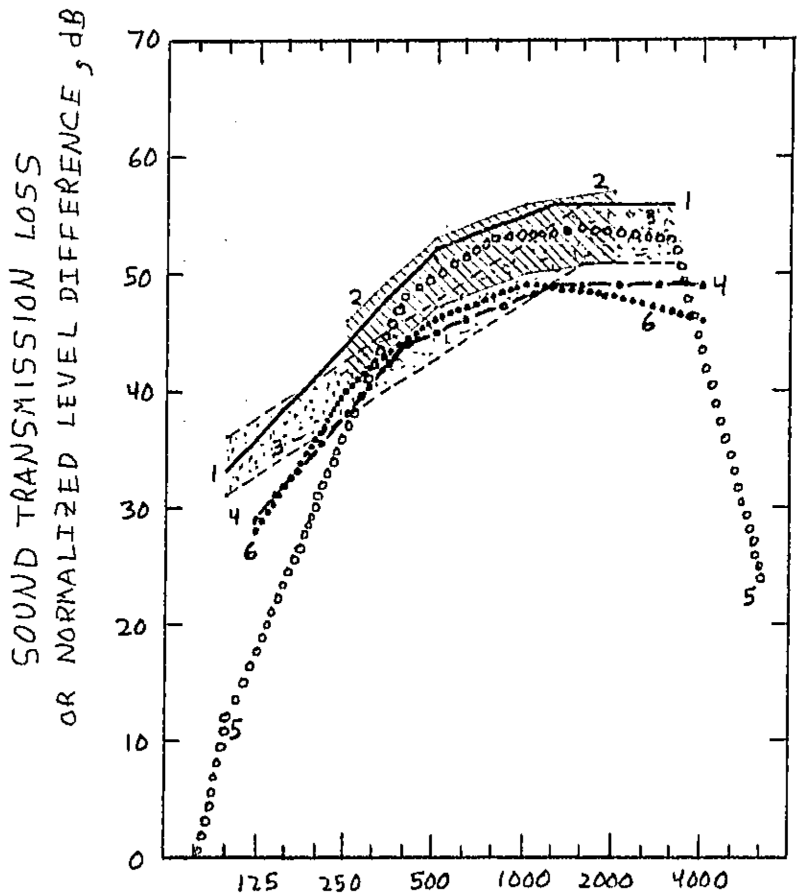


Figure Ø 7. Differences Among Various Reference Curves

1	———	Germany, Austria, Denmark (Field)	TL
2	(hatched)	Netherlands	LD
3	(stippled)	England (Flats)	LD
4	—·—·—	U.S.A. (FHWA M.P.S.)	TL
5	ooooooo	van den Eijk (L_{10} to 20 phon in each octave band)	LD
6	••••••	Northwood (for household noise to NC-25)	LD

result of flanking paths, it is not surprising that many buildings are still being produced which are inadequate from an acoustical viewpoint.

3. NOISE ISOLATION VERSUS NOISE INSULATION

In recent years increased attention has been given to the need to shift the emphasis in building codes from sound transmission loss of partitions to noise isolation, or reduction, between spaces, expressed in terms of a sound level difference. Since differences in workmanship can significantly affect the transmission loss of a partition and since there may exist serious flanking paths, the specification of a minimum sound transmission loss of a party wall or a floor-ceiling assembly does not guarantee adequate noise isolation between spaces. Schultz [33] has advocated that the primary building code requirement be the achieved noise reduction, or level difference, between two spaces. Specifications of sound tranmission loss should provide assistance to the building designer in achieving the desired performance, but the main objective should be the isolation required, not the sound transmission, or insulation, that may or may not lead to that isolation.

ASTM E336 [34] provides for computation of the Noise Isolation Class (NIC) which is a single-figure rating obtained by fitting the STC contour [35] to the one-third octave band sound level differences between rooms in the frequency range from 125 to 4000 Hz.

3.1. Review of Proposals Based on Weighted Level Differences

Because of the large amount of data required when measurements of noise isolation, or of sound transmission loss, are made in frequency bands (e.g., one-third octaves), there has been interest in the single values obtained when a single weighted (e.g., A-weighted or C-weighted) sound level is measured in both the source and the receiving room. In 1965 Gosele [36] and Gosele and Bruckmayer [37] noted that strong correlations exist between partition ratings based on the ISO procedure (see Section 2) and ratings based on the difference between the A-weighted sound level in the source room and the A-weighted level in the receiving room. These observations were later confirmed by Gosele and Koch [38], Fuchs [39] and Harman [40]. Similar agreements have also been noted for outdoor-to-indoor noise reductions by Scholes and Parkins [41]. These observations led Siekman, Yerges and Yerges [42] to propose a simplified field sound transmission test for partitions which is based upon an A-weighted level difference. Quindry and Flynn [43] and Flynn [44] have also demonstrated a good correlation between ratings based on level differences and those derived from the ASTM/ISO procedures; however, their data indicate that the best correlations are obtained when a C-weighted sound level is used in the source room and an A-weighted level is utilized in the receiving room.

Donato [45], in a study on insulating houses against aircraft noise, found a good correlation between Sound Transmission Class and the difference between the outdoor and indoor Perceived Noise Levels.

3.2. Evaluation of Evidence Behind Weighted Level-Difference Schemes

The previous section indicates that, in all of the investigations, good correlations were observed between ratings based on weighted level differences and those obtained using the ISO/ASTM procedure. In addition, there appears to be a consensus regarding the desirability of using the A-weighted level in the receiving room. Similar consensus, however, does not exist with respect to which weighted function should be used in the source room since some investigators advocate the use of an A-weighted level while others advocate the use of the C-weighted level.

Be that as it may, it is interesting to note that all the proposals reviewed above were justified on the basis of the strong correlation observed between ratings based on level differences and those based on the ASTM/ISO methods (and therefore traceable to the before mentioned grading curves). In view of the lack of evidence regarding the validity, from a human response viewpoint, of the ISO and ASTM rating methods, one cannot but wonder why the observed correlations with these schemes have been utilized as the main support for the adoption of level-differences in building codes. For this reason, at least insofar as typical household noises are concerned, we espouse the view of Schultz [46] who expressed the opinion that it is not necessary to demonstrate high correlation between level-differences and other rating schemes since the A-weighted level-difference has as much independent claim to validity as that of either the NIC or STC procedures in predicting human response to building noise.

4. EVALUATION OF SELECTED RATING SCHEMES USED TO ASSESS ENVIRONMENTAL NOISE

In developing criteria for building noise it is important to keep in mind that people are responding to their environment as a whole and not to the noise isolation or to the characteristics of an intruding noise source, per se. Consequently, the major task that confronts acousticians concerned with building noise should be to agree upon a rating scheme for the interior acoustical environment. If such agreement can be reached, then one can infer what noise isolation is needed to achieve the desired environment. For that reason, in this section, selected rating schemes for assessing environmental noises in terms that are relevant to human response are examined.

During the past 50 years or so, a great deal of effort has been expended to develop schemes for predicting human response to noise from measurements of the physical attributes of the noise. The result of these efforts is a plethora of schemes ranging from simple to complex. It is not the purpose of this section to review all the schemes or methods developed over the years for rating noise according to its effects on people, but rather to evaluate some of the most widely used schemes in terms of their relevance to the problem of noise pollution in the home.

In order to facilitate the organization of this section, we have followed the example of Schultz [47]. The selected methods have been combined according to the particular aspect of the human response to noise which it is purported to address (e.g., auditory magnitude, interference with speech communication, noisiness, etc.)

4.1. Evaluation of Selected Schemes for Evaluating Auditory Magnitude

Much of the research conducted within the last 50 years has focused upon combining the frequency content and overall intensity of the noise into a metric related to the perceived magnitude (e.g., loudness) of the noise as experienced by a person.

Although there are disagreements among various studies regarding the actual values of the constants entering into the function relating the loudness experienced and the intensity of the noise, there appears to be a general consensus regarding the form of the function. Loudness is generally thought to grow as a power function of sound pressure [48,49,50]. In practice what this means is that each time the intensity level of a sound is increased by 10 dB, the loudness experienced increases approximately by a factor of two. Furthermore, it is known that the human ear is not equally sensitive to sound at all frequencies.

The relative sensitivity of the ear at various frequencies has usually been studied by determining the sound pressure level that is required for a given sound to give rise to the same loudness experience as that produced by a reference sound at a prescribed sound level. Data from these studies are typically shown as a series of loudness contours which indicate at what intensities sounds of different frequencies produce similar loudness experiences. Equal loudness contours have been determined for pure tones [51,52,53,54,55] and for bands of noise [56] in the laboratory under well controlled conditions where many parameters are held constant. Traditionally, contours have been developed with a reference sound which has been either a 1000 Hz tone or a noise band centered at 1000 Hz.

Results of studies of the kind described, generally agree that the ear is most sensitive to sounds at frequencies between approximately 500 and 6000 Hz. That is, for a very broad-band noise the middle region of the audible frequency range contributes most to the sensation of loudness. However, results also demonstrate that as the intensity level of a sound, or a noise, increases from moderate to high levels, the relative contribution to the loudness experience of low and high frequencies increases until they equal that of mid-frequencies at very intense sound levels.

Findings of the kind described above are embodied in the A, B, and C weighting networks of the sound level meter. Indeed, in order to compensate for the differential frequency sensitivity of the ear, sound level meters are designed to weigh the overall spectrum of the noise in such a way as to approximate the frequency response of the ear. That is, when a sound is passed through the various networks of the sound level meter, each frequency region in the noise contributes to the total reading by an amount appropriately related to the subjective magnitude associated with that frequency. In order to account for the findings that the sensitivity of the ear to various frequencies varies with the overall intensity of the noise three networks are included in most meters. The A, B, and C networks were originally intended to represent the response of the ear to low, moderate and high intensities, respectively. However, over the years it became apparent that in real life situations the A-weighted sound pressure level is a relatively good predictor of human response to environmental noise [57,58] at all levels. For this reason, the A-weighted level is emerging as the most widely used network when measurements are made with a sound level meter.

In spite of being a good indicator of human response, the A-weighted sound level is not perfect in this regard. For this reason, various investigators have attempted to improve the accuracy of prediction by incorporating more details to the method based on the simple A-weighted sound level, as more parameters relating to human response became available from further laboratory investigations.

Generally, refined schemes are based on a segmentation of the sound pressure spectrum of a noise into a series of contiguous frequency bands by means of electrical networks so as to display the distribution of sound energy over the audible frequency range. From data thus obtained, a "loudness level" can then be computed by first assigning to each frequency band a loudness index designed to represent the potential contribution to loudness of that band, and then correcting this index by applying a weighting to it to account for the fact that bands with higher loudness indices may inhibit or mask the contributions of that band. The weighted loudness indices are summed appropriately to obtain the overall loudness level of the noise. A number of variants to this general approach are now available. [59-68]. All of these procedures are complex; consequently it is doubtful that they could be successfully used to develop criteria for incorporation into building codes. This conclusion is further warranted when it is considered that in most investigations comparing the A-weighted sound level performance, relative to the more complicated computational schemes, it is found that the A-weighted sound level performs essentially as well as the more complicated methods in rating the noise environment with respect to human reactions. [69-73]

4.2. Evaluation of Selected Rating Schemes Based on the Concept of Noisiness

As Kryter has indicated, [74] in many noise control problems it is not how loud a sound is that concerns us most but rather how noisy and unwanted it is. Inherent in this statement is the assumption that loudness and noisiness are two distinct attributes of the human response to noise. Investigations carried out in the late fifties by Kryter [75-78] suggest that this may be the case and, that, although loudness is a major contributor to noisiness (the unwantedness of a given noise), the two concepts are not synonymous.

Kryter's findings were chiefly the outcome of a series of laboratory investigations of the subjective response to aircraft noises. In these studies, ratings based on laboratory jury judgments of propeller and jet aircraft noises were compared to ratings based upon computed loudness levels. The result of these comparisons revealed that, although the then available technique for computing loudness from physical attributes of the noise (Mark II of Stevens) resulted in noise ratings similar to those based on jury judgments for propeller aircrafts, the loudness computation consistently underestimated the noisiness or unwantedness of jet aircraft noises.

These findings led Kryter to investigate the relationship between loudness and noisiness further. In a series of laboratory investigations, loudness contours and noisiness contours for bands of noise and for pure tones were established and then compared [77]. These contours were determined by requiring subjects to equate in terms of both loudness and noisiness, bands of noise and pure tones, to a prescribed stimulus (e.g., a 1000 Hz tone or a band noise centered at 1000 Hz). The results of these studies showed that subjects responded differently depending upon whether they were matching the experimental stimuli for equal loudness or equal annoyance. Although the data obtained in this study showed a rather large scatter, Kryter concluded that his findings indicated that annoyance and loudness are indeed two distinct attributes of the human response to noise. Kryter's data reveal that the annoyance response at various frequencies is generally similar to the loudness response.

However, when loudness contours and annoyance (or noisiness) contours were compared it was found that at some frequencies marked differences were consistantly observed. For example, it was noted that at some frequencies annoyance contours were as much as 5 to 10 dB lower than corresponding loudness contours.

Findings of this kind led to the development of a new scale for assessing noise called the Perceived Noise Level (PNL). This method is basically modelled on Stevens methodology [60] derived from loudness experiments. Thus, as in the computational procedures for loudness, the band levels are measured, then weighted indices are applied, and results summed up to arrive at a single number index. Instead of assigning loudness indices to each measured band level, a perceived noisiness index is assigned. The unit of perceived noisiness is the noy and values are obtained from contours of equal "noisiness".

Since it was originally proposed, in the late fifties and early sixties, the PNL methodology has been further refined to account for discrete frequency components of tones associated with aircraft noises as well as for the fact that, everything else being equal, long duration flyovers are more annoying than short duration flyovers. [77,78] All of these developments involve detailed studies of noise spectrum and complex computational procedures which are embodied in a rating procedure known as the Effective Perceived Noise Level (EPNL). [79]

It must be emphasized that in the derivations associated with the noisiness methodology the same assumptions and mathematical derivations were utilized as in the scales based on loudness. The only exception as noted above is that the loudness concept is replaced by that of annoyance, where annoyance refers to the unwantedness or unacceptability of a noise. Furthermore, as in the development of methods based on loudness, methods based on annoyance were chiefly derived from laboratory investigations with relatively few ties to "real life" situations.

As noted previously, standard sound level meters have, for many years, included A, B, and C weighting networks which approximate equal loudness contours. Very recently, the "D-weighting network" has been standardized [80] for use in sound level meter measurements of aircraft noise. The D-weighting network has a frequency response that approximates the shape of the inverted 40 noy contour (which corresponds to a Perceived Noise Level of approximately 93 dB). While sound level meters do not sum contributions from different frequency regions in the same manner as is used in the computation of Perceived Noise Level, readings from a sound level meter using a D-weighting network should agree (within a known additive correction) reasonably well with calculated Perceived Noise Levels, at least in the range of, say, 80 to 100 dB, for most spectra of interest (the agreement would be expected to be worse for spectra that are shaped approximately like the 40 noy contour). Because of the high levels for which the D-weighting is intended, and because at present its use is normally restricted to outdoor aircraft noise measurements, it will not be considered further in this paper as a candidate for use in conjunction with building noise criteria.

4.3. Evaluation of Selected Noise Rating Schemes Which are Based Upon Speech Interference

One of the most widely recognized effects of noise is its ability to interfere with auditory communication. Noise intereference with speech is often cited as one of the most annoying aspect of living in a noisy environment; thus there has been considerable interest in schemes for rating the acoustical environment in terms of its potential for interfering with speech.

The determination of criteria based on speech communication should include consideration of three factors:

(1) the vocal power, as a function of frequency and time, achieved by various speakers under various conditions;

(2) the degree of speech recognition in the presence of various types of noise; and

(3) the definition of what constitutes acceptable speech communication for both speaker and listener.

Speech can be analyzed into a finite number of speech sounds which differ from each other in terms of their total intensity, length of build-up and decay, and the distribution of intensity with respect to frequency. For example, the vowels as a group carry relatively large amounts of energy which are distributed into harmonics of the fundamental frequency of the voice. These harmonics have distinguishable frequency regions which differ for each vowel. The consonants, on the other hand, carry much less energy but the little energy which they do carry is found in higher frequency regions than for the vowels. In general it is known that the frequency range of speech covers the whole region between 200 and 6000 Hz. However, most of the information contained in speech is carried by the consonants, which, because they carry little energy, are easily masked.

When one speaks, the various basic sounds are combined into orderly sequences of phonemes to form syllables which themselves are arranged into words and sentences. The result is an acoustical signal which constantly undergoes very rapid fluctuations both in intensity and in frequency. In order for a listener to understand speech he must be able not only to detect the various sounds but also integrate and recognize the constantly shifting patterns. When noise is present, some of the sounds and the shifting patterns are lost and the speech become more difficult to integrate. As a result, speech intelligibility deteriorates in amounts which are related to the intensity of the noise and to its bandwidth relative to those of the speech signal.

Observations such as these are the basis of the Articulation Index developed by French and Steinberg [81] as a means of predicting speech intelligibility from a knowledge of speech and noise spectra. This index represents a measure of the portion of speech which is available to the listener when communication occurs in a noisy system. In effect the Articulation Index takes into account the sound level differential between speech and noise (e.g., signal-to-noise ratio) in 20 contiguous bands located between 200 Hz and 6000 Hz which, under optimal conditions, would contribute equal amounts to the Articulation Index.

The basis for the Articulation Index can be summarized as follows: (1) the total variation in intensity levels of successive speech sounds is constant throughout each frequency region and roughly equal to 30 dB; (2) the relative occurrences of intervals of different intensities are roughly identical for each frequency region for both men and women;

(3) the levels of speech peaks, as approximated by the level exceeded one percent of the time (L_1), is about 12 dB above the long average intensity level at all frequencies of concern.

The Articulation Index, as computed from the signal-to-noise ratio in each of the 20 frequency bands which have been found to contribute equally to speech intelligibility, require frequency analysis in bands that are not commonly available. The American National Standard [82] Methods for the Calculation of the Articulation Index includes alternate procedures based on one-third octave or octave spectra.

The Articulation Index is based upon, and has been principally validated against, intelligilibity tests involving adult male talkers and trained listeners. It adequately predicts speech intelligibility in the presence of steady-state noise and contains provisions for predicting the effect of noise having a definite on-off cycle. It does not purport to predict the intelligibility of speech in the presence of fluctuating noise levels. The method cannot be assumed to apply to situations involving female talkers or children. It must therefore be used with caution in estimating speech interference in ordinary home and work situations. Finally, the complexity of the calculation procedure required to obtain the Articulation Index limits its usefulness in the measurement and monitoring of noise levels on a routine basis.

The Speech Interference Level (SIL), which is being proposed as an American National Standard, is a simple numerical method for estimating the speech-interfering aspects of noise based on physical measurements of the noise. Unlike the Articulation Index, SIL does not include specific consideration of the level and spectrum of the speech but employs a table or a monograph for estimating the noise levels which will seriously restrict speech communication in terms of general voice level and distance between communicators. Originally, the Speech Interference Level, SIL, was defined [83] as the arithmetic average of the sound pressure levels in the three (old) octave bands: 600 to 1200, 1200 to 2400, and 2400 to 4800 Hz. In terms of the new, or preferred, band-center frequencies [84], several definitions have been considered, two of which are worthy of note: (1) the "preferred-frequency speech interference level", PSIL, which is the mean of the octave band levels centered on 0.5, 1, and 2 kHz, and (2) the speech interference level, SIL (0.5-4), defined as the mean of the octave band levels centered on 0.5, 1, 2, and 4 kHz, which is the version being considered for adoption as an American National Standard.

For steady-state noises, each of the versions of the Speech Interference Level is a resonably accurate predictor of the relative ranking of noises with respect to their speech-interfering properties. That is, two noises which are equally-interfering with speech communication will have very similar Speech Interference Level ratings (typically within 5 dB). Speech Interference Level can be used for rough, quantitative estimation of monosyllabic word intelligibility in the presence of continuous, random noise. However this procedure is not appropriate for noise spectra with considerably more energy at high frequencies than at low or when any of the following conditions exist: (1) the level of the noise is not of a continuous-in-time, steady-state nature; (2) the frequency spectrum of the noise is not constant with time; and (3) the speech and noise are subject to perceptible echo or reverberation.

Webster and Klumpp [85] have developed charts which can be used to estimate the voice level and distance between talker and listener for satisfactory face-to-face communication as limited by ambient noise levels having various values of Speech Interference Level. For many types of noise, the Speech Interference Level can be approximated by the A-weighted sound level [86]. Because the A-weighted sound level can be read directly from a sound level meter, it is an easier measure to obtain than SIL. However, if significant high frequency energy is present, some caution should be exercised since sound level meter measurements tend to overrate the speech-interference properties of high-frequency noise.

While both the Articulation Index and the Speech Interference Level can be extremely useful, there is a need to develop predictive techniques for speech interference with male and female speakers, both adult and child, and untrained listeners in a real, rather than a laboratory, situations. Consideration should also be given to the additional problem of listeners suffering from impaired hearing. Statistical predictors need also to be made available which take into consideration the speech-interference aspect of rapidly varying and fluctuating noises such as those produced by heavy traffic.

The data base regarding voice level embodied in the speech interference schemes comes from a very limited set of measurements. The total number of talkers on which our present knowledge is based is surprisingly small (total 35 subjects). In addition, most of the data relate to male speakers and none are available on children's speech.

Crandall and McKenzie [87] used 5 male speakers. Dunn and White [88] studied the speech of 6 males and 5 females; Rudmose, Clark, Carlson, Iensenstein and Walker [89] used 7 males; Stevens, Egan and Miller [90] studied speech from 1 male and 1 female speaker; Benson and Hirsh [91] used 5 males and 5 females while Pickett and Pollack [92] used 5 males. Other speech data can be found in the literature; however, these data are traceable to the works already mentioned.

One of the most consistent findings among all the studies is the fact that there exists a great deal of variability among speakers. For example, Dunn and White report differences among speakers of the same sex of the order of 18 dB in some frequency regions, while Rudmose et al. report differences of the order of 10 dB. However, as observed by Galloway [93], when the data contained in the various papers are analyzed in terms of band levels relative to overall levels the variability of any given band is reduced to about 4-5 dB. Thus, one may conclude that while speakers vary greatly as to their power output, the various band levels relative to the overall are fairly stable from one study to the next. However, the total speech power output is an important determinant of the amount of energy available to the listener.

There are some discrepancies among the data of various researchers in terms of both the intensity level of speech and the form of the spectrum during "normal conversational speech." For example, Dunn and White in their study report a concentration of energy in the 500 Hz region in male speech which does not appear in the Benson and Hirsh data and is somewhat ambiguous in the Rudmose et al. data. In addition, Dunn and White report 66 dB (re 20 μPa) as the normal conversational level of speech at one meter for male subjects. This figure agrees well with the data of Rudmose et al. in which a value of 68 dB is reported (when computed from their reported sound power level) but disagrees with the value of 57 dB reported by Benson and Hirsh. The overall long-term, root-mean-square sound pressure level of normal male speech has varied among studies and among individual speakers within a given study, as indicated by the results shown in Table 1.

Table 1. Long-Term, Root-Mean-Square Speech Levels of Male Speakers, Corrected to a Distance of One Meter in Front of the Lips

Investigators	Sound pressure level, dB re 20 μPa		
	Mean of subjects	Max subject	Min subject
Dunn and White [88]	66	70	60
Rudmose, et al. [89]	68	72	60
Benson and Hirsh [91]	57	57	56

Since the total number of subjects on which the data are based is very small, and the variations among subjects are very large, it is impossible to assess the significance of the differences, both with respect to actual value and shape, found among the various studies.

In addition, some inconsistencies appear to be present in the speech spectra given in the American National Standard methods for the calculation of the Articulation Index. Specifically, if one uses the spectrum level (i.e., the level corresponding to a 1-Hz bandwidth) given in that standard for use in conjunction with the "20-band method" to compute the equivalent 1/3-octave band spectrum, differences ranging from 2-5 dB between the 20 band and the third-octave spectra exist at frequencies above 1000 Hz as shown in Figure 7a. Since both spectra are derived from the same data,

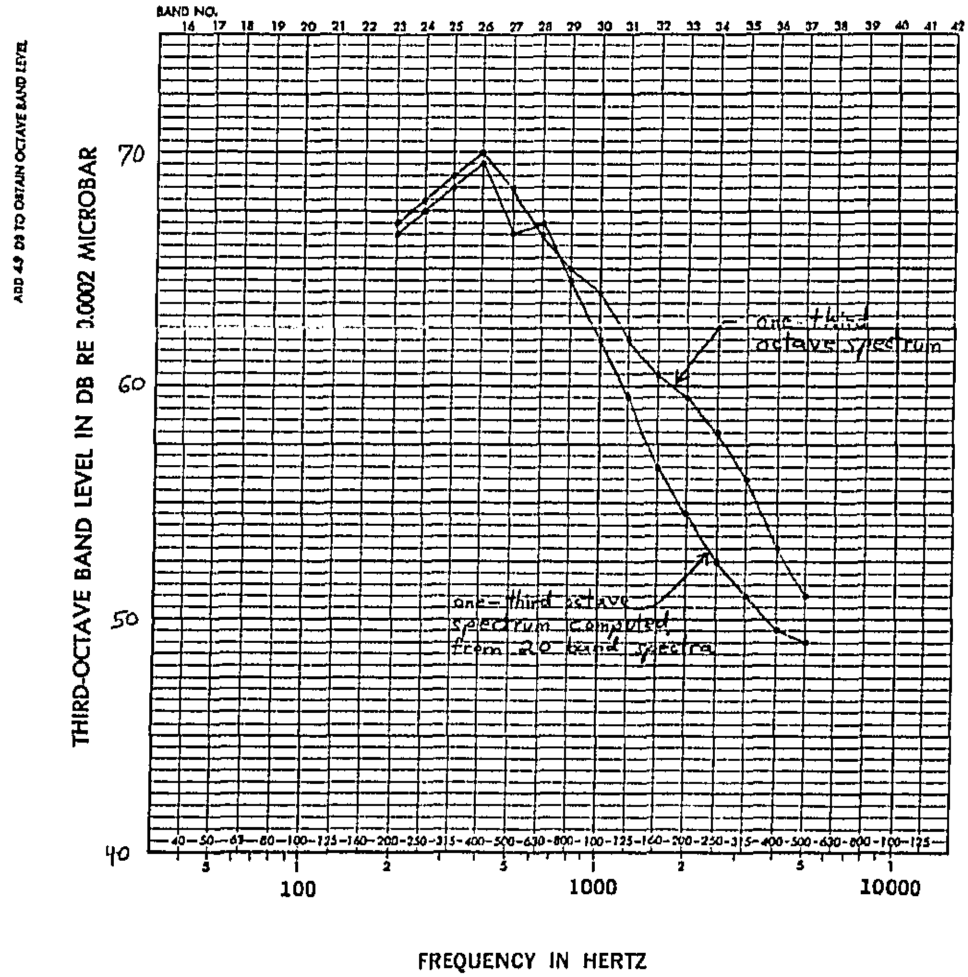


Figure 7a. Differences between spectrum level based on the 20 band and one-third octave band spectrum appearing in the ANSI standard for the calculation of AI.

and since both are purported to represent voice level during normal conversational speech, there should not be any difference between the two spectra.

An additional problem is associated with the speech data upon which all speech criteria rest. As observed by Galloway [93], in the development of the Articulation Index and other methodologies, only the data of Dunn and White were available to define the statistical distribution of speech level. Furthermore, since the Dunn and White data appeared to suggest that the statistical distribution of speech levels was similar in all bands for both male and female speakers only the data of the 1000 to 1400 Hz band obtained on male subjects was used in the development of the Articulation Index. These data were utilized to show that the dynamic range of speech is 30 dB and that the peak values, as approximated by the level exceed 1% of the time, are 12 dB above the long-term root-mean-square value over the frequency range of concern. Thus, present speech criteria are traceable to only one study of the statistical distribution of speech levels done 35 years ago and rests upon the data obtained on only 6 male subjects and in a frequency range between 1000 and 1400 Hz!

Although, Kryter [94] provides comparisons of predicted and measured intelligibility of speech in the presence of widely different noise spectrum shapes and various signal-to-noise ratios, his data validate the AI method only for continuous spectra and for male speakers. Since it is reasonable to assume that in most households women and children do talk, some would even say too much, it is unlikely that one could justify a design goal for dwellings on the basis of data that excludes both women and children!

DRAFT

4.4. Evaluation of Schemes Based Upon Consideration of Both Speech Interference and Auditory Magnitude

In an effort to "bridge the gap" between schemes developed chiefly from laboratory investigations of human response to noise and the real life situations associated with the experience gained by the consultant working in the field, Beranek [95] proposed the Noise Criteria Curves (NC) which embodies considerations of both loudness and noise interference with speech communication. It represents as far as is known to the present writer, the first attempt to arrive at criteria that are based upon both laboratory data and consulting experience gained in the field.

The Noise Criterion Curves, introduced in 1957, specify the maximum noise levels that can be present in each octave band of noise in order to achieve a specified NC criterion. These curves were derived from another set of curves, the Speech Communication Curves, SC. [96-97]. NC and SC curves are reproduced in Figures 8 and 9, respectively. The SC curves are somewhat similar to the NC curves except that in the case of the SC curves, the curves are approximately parallel and separated from each other by approximately 10 dB in most of the frequency range. The SC curves have steeper slopes at low frequency than do the NC curves. Although Beranek [97] did attempt to explain the actual process by which the SC curves were modified to become the NC curves, the process is not clear as pointed out by Schultz [98]. It can only be conjectured that the reason for the change was that the NC curves conformed better to the loudness contours, and, therefore may have been thought to be a better descriptor of the hearing mechanism.

The data on which the SC and NC curves were based included an extensive research program of attitudes and opinions of office workers

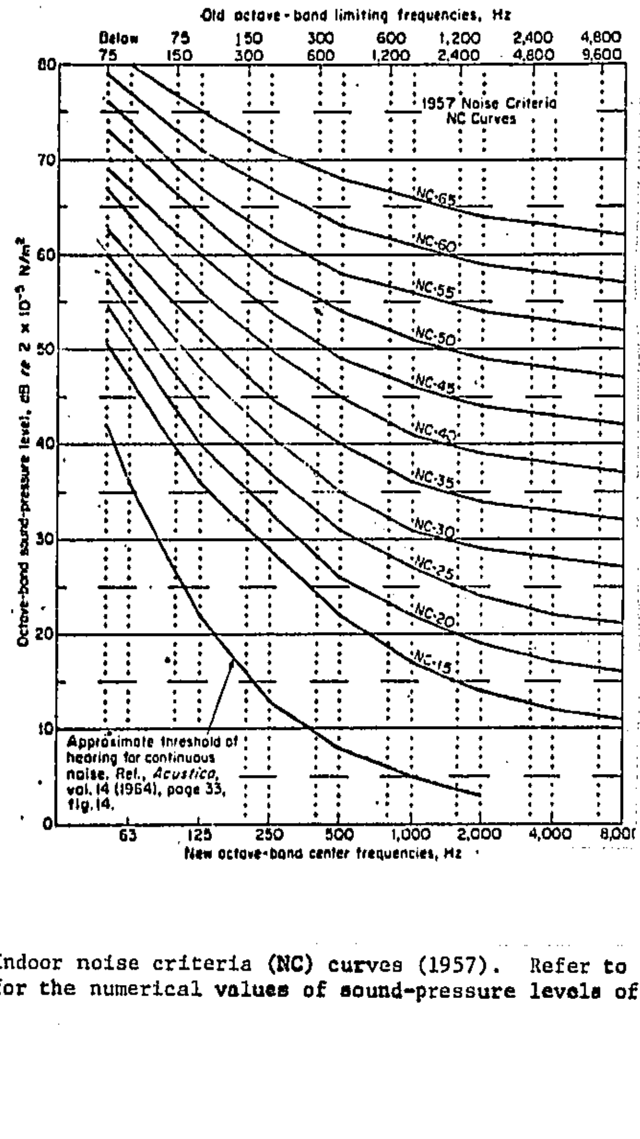


Figure 8. Indoor noise criteria (NC) curves (1957). Refer to Table 18.3 for the numerical values of sound-pressure levels of these curves.

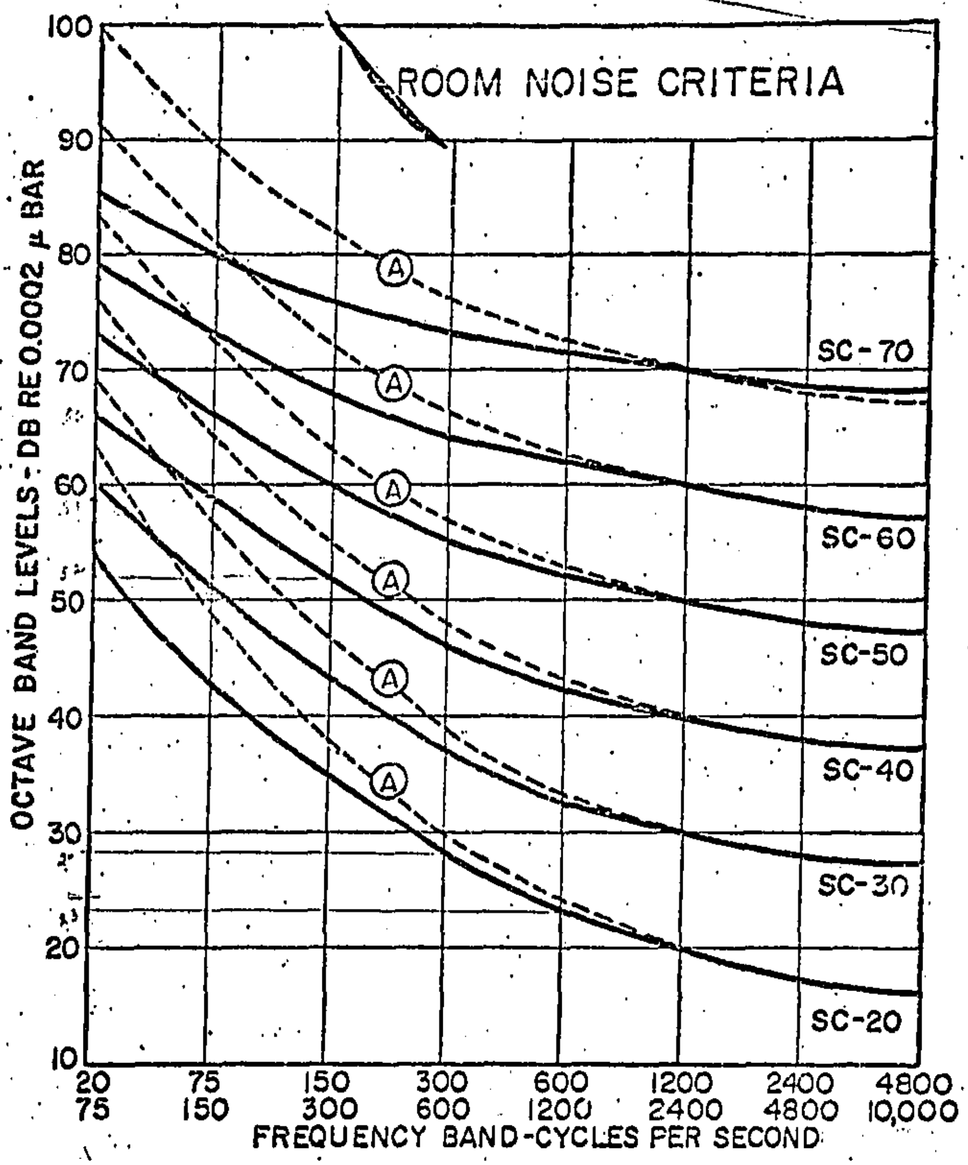


Figure 9. Speech Communication Curves (Beranek, 1956)

regarding noise and its effects on their ability to perform their work and to communicate by speech. These opinions were obtained through the use of rating scales. These were then correlated to various physical measures of the noises present in the offices studied. The respondents in these studies were chosen among office workers at a large Air Force Base and among office workers in several commercial office buildings where noise problems existed and had to be corrected because of occupant complaints [97,99].

The results of the office studies revealed that occupants were aware of ambient noise levels and their effects on speech communication. It was also found that low frequency sounds were annoying even though they were not sufficiently intense to actually mask speech sounds. Thus, two important parameters emerged as particularly useful in assessing the way in which people rate acoustic spaces in office buildings. These parameters were the Speech Interference Level, SIL, and the Loudness Level, LL. Furthermore, results indicated that if the SIL values did not exceed 40 dB and if the noise spectrum was maintained within a shape that yielded a loudness level (LL) that was 22 units above the value of the SIL, the noise was relatively acceptable to workers and did not interfere with speech communication. The SC curves were derived accordingly. In subsequent work, the NC curves were presented together with a table delineating the various NC Spectra which are compatible with various uses such as churches, hospitals, homes and others. [99] The origin of the values presented are unclear. They do, however, correspond closely to other criteria presented by Knudsen and Harris in terms of A-weighted Sound Levels. [100]

The NC curves have received widespread acceptance both in the United States and in Europe. They are often used as design goals for buildings. Rather similar curves, the Noise Rating Curves (NR) have been proposed as an international standard [101].

Recently it has been demonstrated that if one deliberately generates a spectrum which conforms with the NC curve the sound heard does not appear natural. It is even unpleasant because it is both "hissy" and "rumbly". [102] These observations suggest that the effect of the low frequencies and high frequencies upon human response were underestimated by the NC curves. As a result, a new set of curves, the Preferred Noise Criterion Curves, PNC, have now been proposed as a replacement for the NC curves [102,103]. This new set of curves, shown in Figure 9, are lower at both high and low frequencies than the original NC curves. Although, the new PNC curves have now been proposed for a few years (1971), there does not appear to be a great deal of human response data to support their adoption.

In view of the acceptance usually given to the Noise Criteria approach, and the recently expressed dissatisfaction with the methodology, it may be of interest to examine the data base upon which it rests more critically.

It may be observed that most spectra published in the early studies had, for the most part, a shape which did not conform to that of the NC curves. In some instances the published spectra differed from the NC curve that most closely fits the major portion of the noise by 8 to 15 dB at some frequencies. The proposed PNC curves do appear to remedy that situation, although still not completely doing justice to the very low or very high frequencies.

In addition, it may be observed that the motive for the original studies of Beranek was the existence of a deplorable situation which

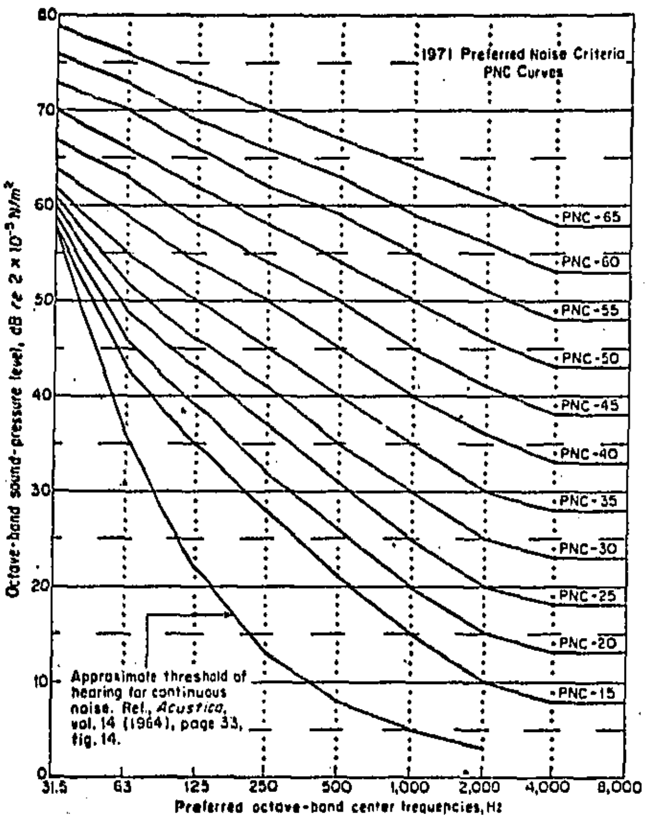


Fig. 9. Preferred noise criteria (PNC) curves (1971).

had resulted in complaints; thus, the purpose of studying the noise situation was to lower the rate of complaints to acceptable levels. While this practice is consistent with a consulting view point, it is a "far cry" from developing design goals based on optimum conditions.

Furthermore, all the data on which the NC type methodology is based comes from investigations of the "requirements" of office workers and relate to noise spectra found in offices. Although the methodology was extended to other types of buildings including dwellings, there is no evidence that requirements for quiet in the home are identical to those of offices. Consequently, there exist some real but unanswered questions regarding the validity of extending this approach to the problem of noise in dwellings.

Another important drawback to the NC methodology is that available data relate primarily to continuous noise spectra, thus neglecting to account for the time variation of the noise which is probably important in the assessment of interior spaces.

4.5. Evaluation of Schemes Based Upon Consideration of Community Response to Environmental Noise

Since the early 1950's, a number of investigations in various countries have involved social surveys and physical measurements of noise to assess the effects of environmental noise in residential areas.

Although all of these studies had basically a similar goal -- to arrive at a methodology for relating the human response (to environmental noise in residential areas) to the physical attributes of the noise -- a variety of methods have evolved. These include, for example, the

Community Noise Rating (CNR), the Noise Exposure Forecast (NEF), the Community Noise Equivalent Level (CNEL), the Noise and Number Index (NNI), and the Traffic Noise Index (TNI).

A priori, it may appear that these ratings are widely different; yet they share many attributes. The similarity among ratings is reflected by the fact that there exists a high degree of correlation among all ratings of community noise, of the order of 0.9 [104]. Furthermore, predicted community responses derived from the use of these schemes are remarkedly similar.

Basically, there are two ways of assessing community response to environmental noise exposure. The first one consists of examining the action taken by individuals, or groups of individuals, against identifiable noise sources, such as complaints to officials or law suits. The second approach consists of examining the responses made by people interviewed in social survey questionnaires.

The results of the various social survey questionnaires which have been performed in the United Kingdom [104,108], Sweden [109-112], Austria [113,114], France [115-118], the Netherlands [119] and the United States [120] reveal that people who are exposed to various environmental noise levels in residential areas show a general adverse reaction to noise. The magnitude of this response is related to the level of the noise, to its spectrum, to the variation of both these quantities with time, as well as to some socio-economic variables and attitudes.

The adverse general reaction of people to noise is complex and involves a combination of such factors as interference with speech communication, interference with sleep, a desire for a tranquil environment, and the ability to use telephones, radios, and TVs satisfactorily. In addition, this response, which generally is presented in terms of the percent of people in a given population that express a "high degree of annoyance" on a social survey, is predictable and stable when expressed in terms of the average response of groups of people. This is not to say that people have the same susceptibility to noise. Indeed they do not, as can be shown by the fact that in practically all studies a poor correlation, usually under 0.5, exists between noise ratings and individual annoyance scores. Even groups of individuals are found to vary in response, depending upon previous exposure, socioeconomic status, age, political cohesiveness, and other social variables. However, results of all studies reveal that in the aggregate, the <u>average</u> response of groups of people is highly correlated with a number of different measures of cumulative noise exposure.

The findings of social surveys are in agreement with the general finding based upon examinations of overt responses to the noise. Actions against noise may take various forms, ranging from the registration of a complaint to an offical to actual court actions. Although complaints have been found to be only a partial indicator of the number of people annoyed in a community, there do appear to be predictable relationships among annoyance, as reported in social surveys, rate of complaints, and environmental noise levels [121].

While it is not the intent of this section to review the various rating schemes, the evolution of one of the families of community noise assessment procedures is given to illustrate the common elements among schemes which, a priori, may appear to be widely different.

In the United States, the first method proposed for assessing community reaction to noise was that of Bolt, Rosenblith and Stevens [122], known as the Composite Noise Rating, CNR.

This method was the outgrowth of the concern of governmental agencies with aircraft noise. It was originally proposed only as a scheme for explaining the community reaction to actual noise exposure in a series of about eleven actual case histories involving different types of noise sources. It was therefore a method derived from consulting practice and from interpretation of the research data then available.

The original Composite Noise Rating required that the noise be measured and graphed as octave-band sound pressure levels. The resulting graph would then be compared to a family of curves which somewhat resembled loudness contours and which were separated by 5 dB in the region of the mid-frequencies. On the basis of these comparisons, a noise rank level was assigned to the noise, according to the highest rating curve into which a measured spectrum intruded. The value thus obtained was then adjusted by a series of noise corrections based on: noise spectra, ambient community levels, "intrusiveness", "impulsiveness", "repetitiveness", and previous exposure of the community. In addition, corrections were applied for the time of day and the period of year during which the noise intruded.

Each correction factor had the effect of either raising or lowering the rank level originally obtained. In addition, a range of community responses consisting of five discrete points were provided for the purpose of estimating the probable effect of a given noise. These reactions were: No reaction, sporadic complaints, widespread complaints, threat of legal action, and vigorous community reaction.

Since its proposal, in 1955, the method has undergone numerous changes. One of the most important was the substitution of the Perceived Noise Level (see Section 4.) as a means of determining the noise level rank. In addition, refinements were added to the correction system. Finally, a scheme for computing the effects of a large number of separate events was incorporated into the system. Eventually the method was modified into what is now the Noise Exposure Forecast [123] which is part of the procedure [124] utilized by the Federal Aviation Administration for assessing land use around airports.

Recently, the U.S. Environmental Protection Agency has made an effort to simplify and integrate the accumulated knowledge concerning noise. effects and has proposed the Day-Night Sound Level (L_{dn}) as a basic measure of environmental noise [125,126]. This measure is conceptually similar to the other rating schemes, as exemplified by the discussion of CNR above, but has been judged by EPA to be simplier to use.

In order to test the applicability of using rating schemes derived on the basis of outdoor levels to the rating of interior spaces, it is necessary to establish the relationship between indoor and outdoor sound levels. With this goal in mind, a set of indoor and outdoor data that were obtained in an earlier EPA Study [127] have been analyzed further. In the EPA Study, indoor levels were measured at the same time as outdoor levels at 15 sites in urban residential areas located away from any major identifiable noise source such as a highway or an airport. Although the EPA Study included a set of 15 sites only 12 among these contained sufficient data for the present analysis. In this study, noise measurements consisted of continuous monitoring and recording of

A-weighted sound level on digital tape. From these data, hourly average sound level (L_{eq}) had been derived for each site and for both indoor and outdoor conditions. These hourly average levels provide the data for the analyses reported here.

From these data, the average sound levels (L_{eq}) for various periods of time were computed for each site and for both indoor and outdoor conditions. Computations were performed for daytime (0700-2200), nighttime (2200-0700), evening (1900-2200) and the middle of the night (0100-0500). The results of these calculations are presented in Figures 10-13a where each data point represents a site, and the average indoor sound levels (L_{eq}) are plotted versus the outdoor levels. From these data, the mean sound level (e.g. arithmetic mean for the 12 sites), and the standard deviation about that mean, were computed for both outdoor and indoor conditions and for each time period. In addition, the correlation coefficient between indoor and outdoor sound levels for each time period were determined. The results of these computations are summarized in Table 2. Inspection of the entries in this table reveals that the correlation between indoor and outdoor sound levels is extremely weak, (0.3 or less) except during the late night hours, from 1 a.m. to 5 a.m. when the correlation coefficient is 0.54. Furthermore, despite the noise isolation provided by the building structure, measured indoor levels were slightly higher than those measured outdoors during the period extending from 7 a.m. to 10 p.m. During the evening hours from 7 p.m. to 11 p.m. both the indoor sound levels and the standard deviation exceeded those observed outdoors significantly. During the late night hours from 1 a.m. to 5 a.m. the indoor noise levels were markedly lower than those measured outdoors, 37 dB versus 50 dB.

Indoor vs. Outdoor Energy Means For 12
EPA Sites (Averaged over hours 07-22)

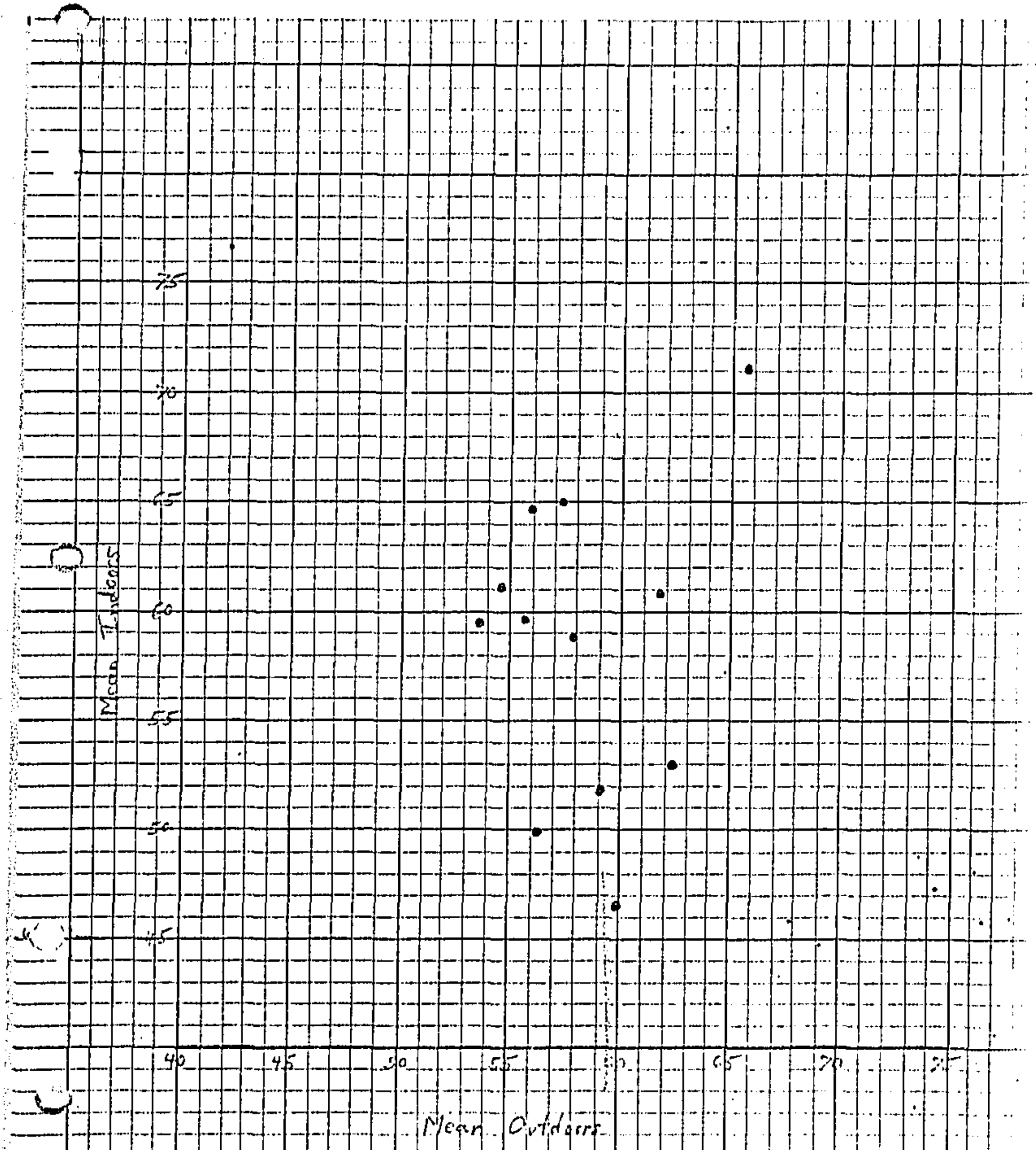


Figure 10

Indoor vs. Outdoor Energy Means for 12
EPA Sites (Averaged over hours 22-07)

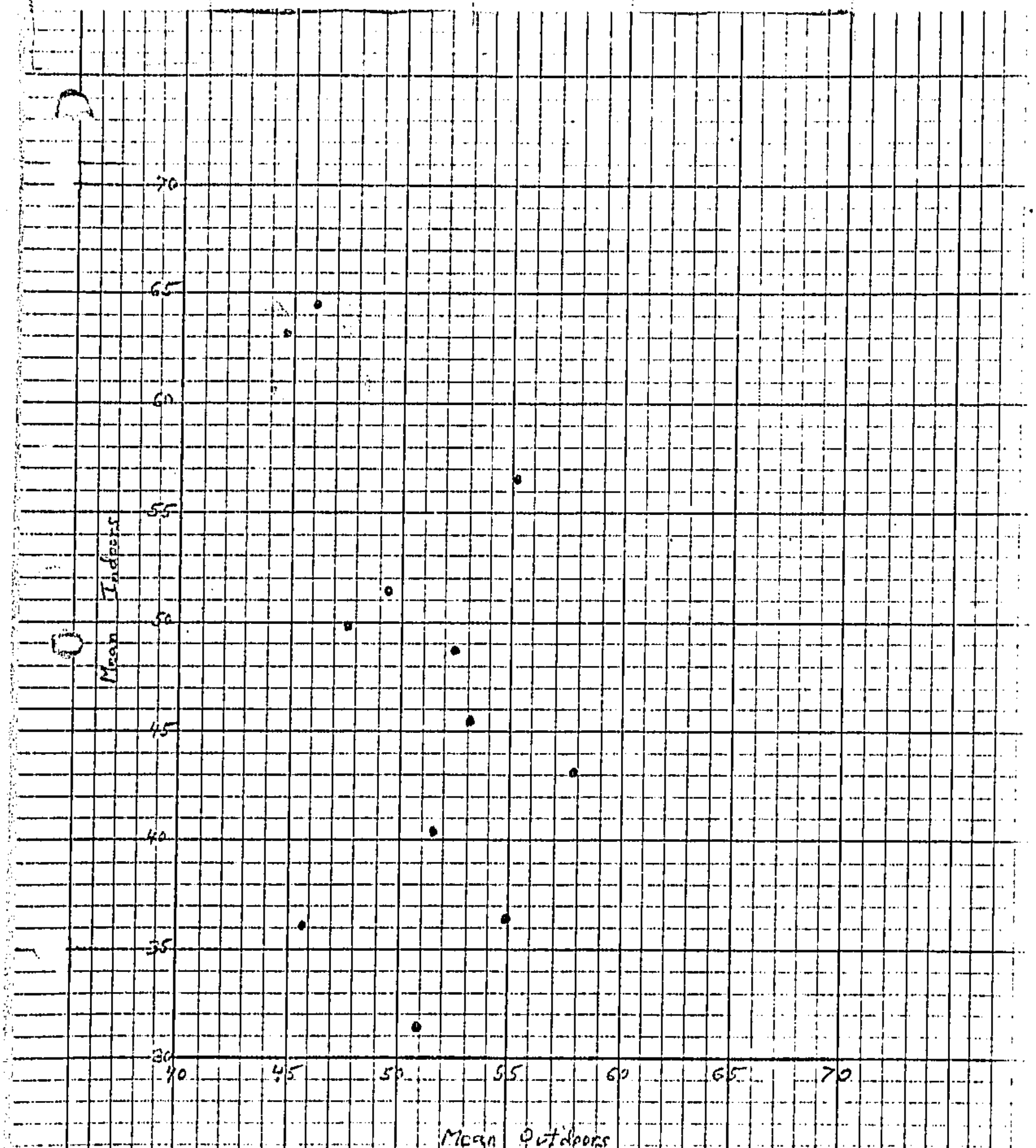


Figure 11

Indoor vs Outdoor Energy Means for 12
EPA Sites (Averaged over hours 19-22)

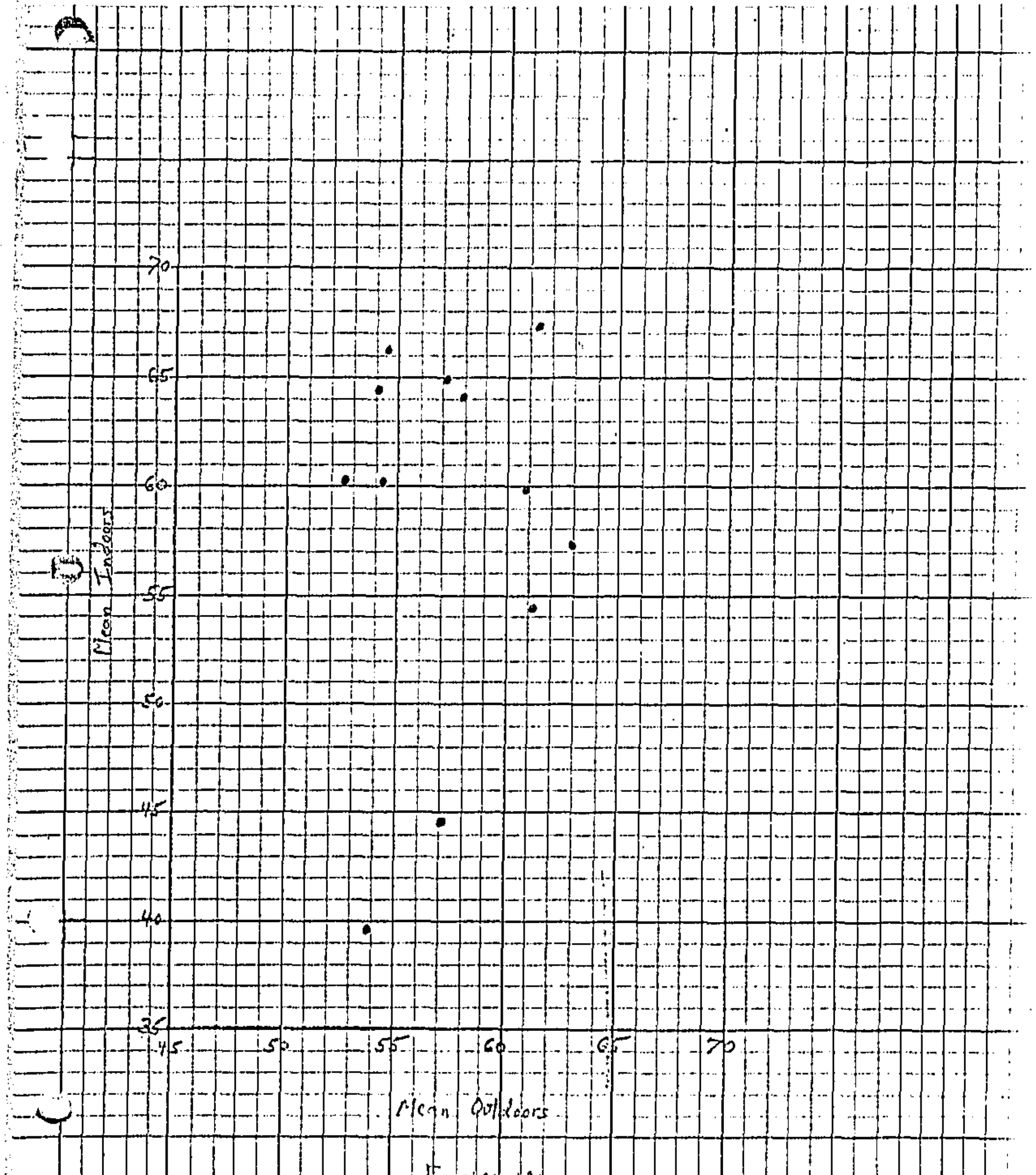


Figure 12

Indoor vs. Outdoor Energy Means for 12
EPA Sites (Averagedoover hours 01-05)

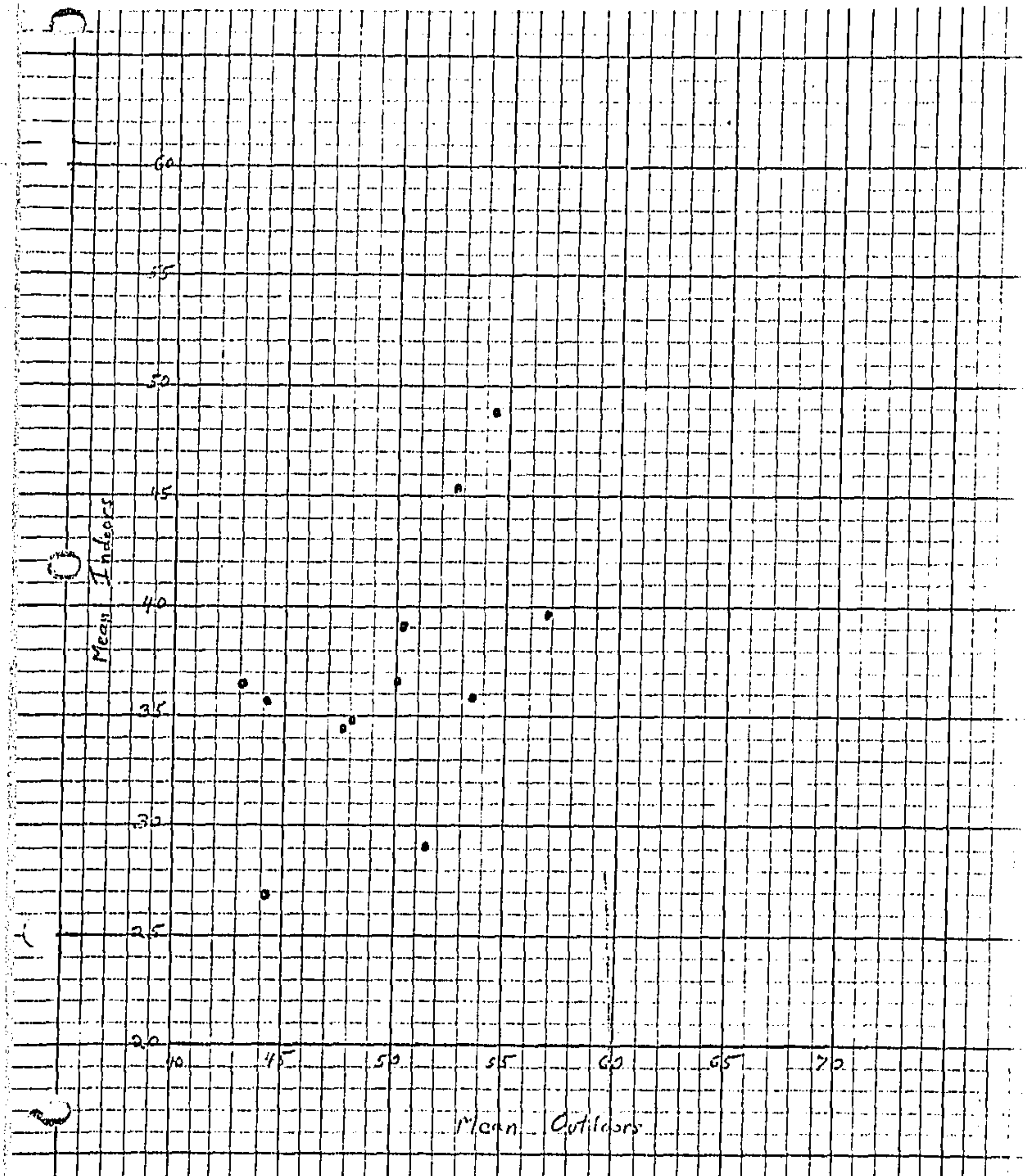


Figure 13

Table 1.

Comparison of Outdoor and Indoor Sound Levels
for a Set of 12 Sites Located in Urban Residential
Areas Away from Any Major Identifiable Noise Source.

Time of Day

	Daytime (0700-2200)	Nighttime (2200-0700)	Evening (1900-2300)	Late at Night (0100-05000)	L_{dn} L_{dn}
Outdoors					
mean sound level in dB	58.3	51.4	57.3	49.7	59.9
standard deviation in dB	3.5	4.0	3.5	4.4	3.7
Indoors					
mean sound level in dB	58.5	47.0	58.6	36.9	59.9
standard deviation in dB	7.0	10.4	8.6	6.0	7.7
Indoor/ Outdoor Correlation Coeff.	0.1	- 0.3	0.1	0.54	-0.2
Difference between indoor and out-door levels	+0.2	- 4.4	1.3	-12.8	0

The minimum indoor level which occurred during the middle of the night (e.g., 0100-0500) hours, when most people are likely to sleep, is probably governed by the intrusions from outdoors in the majority of cases. However, during the day and the evening, when people are awake and active, the indoor sound levels appear to be chiefly due to the activities of the tenants, including speech, use of TV, radios, household appliances, home tools and the like. Furthermore, the large standard deviations observed with indoor noise levels during the day and the evening, relative to those associated with outdoor levels, suggest that people's activities vary considerably from household to household, depending upon the size of the families, the age of family members, socio-economic status and other variables. Unfortunately during the course of the EPA Study, no data were obtained on these matters so that this hypothesis cannot be tested.

The conclusions of the analyses performed during the preparation of this report must be interpreted with great caution since the sample on which the data are based was very small (12 cases) and drawn from a limited population that not only does not represent all types of environments in which people live but which intentionally excluded noisy areas such as those around highways and airports. Nevertheless, the data presented above suggest that in relatively quiet urban residential areas, were outdoor Day-Night Noise Levels (L_{dn}) range from approximately 52 to 65 dB, and where no major highway or airport are present, indoor sound levels appear to be primarily related to people's activities. During the nighttime, when people are asleep, the acoustical climate of the home appears to be determined by the outdoor intrusions. Typically, indoor noise levels have been estimated from outdoor noise measurements by subtracting the estimated noise isolation provided by the structure.

This procedure may be questionable in view of the results of the above analyses, at least insofar as residential areas located away from major highways or airports are concerned. The practical implication of this finding is that, for those people who live away from major identifiable noise sources, controlling noise sources outdoors may have little, if any, effect on the noise climate of the home given that the noise isolation provided by the building is at least as good as in the 12 cases studied.

5. Conclusions

In the previous sections of this report an evaluation has been made of methods that could be utilized to specify noise criteria for dwellings. The purpose of this examination was to select criteria which are practical, but relevant from a human response viewpoint, and which could eventually be incorporated into building codes.

A review of the literature indicates that building codes typically approach noise control problems in dwellings through specification of the acoustical properties which building elements must achieve in order to be acceptable. The emphasis in the past has been on interior partitions such as party walls and floor-ceiling assemblies. Social survey data clearly indicate that people's responses to indoor noise are somewhat dependent upon the acoustical climate outdoors. For example, people who live in noisy areas are less aware of their neighbors' noises than are people who live in quiet areas. Yet none of the national building codes has included requirements for outdoor-to-indoor isolation. In fact, at the present time, a standardized method for the measurement of outdoor-to-indoor noise isolation does not even exist.

In Section 2 of this report, it was noted that much of the research effort in this area has focused primarily upon the development of single-number rating schemes for specifying the performance of partitions. Typically, these schemes are based upon the comparison of a measured transmission loss curve with a standard grading curve. Precise and well-defined rules exist for making the comparison; yet, there exist very little back-up data, from a human response point of view, to support the selection of the curve against which partitions are judged.

As was shown in Section 2, unresolved questions exist regarding the most appropriate shape for the grading curve, its cut-off points, the meaning of departures from the curve and the importance of coincidence dips. As was shown in the recent French study discussed in Section 2, it appears that dwellings that conform to requirements derived from the grading curve do not provide sufficient noise isolation since, in this study, 40 percent of people living within such dwellings complained about their neighbors' televisions and radios. In addition, since differences in workmanship can significantly affect the performance of a partition and since, in actual constructions, there may exist serious flanking paths, the specification of a minimum transmission loss for a partition, does not guarantee adequate noise isolation as witnessed by the observed discrepancies between laboratory tests results and actual field performance.

The need to shift the emphasis in building codes from sound transmission loss (of partitions) to noise reduction (expressed in terms of a level differences between spaces) was discussed in Section 3 of this report. It is recommended that the primary building code requirement should be on the achieved noise reduction between two spaces. This is not to say that specifications of sound transmission loss should be dropped altogether but rather that these should be used primarily as tools to be utilized by the building designer as means of achieving the desired performance. Consequently, the main objective in a building code should be the isolation required and not the sound transmission loss, or insulation, that may or may not lead to that isolation. In fact, several levels of measurements should be specified:

(1) Laboratory measurements to develop design data on potential performance of partitions;

(2) Pass/Fail field measurements of isolation, designed for the use by personnel untrained in acoustics, which can be used to separate clearly acceptable performance from clearly unacceptable performance;

(3) Refined measurements of isolation that can be used to address those cases that cannot be adequately resolved by the Pass/Fail procedures.

Suggestions such as those described in Section 3 of this report, and above, are certainly a step in the right direction. However, in considering the development of noise criteria for dwellings it is important to keep in mind that people respond to their environment as a whole and not to the noise isolation or the characteristics of intruding noise, per se. Consequently, the major task which confronts acousticians is that of choosing a scheme for rating the interior acoustical environment. Once such a scheme is selected and people agree to adhere to it, the noise isolation required to achieve the desired goal can easily be inferred.

The development of a methodology for rating the interior environment is difficult, as was discussed in Section 4. Since human response to noise cannot be measured directly with presently available techniques and instruments, there is the need to develop schemes for inferring human response to noise from the physical and measurable attributes of the noise. To provide such a scheme it is necessary to choose which aspect(s) of human response is of most concern. Is it loudness, noisiness, interference with speech communication, interference with sleep, or interference with the ability to use TV and radio satisfactorily?

In order to illustrate the importance of this choice, calculations were made of the isolation that would be required, for a particular source room spectrum, in order to reduce the noise level in the receiving room so as to satisfy each of several criteria. The spectrum used corresponded to the octave band levels exceeded ten percent of the time in van den Eijk's study [18] of radio programs. Two attributes of human response were studied. "Loudness" was computed using the procedures of Fletcher and Munson [19], Stevens Mark VI [20,67], and Stevens Mark VII [21]. "Noisiness" was computed using Kryter's Perceived Noise Level, as now standardized [25,26,124]. In addition, computations were made using the A-weighted sound level, which is widely used as a surrogate for loudness and the general adverse response to noise. For each scheme used to rate the noise in the receiving room, computations were made of the isolation required so that each octave band contribute equally to each of the ratings; that is, the contribution to loudness, "noisiness", or A-weighted level of each octave band would be the same. In order to tie the five schemes together, the isolation was computed that would result in the "loudness", "noisiness", or A-weighted level rating in the receiving room being equivalent to the sensation produced by a band of noise centered at 1 kHz having a sound pressure level of 40 dB re 20 μPa. The results of these computations are shown in Figure 14. It can be seen that, depending upon which rating scheme is utilized to define the noise environment in the receiving room, curves of isolation versus frequency are derived which differ both with respect to shape and actual values of isolation. Note that if the A-weighted level is used to rate the receiving room spectrum the required isolation is much less than for loudness or noisiness. This occurs because the perceived magnitude of

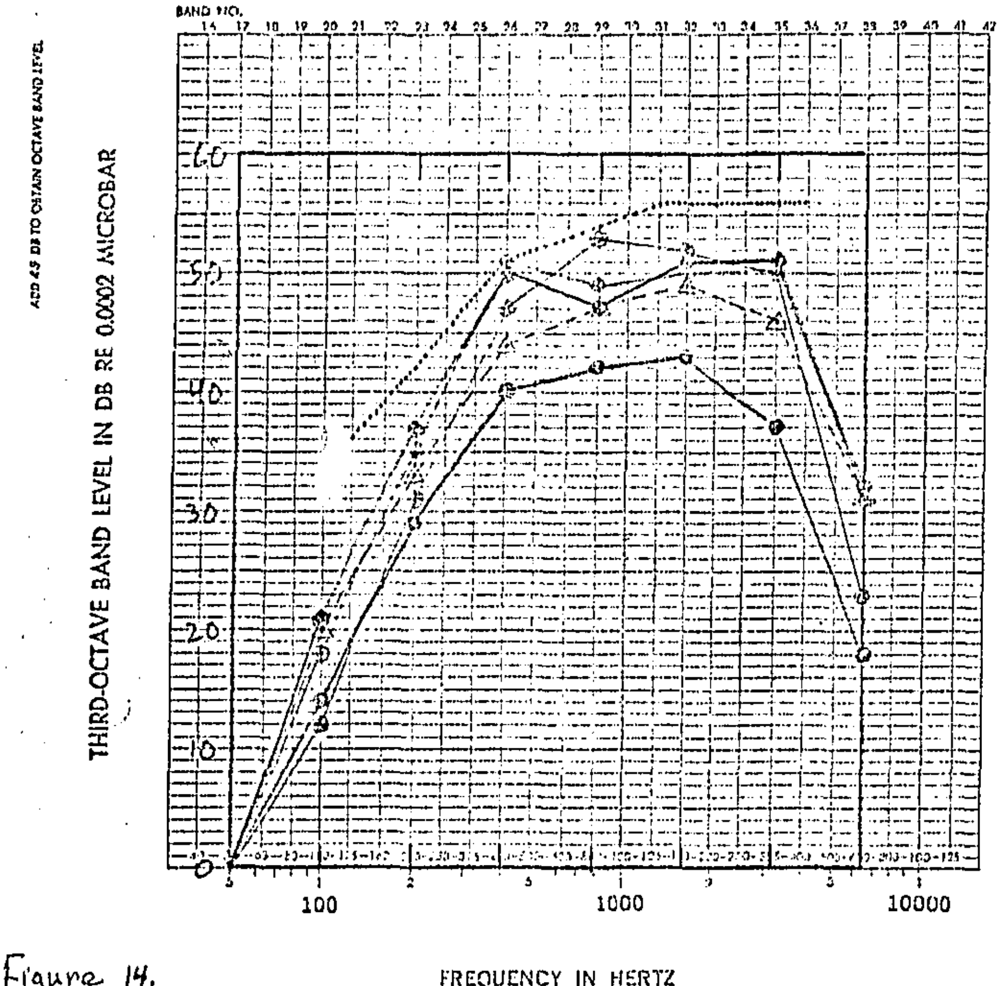


Figure 14.

—o— Fletcher and Munson

--△-- Stevens Mark VI

—o— Stevens Mark VII

—o— Perceived Noise Level

—o— A-weighted

.... NIC-52

broad-band noise increases more rapidly with bandwidth than does the sound level.

In order to examine further the effect of the rating scheme (for the receiving room noise) on the shape of the required isolation curve, a number of computations were performed using other typical indoor and outdoor spectra, shown in Figures 15 and 16 , respectively. Using these spectra, the isolation required in order that each one-third octave band contribute equally to each of several rating schemes of the receiving room spectrum were derived. Specifically, the isolation required in each one-third octave band was computed so that the receiving room spectrum shape conforms to that of a PNC-35 contour, a 1 sone contour (Mark VII), a 1 noy contour, or an inverted A-weighting contour which are shown in Figure 17 . Since only the shapes of the isolation curves are being examined in these computations, all of the curves were normalized to a common value at 1 kHz. The shapes of the isolation-versus-frequency curves needed to maintain these spectral shapes in the receiving room are shown in Figure 18, 19 , and 20 for source room spectral shapes corresponding to Northwood household noise, speech, and a food blender, respectively. For household noise and speech, the computed isolation requirements above approximately 1000 Hz do not increase as rapidly with frequency as does the actual isolation to be expected from typical party walls between dwelling units. Thus, unless there is an unusually severe coincidence dip in the frequency range above about 1 kHz, the overall rating of the noise isolation between spaces would be governed by the isolation in the frequency range from, say, 125 to 500 Hz. On the other hand, for a source having a spectrum such as that shown for the food blender, the overall rating of noise isolation would

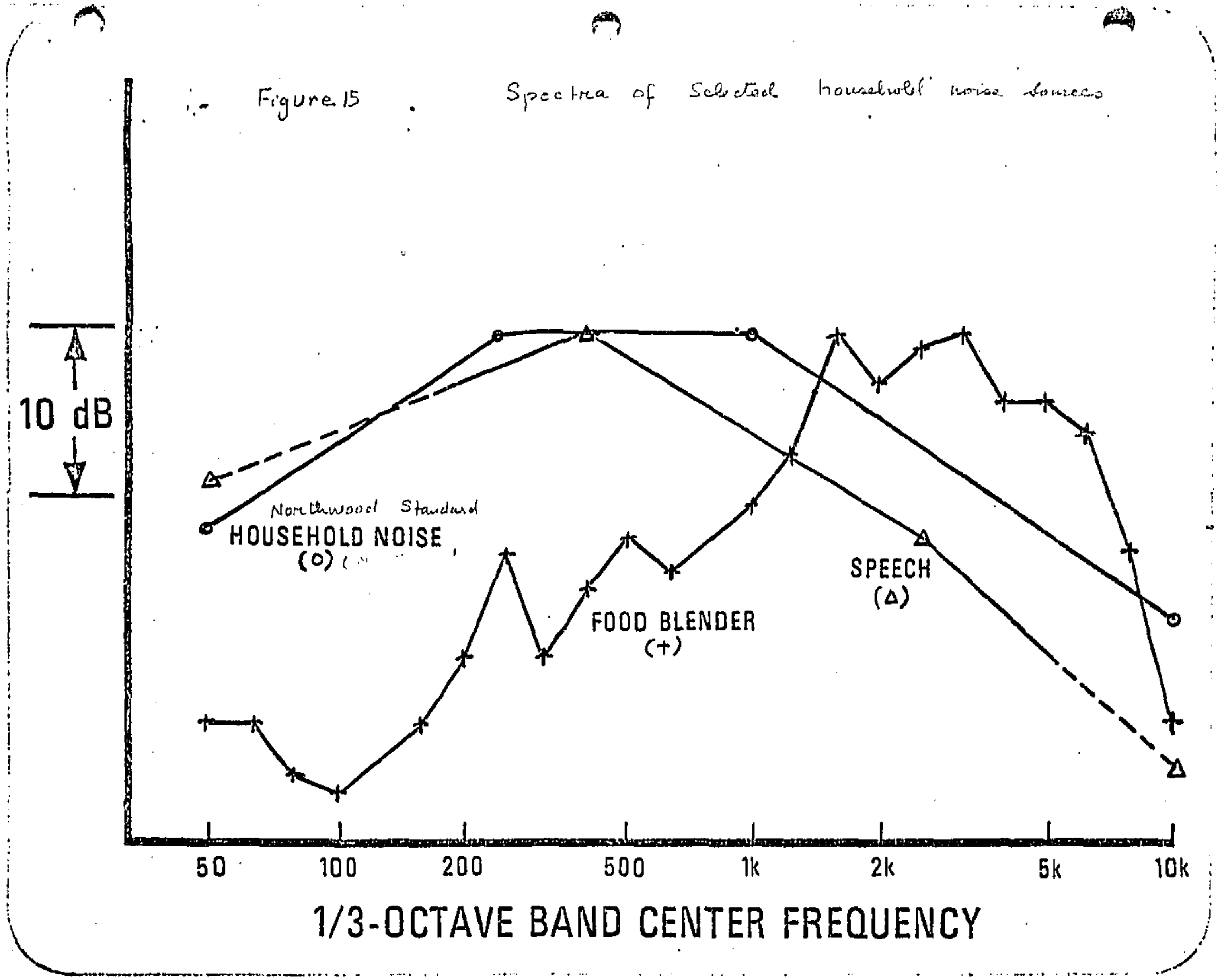
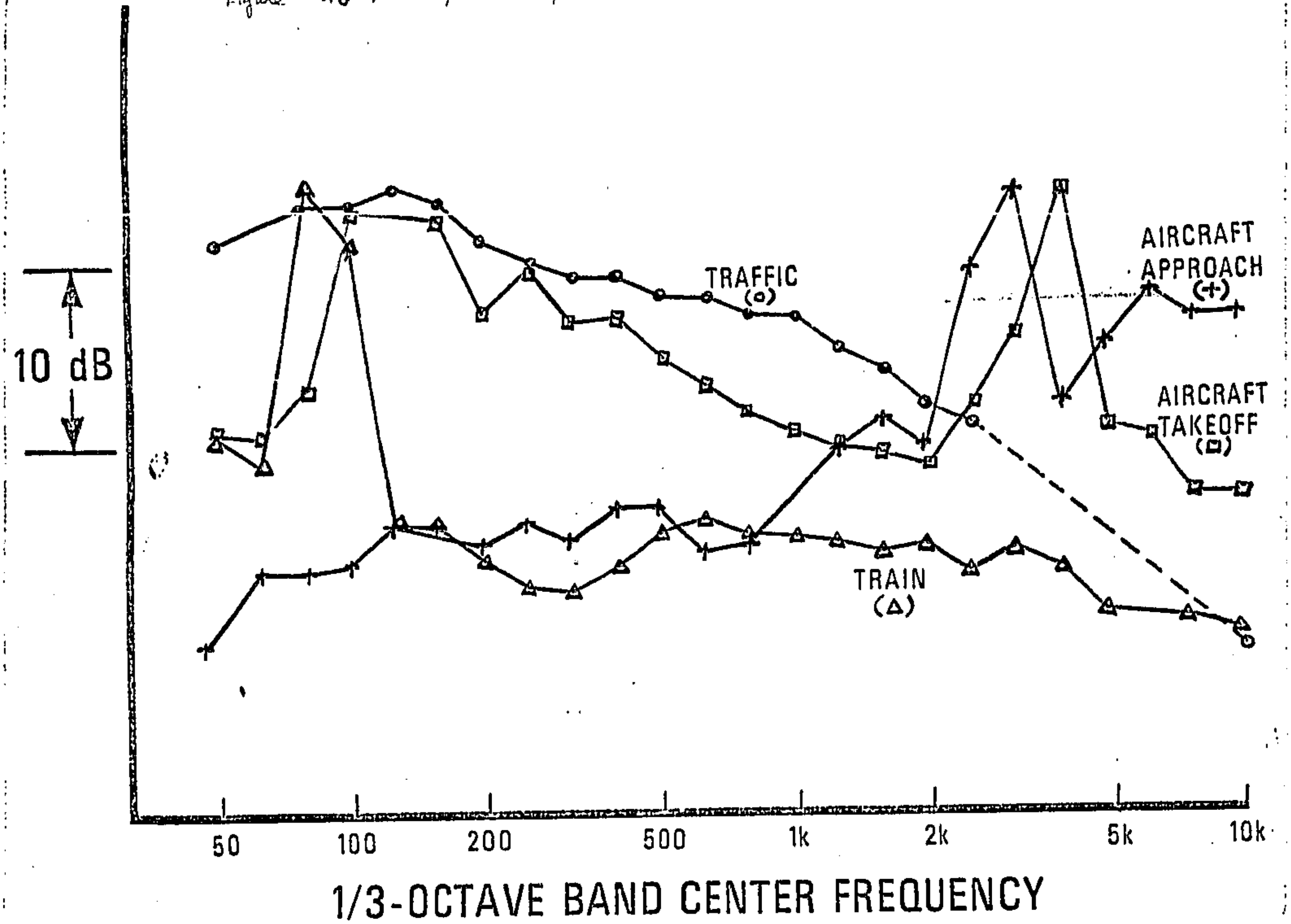


Figure 15
Spectra of Selected household noise sources
10 dB
Northwood Standard
HOUSEHOLD NOISE
(O)
SPEECH
(Δ)
FOOD BLENDER
(+)
50
100
200
500
1k
2k
5k
10k
1/3-OCTAVE BAND CENTER FREQUENCY

Figure 16. Spectra of Selected Outdoor Noise Sources.



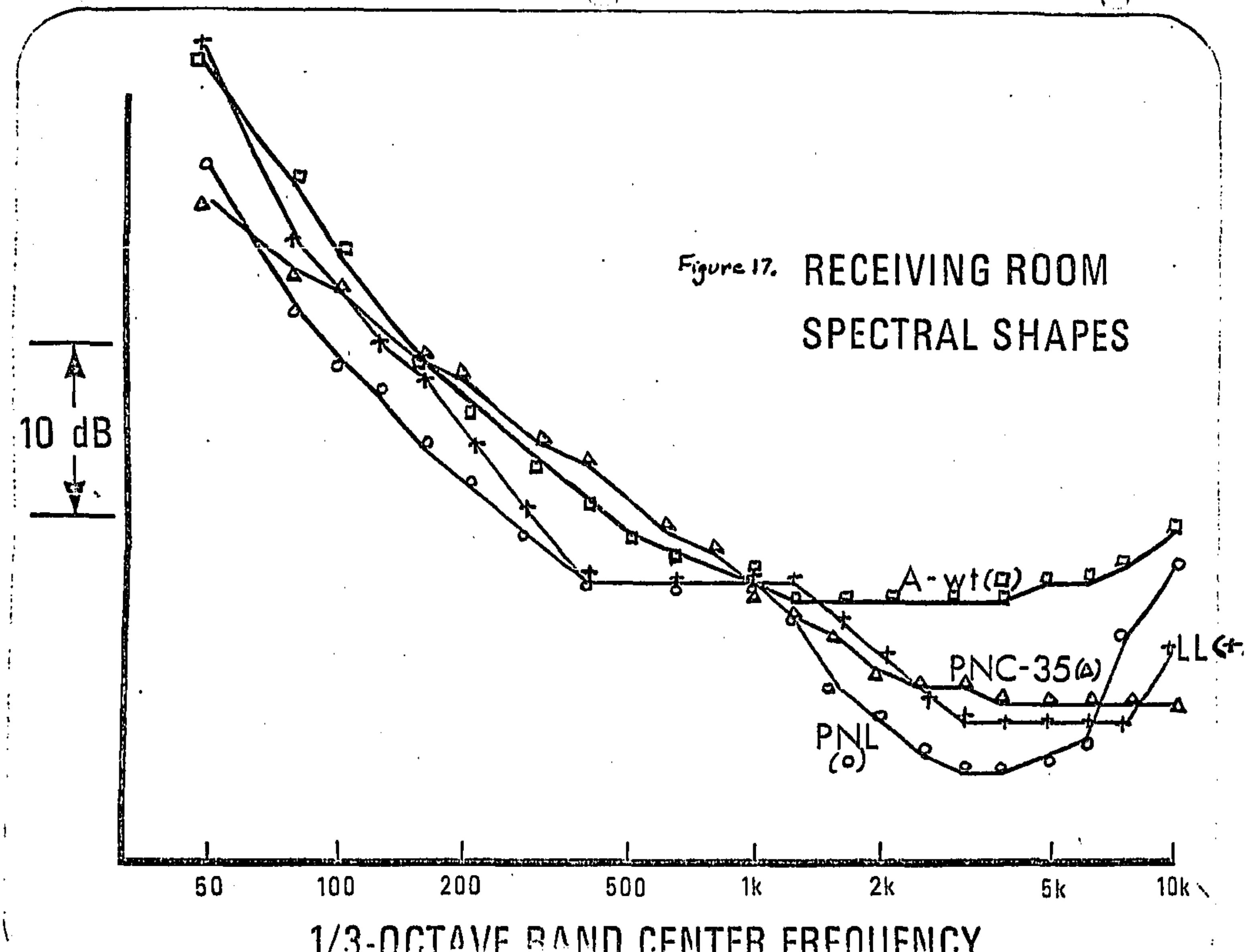


Figure 17. RECEIVING ROOM SPECTRAL SHAPES

Figure 18. NOISE ISOLATION Required to maintain PNC-35, inverted A-contour, PNL 1 Noy and Loudness of 1 Sone in Receiving Room for Household Noise

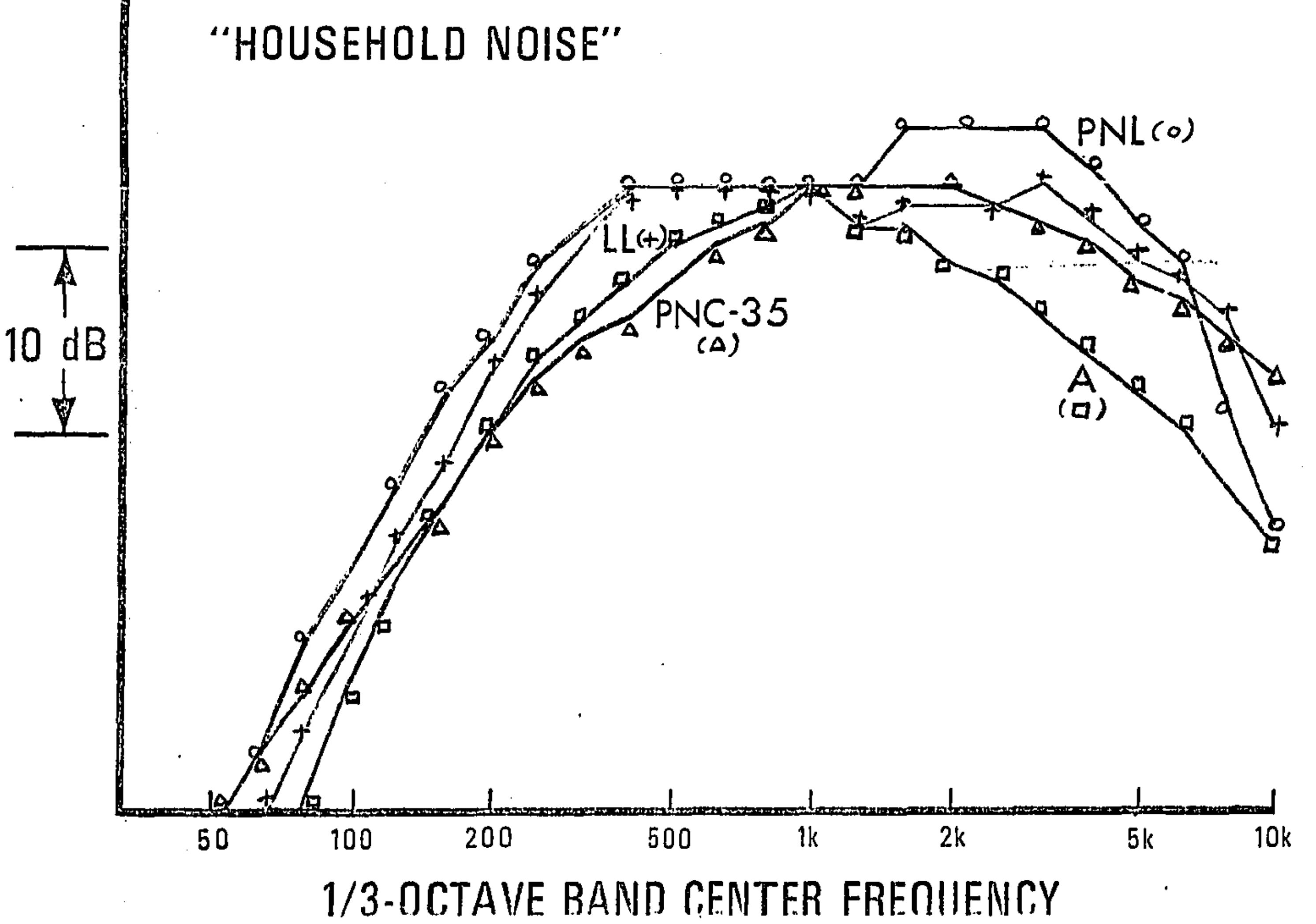


Figure 19. NOISE ISOLATION Requirements for Speech

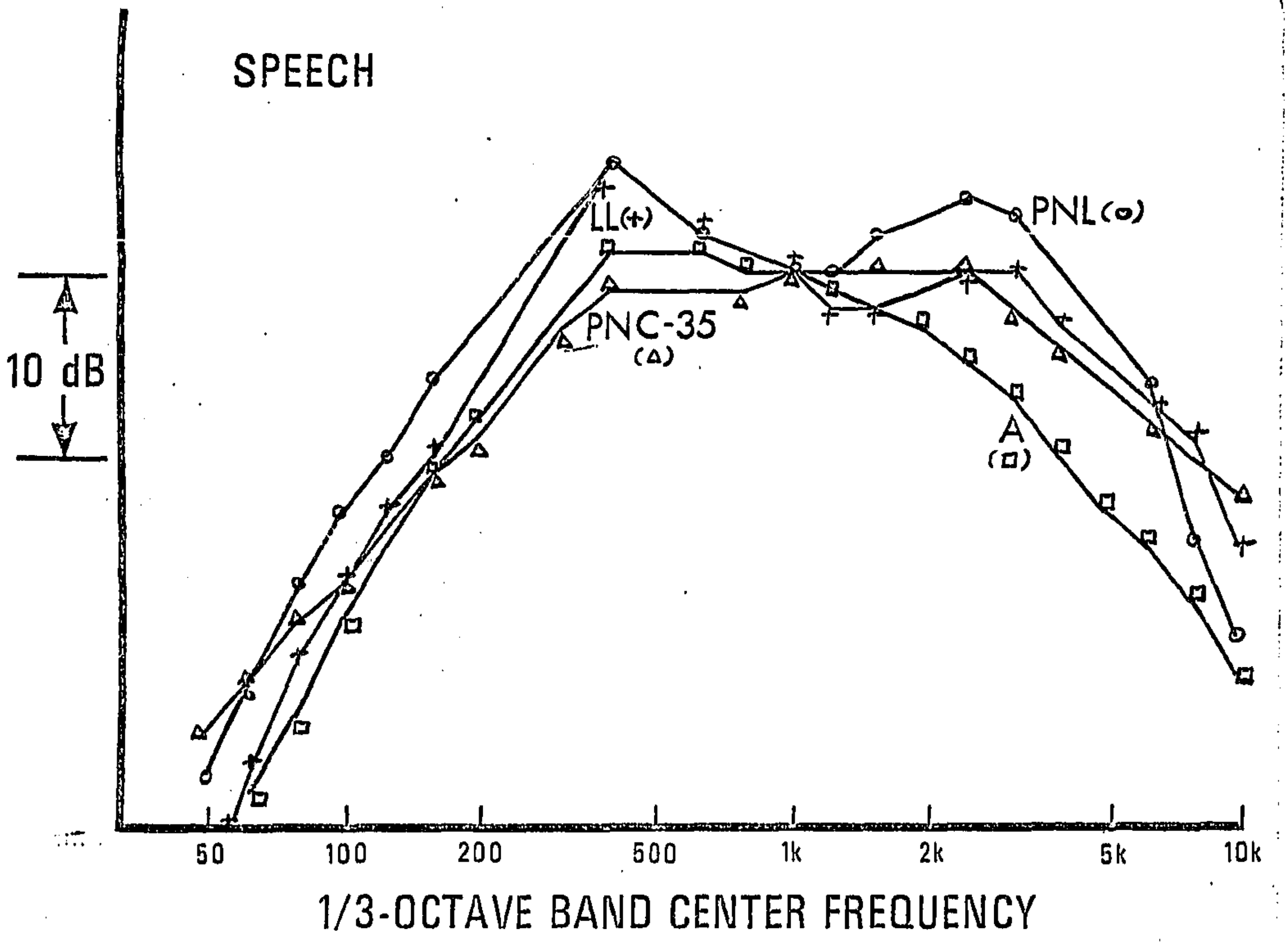
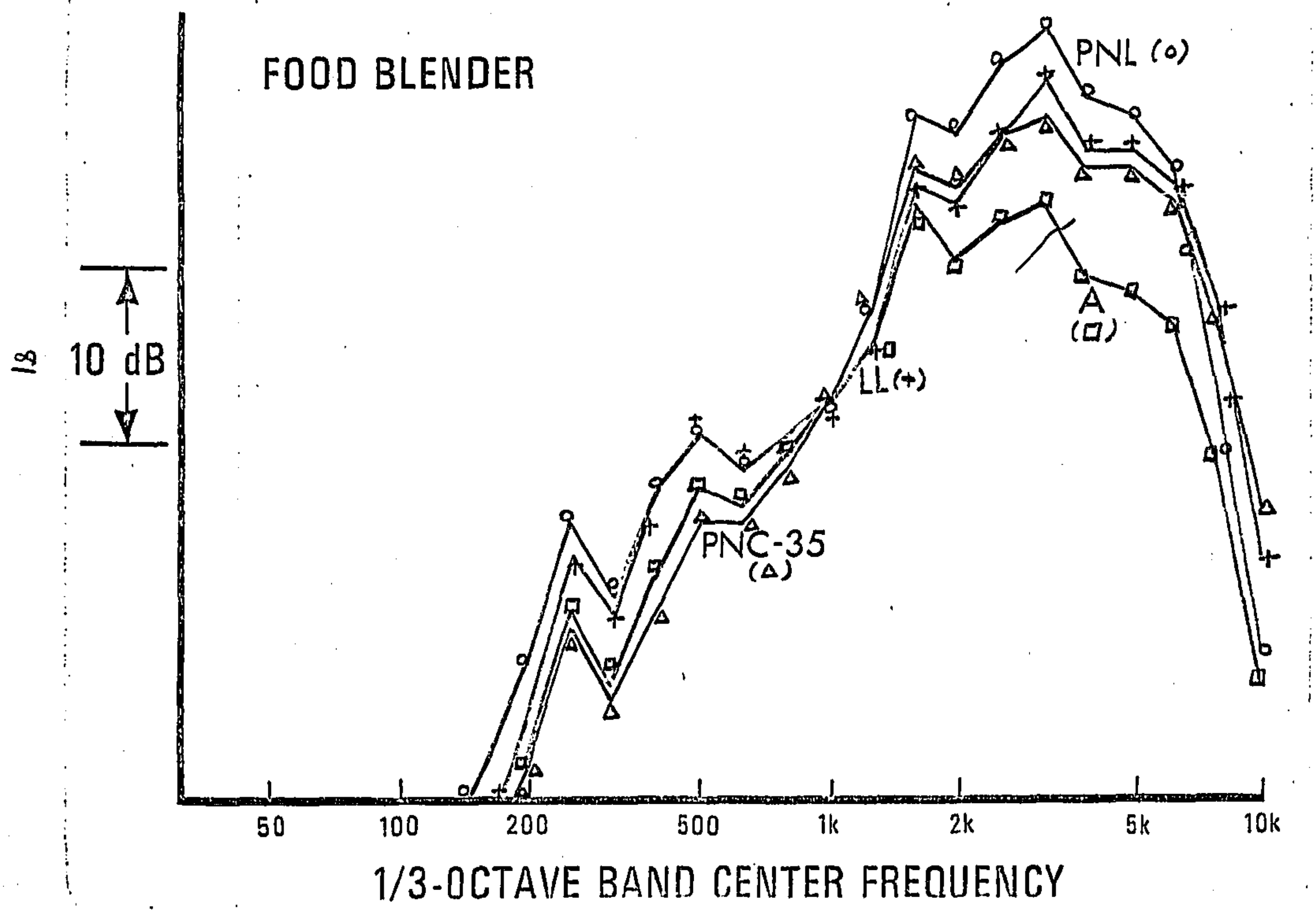


Figure 20. NOISE ISOLATION Requirements for FOOD BLENDER



frequently be governed by the performance between 1600 and 4000 Hz, particularly if there were a coincidence dip in this region. With the possible exceptions of food blenders (which typically have a very short duty cycle) and vacuum cleaners, there probably are not many indoor noise sources which have sufficiently high noise levels at frequencies above, say, 1600 Hz to become serious noise problems in a neighbor's dwelling. Thus, from a practical point of view, unless there are very pronounced high frequency coincidence dips, ratings of the noise isolation between dwelling units would usually be governed by the performance at frequencies below about 1000 Hz. For source room spectra such as those shown in Figure for household noise and speech, any of the four grading curves shown in Figures 18-20 would be expected to yield rather similar ratings (if the same summation rule were used in each case; and these ratings would be commensurate with the Noise Isolation Class computed using the ASTM contour [11]. In particular, rating the isolation in terms of A-weighted level differences would appear to be quite reasonable, as suggested by Schultz [46]. However, if the source spectra contained considerably more low-frequency energy than the spectra of household noise and speech, the isolation ratings could differ significantly, depending upon which grading curve is used. Thus for such sources a choice among loudness, noisiness, etc. could be quite important. If there are deficiencies in the high frequency isolation (e.g., due to a coincidence dip or a leak), an isolation rating based on the Perceived Noise Level would be more sensitive to such deficiences.

Turning to outdoor spectra, the isolation curves derived in order to maintain the indoor noise intrusion spectrum along a PNC-35 contour, a 1 noy contour, a 1 sone contour, and an inverted A-weighting contour are shown in Figures 21 , 22 , 23, and 24 for each of the outdoor spectra shown in Figure 16 . Observation of these figures shows that when the outdoor noise source produces a large amount of high-frequency noise, such as in the case of a large turbofan aircraft on approach, the indoor noise spectrum will be dominated by this frequency region. A rating based upon either loudness level (Mark VII) or noisiness (PNL) would emphasize this high frequency region even more than would one based upon either a PNC contour or an inverted A-weighting contour. Thus, if one were to be concerned with the possibility of a coincidence deep at about 3000 Hz in an exterior shell element, it is important to choose a rating that takes appropriate account of this frequency region.

When outdoor noise spectra are similar in shape to typical household noise, as is the case for traffic noise, the inverted A-weighted contour usually would not lead to noise isolation requirements that are NOT significantly different from those derived using other grading curves.

When the outdoor noise source produces significant low frequency noise, as in the case of a train, the interior noise contains considerable low-frequency energy, in the 50-125 Hz region. For such spectra, a rating based upon noisiness would emphasize these low frequencies slightly more than the other curves considered.

Figure 21

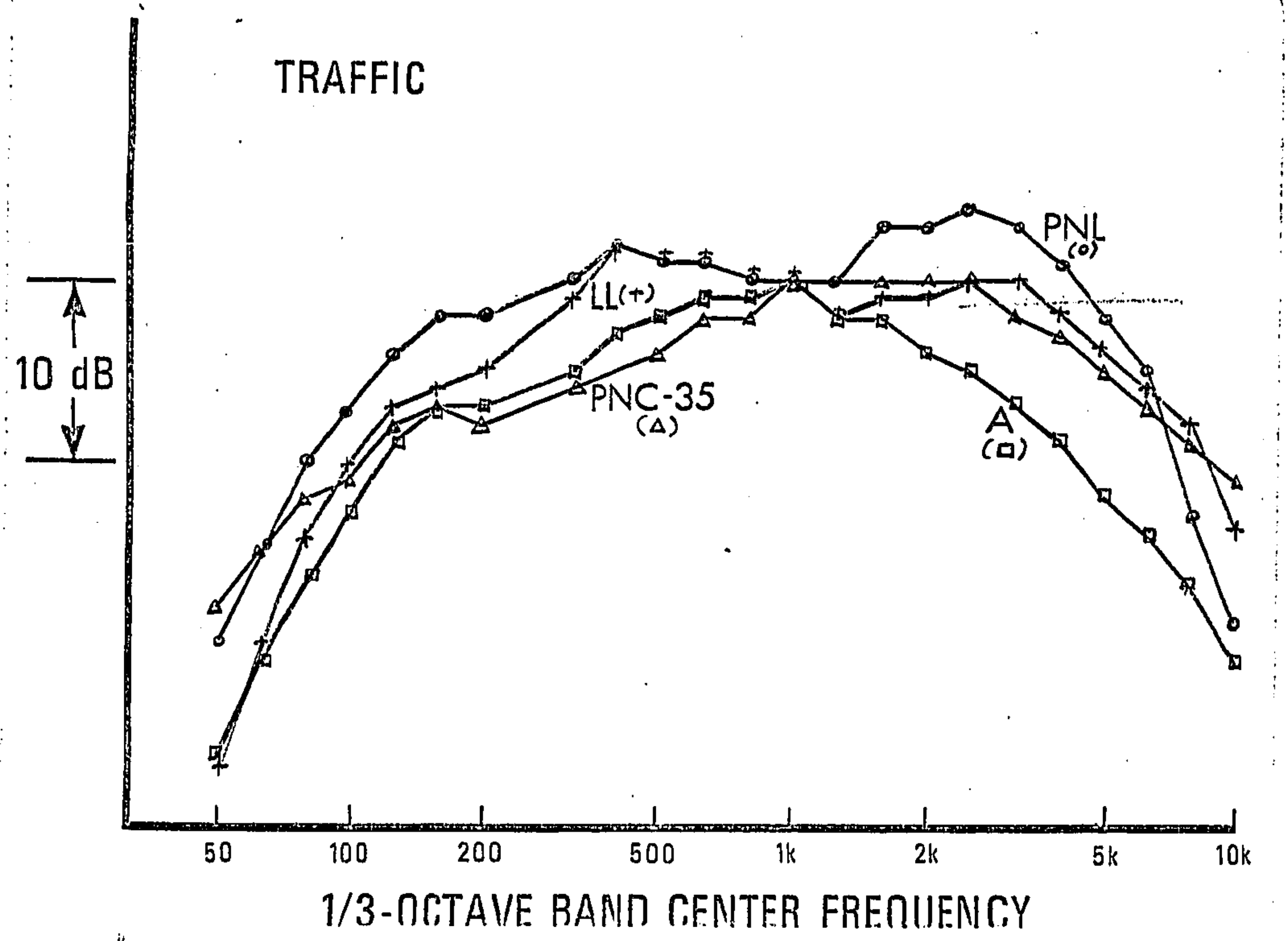

TRAFFIC
10 dB
PNL
(o)
LL(+)
PNC-35
(Δ)
A
(□)
50
100
200
500
1k
2k
5k
10k
1/3-OCTAVE BAND CENTER FREQUENCY

Figure 22

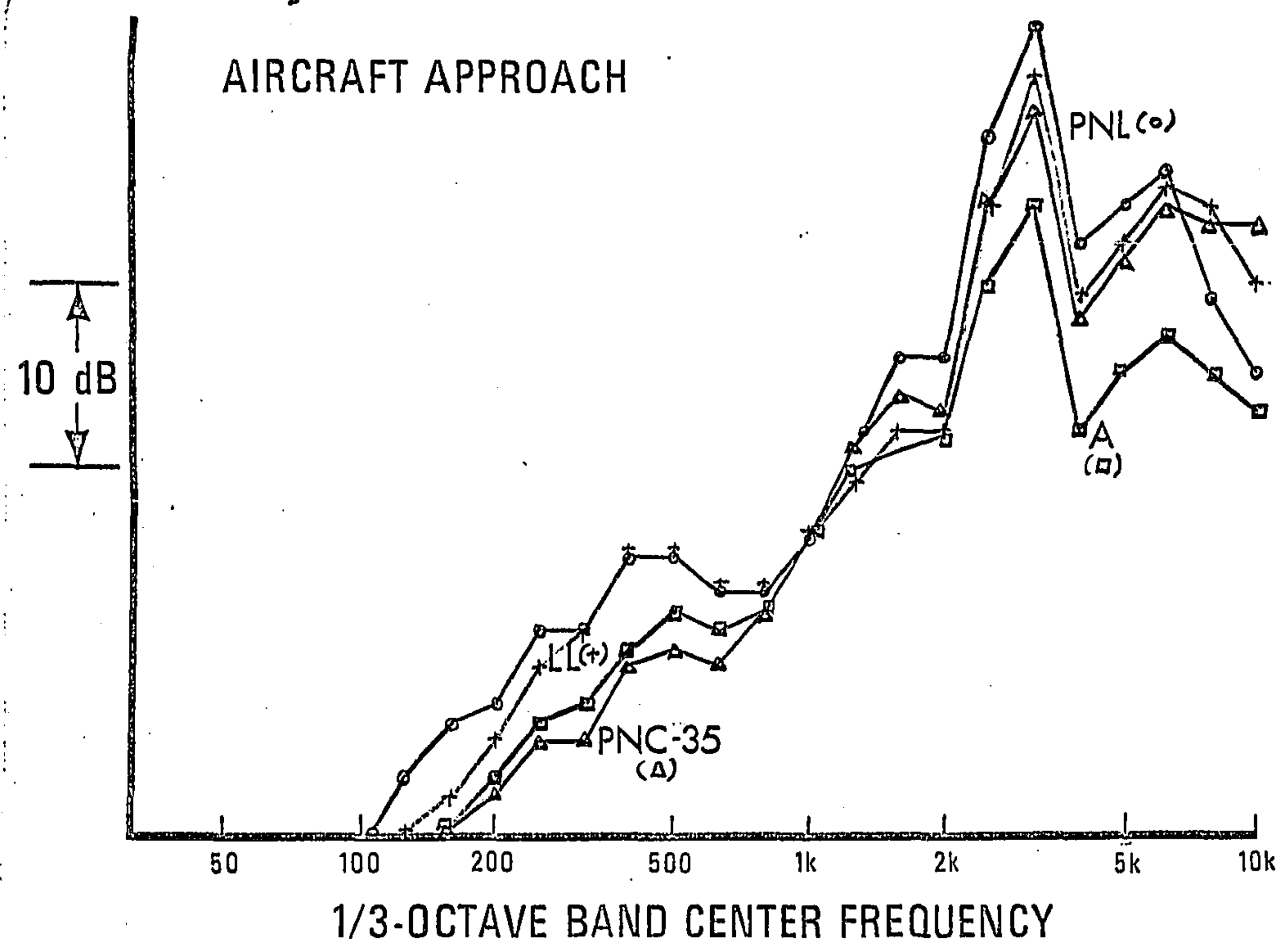
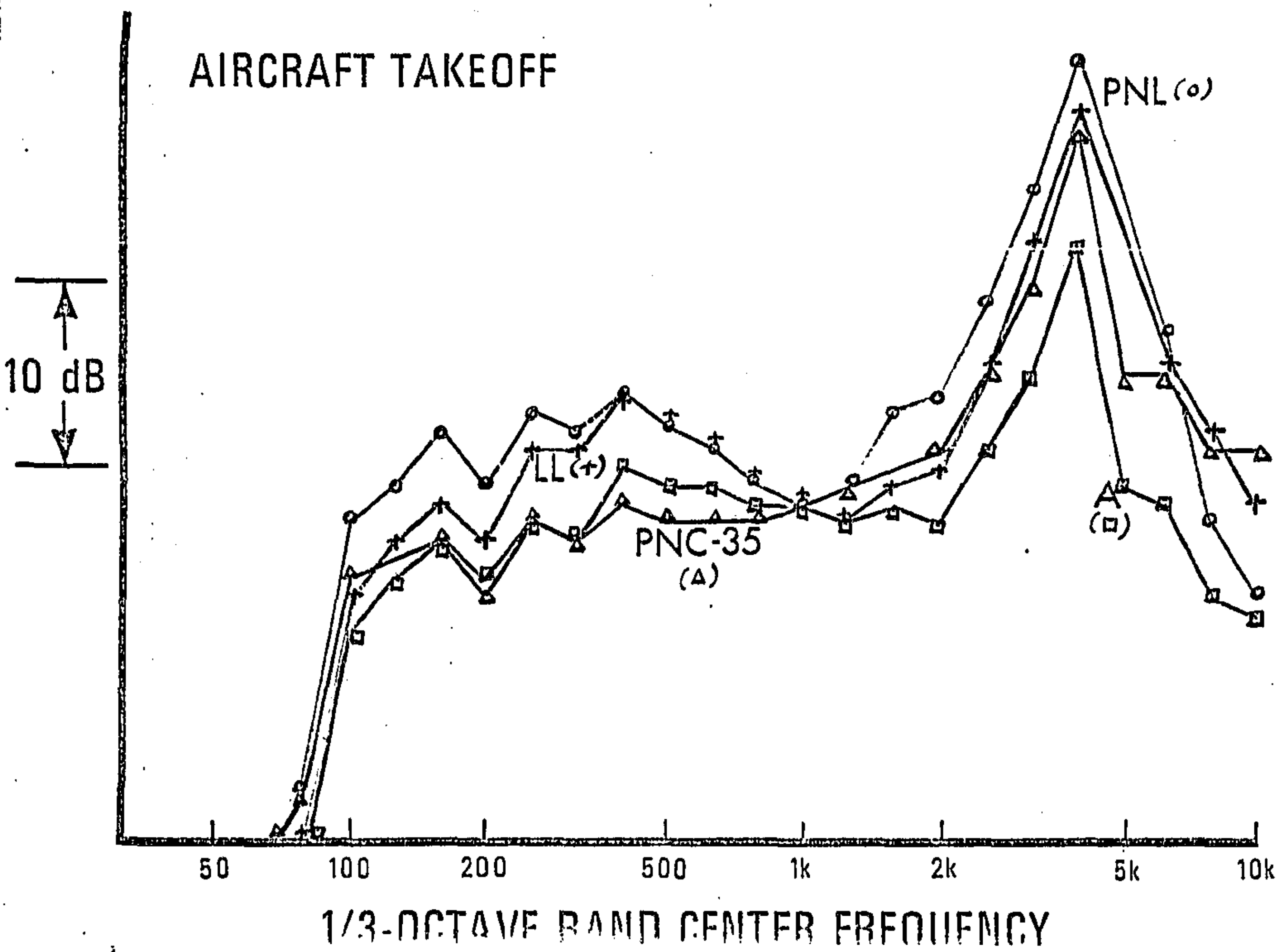
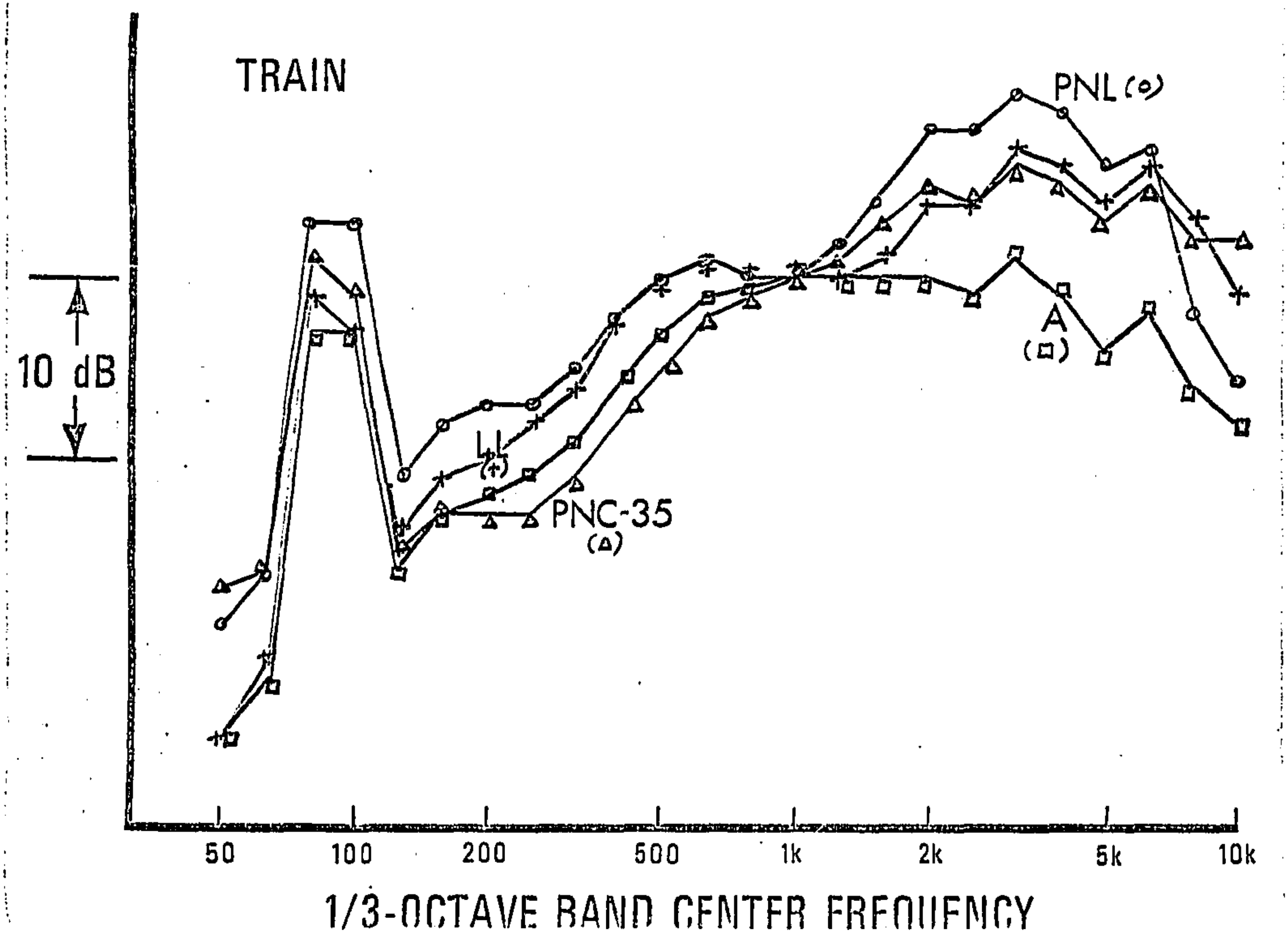

AIRCRAFT APPROACH
10 dB
PNL (o)
LL (+)
PNC-35
(Δ)
A
(□)
50
100
200
500
1k
2k
5k
10k
1/3-OCTAVE BAND CENTER FREQUENCY

Figure 23



AIRCRAFT TAKEOFF
PNL (o)
LL (+)
PNC-35
(Δ)
A
(□)
10 dB
50
100
200
500
1k
2k
5k
10k
1/3-OCTAVE BAND CENTER FREQUENCY

Figure 24


TRAIN
PNL (o)
LL (+)
PNC-35 (Δ)
A (□)
10 dB
50
100
200
500
1k
2k
5k
10k
1/3-OCTAVE BAND CENTER FREQUENCY

Since, to date, it appears that outdoor noise sources are likely to be regulated in terms of an A-weighted levels and since different frequency regions will influence the interior noise depending upon the noise source, outdoor-to-indoor isolation ratings should take into account the probable differences among source spectra. For example, isolation requirements (for the building envelope) that are based upon an A-weighted level difference measured for traffic noise would be very inappropriate for train or aircraft noise.

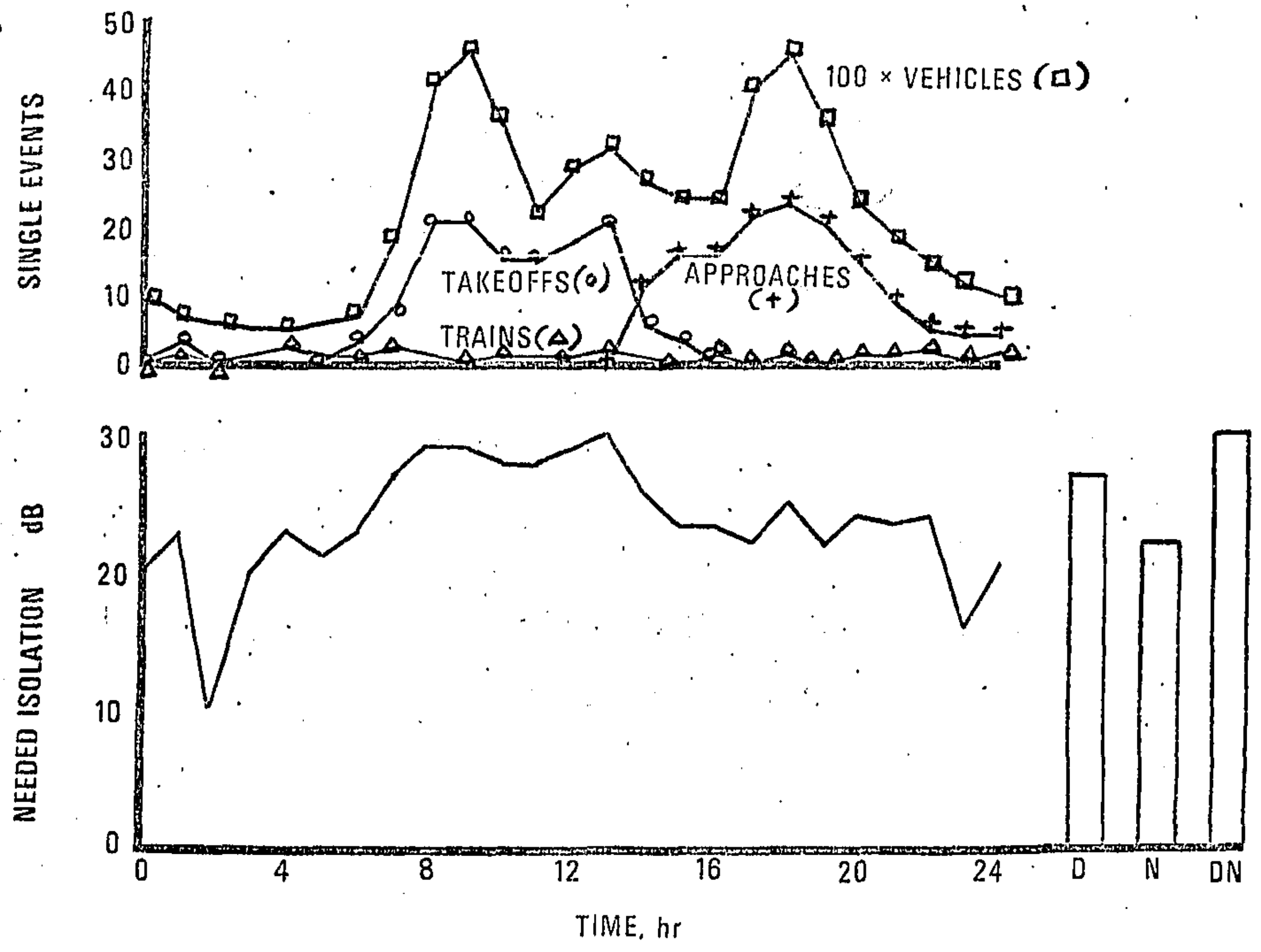
In addition to the problems related to which attribute of human response is of concern (noisiness, loudness, speech interference, etc.) another difficulty arises from the fact that human response to noise is dependent upon the variation of the noise amplitude and spectrum with time. None of the schemes that have either been proposed or incorporated into building codes have even attempted to account for this fact. For this reason, regardless of which psychophysical scale is utilized to rate the interior environment, it is essential in the development of building noise criteria that consideration be given to the need for a cumulative measure of noise which appropriately account for its time variation. Recently, the Environmental Protection Agency has proposed [121] the Day-Night Average Level (L_{dn}) as a candidate for describing the noise environment, both outdoor and indoor. Although it may be premature to generalize methods developed from studies of outdoor environments (see Section 4) the method does appear promising. For this reason an initial exploration of some of the implications of L_{dn} with respect to outdoor-to-indoor required isolation was attempted in the course of this study. Similar computations could be carried out for various cumulative noise measure such as the Noise Pollution Level or the Traffic Noise Index.

To perform the analyses described below it was assumed that a house is located 60 meters away from a freeway, 15 meters away from a railway and in the proximity of an airport so that aircraft overflights were at an altitude of 300 meters. One third-octave band Single Event Noise Exposure Levels were assumed for average passbys of each type of noise source as were average traffic densities for each hour. From these data one-third octave band hourly average noise levels (L_{eq}) at the facade of the dwelling were computed. The results were then utilized to derive the isolation required so that the one-third octave band average level inside the dwelling conform to a PNC-35 contour. From these detailed spectral data, A-weighted hourly average levels were determined, both inside and outside of the dwelling. These data are presented in Table 2 where it can be seen that the A-weighted level differences (e.g. required isolation to maintain PNC-35 indoors) varied from a low of 10 dB during the quietest hour of the night (0200 hour), when there were no trains or planes, to a high of 30 dB (1300 hour) during the period of high outdoor activity. The average A-weighted isolation required to maintain a PNC-35 indoor (or approximately an A-weighted level of 43 dB) throughout the daytime period (0700-2200 hour) was 27 dB. This isolation requirement dropped to 22 dB for the nighttime period (2200-0700 hours). However, when the Day-Night Level was computed the 10 dB night penalty forced the average isolation to 30 dB. This is equivalent to having forced the nighttime interior level to drop to about PNC-25 (or an A-weighted level of approximately 34 dB). A summary of these data are presented in Figure 25 in terms of A-weighted level differences. The upper part of Figure 25 shows the corresponding traffic densities.

Table 2

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	D	N	DN
17	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	63	16	6	14	17	14	16	20	22	22	21	21	22	23	19	16	16	15	10	15	17	16	18	10	15	19	16	23
19	80	32	10	32	35	32	32	35	33	25	33	33	33	36	33	19	32	19	33	19	32	32	35	14	32	32	32	39
20	100	33	15	33	36	33	33	36	34	28	34	34	34	36	33	23	33	23	33	23	33	33	36	18	33	33	33	39
21	125	25	18	22	24	22	25	29	31	31	30	30	30	31	28	26	26	27	28	27	26	27	26	21	23	29	24	32
22	160	27	20	24	26	24	27	31	33	33	32	31	32	33	30	28	28	28	30	29	28	28	28	23	25	31	26	34
23	200	28	21	25	27	25	28	32	35	34	34	33	34	35	31	29	29	30	31	30	29	29	29	24	27	32	27	35
24	250	29	22	26	28	26	29	33	36	36	35	34	35	36	32	30	30	30	32	31	30	31	30	25	27	33	28	36
25	315	31	23	28	30	28	31	35	38	37	37	36	37	38	34	32	32	32	34	34	33	34	32	27	29	35	30	38
26	400	33	24	30	33	30	33	37	39	39	38	38	39	40	36	33	33	33	35	34	34	34	34	28	31	37	32	40
27	500	36	25	33	36	33	36	39	41	41	40	40	40	42	38	35	36	34	37	35	36	36	37	29	34	38	35	42
28	630	37	26	35	38	35	37	41	43	42	42	41	42	43	40	36	37	36	39	36	38	37	39	30	36	40	37	44
29	800	38	27	36	38	36	38	42	44	43	43	42	43	44	41	38	38	38	40	38	39	38	39	32	36	41	37	45
30	1000	39	27	36	39	36	39	43	45	44	44	44	44	45	42	39	40	39	41	39	40	40	40	33	37	42	38	45
31	1250	40	26	36	39	36	40	44	46	46	45	45	45	46	43	41	40	40	41	40	40	40	40	33	38	43	39	46
32	1600	40	25	36	39	36	40	45	47	47	46	46	47	48	44	42	41	40	42	41	41	40	40	34	38	44	39	47
33	2000	41	24	37	40	37	41	46	49	48	47	47	48	49	45	43	42	41	43	41	42	41	41	34	39	45	40	48
34	2500	39	22	35	38	35	39	44	46	46	45	45	46	46	43	40	39	39	40	38	39	39	39	32	37	43	38	46
35	3150	39	20	36	39	36	39	42	44	43	43	43	43	45	41	37	38	36	39	35	38	38	40	29	37	41	38	45
36	4000	37	18	35	38	35	37	41	42	41	41	41	41	43	39	35	36	33	37	32	36	36	38	26	35	39	36	43
37	5000	34	16	32	35	32	34	37	38	37	37	37	38	39	35	31	33	28	33	28	33	33	35	22	32	35	33	40
38	6300	34	12	34	37	34	34	37	37	33	36	36	36	38	35	27	34	24	34	23	34	34	37	17	34	35	34	40
39	8000	31	8	30	33	30	31	34	33	30	32	32	33	35	31	22	30	19	30	18	30	30	33	13	30	31	30	37
40	10000	29	4	29	32	29	29	32	30	25	30	30	30	32	29	18	29	14	29	14	29	29	32	8	29	29	29	35
A-WEIGHTED LEVEL		23	10	20	23	21	23	27	29	29	28	28	29	30	26	23	23	22	25	22	24	23	24	16	21	27	22	30
C-WEIGHTED LEVEL		3	0	2	5	2	3	6	5	3	5	5	5	7	4	0	3	0	3	0	3	3	5	0	2	4	2	9

Figure 25


SINGLE EVENTS
100 × VEHICLES (□)
TAKEOFFS (○)
APPROACHES (+)
TRAINS (△)
NEEDED ISOLATION dB
0
4
8
12
16
20
24
D
N
DN
TIME, hr

Similar computations could be carried out to define the amount of isolation required for interior walls. However, at the present time there exist very few data regarding the statistical distribution of indoor sound levels. Until such data are obtained it is difficult to assess:

-- How much and what types of noise inhabitants of dwellings generate within the course of the normal 24 hour period?

-- How are noises distributed among the various rooms and spaces inhabitated by people during the times that people normally use them?

It is obvious that these questions are very difficult to answer, particularly in dwellings, because human activities and requirements are tremendously variable. Even for groups of people with similar family size, habits, interests and housing types, the answers will undoubtedly vary tremendously, depending upon socioeconomic status, previous experiences and other social, cultural and psychological variables. However, we cannot postpone indefinitely attempts to provide answers because the problem is difficult. We believe that it is probable that we could arrive at reasonable and acceptable criteria for noise in dwelling spaces so long as we agreed that these criteria will have to be based upon the average response of aggregates of people and a philosophy based upon satisfying the largest number of people most of the time.

While considerable efforts will be required to obtain definitive answers to the many questions raised in this report, viable interim solutions can be developed using the existing data base in combination with careful analysis and selected new data. The following steps would be necessary to develop appropriate rating schemes for the indoor noise environment and also to develop corresponding rating schemes for indoor-to-indoor and outdoor-to-outdoor noise isolation:

1. Develop and establish viable methods for practical measurements of indoor noise levels, outdoor noise levels, indoor-to-indoor noise isolation, and outdoor-to-indoor noise isolation.

2. Collect representative data on indoor and outdoor noise levels, on the relationships among outdoor levels, neighbors' indoor levels, and one's own indoor levels, and on the relationships of these contributions to the response of various segments of the national population representing different life styles.

3. Select interim rating schemes for indoor noise, based upon analysis of the data collected above, existing information on outdoor noise levels, and existing information concerning human response.

4. Develop, based on analyses which are extensions of the approach discussed in this report, interim rating methods for indoor-to-indoor and outdoor-to-indoor noise isolation.

5. Develop and execute a long-range research plan aimed at validating the interim rating schemes (for indoor noise, indoor-to-indoor isolation, and outdoor-to-indoor isolation) and at developing the necessary information base to permit future improvement, as required, of these schemes.

References

1. Blomquist, D.S., J. M. Fath, and D. R. Flynn, An investigation of Procedures for Field Measurement of Sound Transmission Loss. Paper presented at the Institute of Noise Control Engineering Arden House, New York, January 16, 1972.

2. Lang, Judith, Differences Between Acoustical Insulation Properties Measured in the Laboratory and Results of Measurements in Situ. Journal of Applied Acoustics, Vol. 2, 1972.

3. Higginson, R. F., A Study of Measuring Techniques for Airborne Sound Insulation in Buildings. Journal of Sound and Vibration, 1972, p. 405.

4. Field and Laboratory Measurements of Airborne and Impact Sound Transmission, ISO Recommendation R140-1960 (ISO, Geneva, Switzerland), 1960.

5. Standard Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions, E90-70, p. 612, Part 18, 1975 Annual Book of ASTM Standards.

6. Ove Brandt, European Experience with Sound Insulation Requirements, JASA, 36, 719, 1964.

7. Cremer, L., The Meaning of the Specification Curves (original Title Der Sinn der Soll Kurven) translated by J. J. Figwer and T. J. Schultz edited and distributed by Wilhelm Ernst and Son, Berlin, 1960.

8. DIN 522 11 (Vornorm). Bauakustische Prufungen. Schalldammzahl und Norm - Trittschallpegel. Einheitliche Mitteilung und Bewertung von Messergebnissen, Sept. 1953.

9. The Building Regulations S1, 1972, No. 317, HMSO.

10. Rating of Sound Insulation for Dwellings, ISO R717-1968; International Organization for Standardization, Switzerland, 1968.

11. Standard Classification for Determination of Sound Transmission Class, E413-73, p. 761, part 18, 1975 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1975).

12. Parkin, P. H., Purkis, J. H. and Scholes, W. E., Field Measurements of Sound Insulation Between Dwellings HMSO, London, 1960.

13. Gray, P. G., Cartwright, A. and Parkin, P. H., Noise in three groups of flats with different floor insulations, HMSO, 1958.

14. Bitter, C. and Van Wieren, P., Sound Nuisance and sound insulation in blocks of dwellings, T.N.O., Rapport No. 24, 1955.

15. Gunnar, O. Jorgen, Noise in Dwellings, Rapport 16, Oslo, 1955.

16. Brandt, O. and Dalen, I., Is the sound insulation in our dwellings sufficient? Byggmastaren B6, 1952.

17. Josse, M. et al., Etude sociologioque de la satisfaction des occupants de locaux conformes aux regles qui sont supposees garantir un comfort acoustique suffisant. CSTB, Paris 1969.

18. Van Den Eijk, J., My Neighbour's Radio, ICA, 3, 1041, 1959.

19. Fletcher, H. and Munson, W. A., Loudness: Its definition, measurement and calculation, JASA, 5, 82, 1933.

20. Stevens, S. S., Procedure for Calculating Loudness: Mark VI, JASA, 33, 1961, p. 1577.

21. Stevens, S. S., Perceived Level of Noise by Mark VII and Decibels (E), JASA, 51, 1972, p. 575.

22. Fletcher, H. and Munson, W. A., Loudness: Its definition, measurement and calculation, JASA, 5, 82, 1933.

23. Copeland, W.C.T., Davidson, I. M., Margest, T. J. and Robinson, D.W., A Controlled Experiment on Subjective Effects of Jet Engine Noise, British Ministry of Aviation, Note No. 427, 1959.

24. Kryter, K. D., Scaling Human Reactions to Sound from Aircraft, JASA, 31, 1415, 1959.

25. Kryter, K. S., Concepts of Perceived Noisiness, Their Implementation and Application, JASA, 43, 344, 1967.

26. Kryter, K. D. and Pearsons, K. S., Some Effects of Spectral Content and Duration on Perceived Noise Level, JASA, 35, 866, 1963.

27. Pearson, K. S. and Bennett, R. L., Handbook of Noise Ratings, NASA, CR-2376, April 1974, page 79.

28. Van Den Eijk, J., My neighbour's television, ICA, 6, E113, 1968.

29. Northwood, T. D., Sound Insulation and the Apartment Dweller, JASA 36, 1964, 725.

30. Beranek, Noise and Vibration Control, McGraw-Hill, Inc., 1971, Chapter 18.

31. Schultz, T., Community Noise Ratings, Applied Science Publishers, Ltd. London, 1972.

32. Clark, D. M., Subjective Study of the Sound Transmission Class System for Rating Building Partitions, JASA, 47, 1970, 676.

33. Schultz, T. J., How Noise Creeps Past the Building Codes, Noise Control Engineering, 1, 1973, p. 4. Errata in Noise Control Engineering, 4, 1975, p. 53.

34. Standard Recommended Practice for Measurement of Airborne Sound Insulation in Buildings, E336-71, p. 738, Part 18, 1975 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1975).

35. Standard Classification for Determination of Sound Transmission Class, E413-73, p. 761, part 18, 1975 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1975).

36. Gosele, K., Zur Bewertung der Schalldammung von Bauteilen nach Sollkurven, Acustica, 15, 1965, p. 264.

37. Gosele, K. and Bruckmayer, F., Vorschlag fur eine Keenzeichnung der Luftschalldammung von Bauteilen, Gesundheits - ingenieur, 86, 1965, p. 172.

38. Gosele, K. and Koch, S., Bestimmung der Luftschalldammung von Bauteilen nach einen Kurzverfahren, p. 87-93 in Berichte aus der Bauforschung, 68, Wilhelm Ernst and Sohn, Berlin, 1970.

39. Fuchs, G. L., Correlation between physical measurements of insulation between dwellings and corresponding subjective judgments, Acustica, 21, 1969, p. 303.

40. Harman, D. M., The role of the dB(A), Appl. Acoustics, 2, 1969, p. 101.

41. Scholes, W. E. and Parkin, P. H., The Insulation of Houses Against Noise from Aircraft in Flight, Appl. Acoustics, 1, 1968, p. 37.

42. Siekman, W., Yerges, J. F., and Yerges, L. F., A Simplified Field Sound Transmission Test, Sound and Vibration, 5, October 1971, p. 17.

43. Quindry, T. L. and Flynn, D. R., On a Simplified Field Measurement of Noise Reduction Between Spaces. Proc. of 1973 International Conference on Noise Control Engineering (Inter-Noise 73), Denmark, 1973, p. 199.

44. Flynn, D. R., Rating of Noise Isolation and Sound Transmission Loss in preparation.

45. Donato, R. J., Insulating Houses Against Aircraft Noise, JASA, 53, 1973, p. 1025.

46. Schultz, T. J., A-Level Differences for Noise Control in Building Codes, Noise Control Engineering, 1, 1973, p. 90.

47. Schultz, T., Community Noise Ratings, Applied Science Publishers, Ltd. London, 1972.

48. Stevens, S. S., The Measurement of Loudness, JASA, 27, 815, 1955.

49. Stevens, S. S., On the Validity of the Loudness Scale, JASA, 31, 995, 1959.

50. Stevens, S. S., Concerning the Form of the Loudness Function, JASA, 29, 603, 1957.

51. Fletcher, H. and Munson, W. A., Loudness: Its definition, measurement and calculation, JASA, 5, 82, 1933.

52. Churcher, B. G. and King, A. J., The Performance of Noise Meters in Terms of the Primary Standard, J. Inst. Elect. Engrs. (London), 81, 57, 1937.

53. Reisz, R. R., Differential Sensitivity of the Ear for Pure Tones, Physiol. Review, 31, 867, 1928.

54. Robinson, D. W. and Dadson, R. S., A Redetermination of Equal Loudness Relations for Pure Tones. British Journal of Applied Physics, 7, 166, 1956.

55. Robinson, D. W. and Dadson, R. S., Threshold of Hearing and Equal Loudness Relations of Pure Tones and the Loudness Function, JASA, 29, 1284, 1957.

56. Pollack, I., The Loudness of Bands of Noise, JASA, 24, 533, 1952.

57. Young, R. W., Don't Forget the Simple Sound Level Meter, Noise Control, 4, 42, 1958.

58. Young, R. W., Single Number Criteria for Room Noise, JASA, 36, 289, 1964.

59. Stevens, S. S., Calculation of the Loudness of Complex Noise, JASA, 28, 870, 1956.

60. Stevens, S. S., Calculating Loudness, Noise Control, 3, 11, 1957.

61. Stevens, S. S., Procedure for Calculating Loudness: Mark VI, JASA, 33, 1577, 1961.

62. Stevens, S. S., Perceived Level of Noise by Mark VII and Decibels (E), JASA, 51, 575, 1972.

63. Zwicker, E., Uber psychologische und methodisch Grundlagen der Lautheit, Acustica, 8, 237, 1958.

64. Zwicker, E., Ein graphisches Verfahren zur Bestimmung der Lautstarke und der Lautheit aus dem Terzpegeldiagramm, Frequenz, 13, 234, 1959.

65. Zwicker, E., Ein Verfahren zur Berechnung der Lautstarke, Acustica, 10, 304, 1960.

66. Zwicker, E., Lautstarke Berechnung-verfahren in Vergleich, Acustica, 17, 278, 1966.

67. ISO Recommendation R532, Method for Calculating Loudness Level, 1966.

68. ANSI S3.4-1968 Computation of the Loudness of Noise.

69. Young, R. W., Don't Forget the Simple Sound Level Meter, Noise Control, 4, 42, 1958.

70. Young, R. W., Single Number Criteria for Room Noise, JASA, 36, 289, 1964.

71. Parkin, P. H., On the Accuracy of Simple Weighting Networks for Loudness Estimates of Some Urban Noise, J. Sound and Vibration, 2, 86, 1965.

72. Young, W. R. and Patterson, A., On Estimating Noisiness of Aircraft Sounds, JASA, 45, 834, 1969.

73. Klumpp, R. G. and Webster, C. J., Physical Measurements of Equally Speech-Interfering Navy Noises, JASA, 35, 1328, 1963.

74. Kryter, K. D., Scaling human reactions to the sound from aircraft, JASA, 31, 1415, 1959.

75. Kryter, K. D., The meaning and measurement of perceived noise level, Noise Control, 6, 12, 1960.

76. Kryter, K. D., Concepts of perceived noisiness, their implementation and application, JASA, 43, 344, 1968.

77. Kryter, K. D. and Pearsons, K. S., Some effects of spectral content and duration on perceived noise level, JASA, 35, 866, 1963.

78. Kryter, K. D. and Pearson, K. S., Modification of Noy Tables, JASA, 36, 394, 1964.

79. Kryter, K. D., Concepts of perceived noisiness, their implementation and application, JASA, 43, 344, 1968.

80. In press by International Electrotechnical Commission.

81. French, N. R. and Steinberg, J. C., Factors governing the intelligibility of speech sounds, JASA, 19, 90, 1947.

82. American National Standard ANSI S3.5-1969, Methods for the Calculation of the Articulation Index.

83. Beranek, L. L., Airplane Quieting II - Specification of acceptable noise levels, Trans. Amer. Soc. Mech. Engrs., 69, 97, 1947.

84. American National Standard ANSI S1.6-1967 (R1971), Preferred Frequencies and Band Numbers for Acoustical Measurements.

85. Webster, J. C. and Klumpp, R. G., Physical Measurement of Equally Speech-Interfering Wavy Noises, NASA, 35, 1328, 1963.

86. Young, R. W., Don't Forget the Simple Sound Level Meter, Noise Control, 4, 42, 1958.

87. Crandall, I. B. and MacKenzie, D., Bell Sys. Tech. J., 7, 116, 1922.

88. Dunn, H. K. and White, S. D., Statistical Measurements on Conversational Speech, JASA, 11, 278, 1940.

89. Rudmose, H. W., Clark, K. C., Carlson, F. D., Eisenstein, J. C., and Walker, R. A., Voice Measurements with Audio Spectrometer, JASA, 20, 503, 1948.

90. Stevens, S. S., Egan, J. P. and Miller, G. A., Methods for Measuring Speech Spectra, JASA, 19, 771, 1947.

91. Benson, R. W. and Hirsh, I. J., Some Variables in Audio Spectrometry, JASA, 25, 499, 1953.

92. Pickett, J. M. and Pollack, I., Speech Intelligibility at High Noise Levels, JASA, 30, 955, 1958.

93. Galloway, W., Private Communication.

94. Kryter, K. D., Validation of the Articulation Index, JASA, 34, 1962, 1968

95. Beranek, L. L., Revised Criteria for Noise in Buildings, Noise Control, 3, 19, 1957.

96. Beranek, L. L., Reynolds, J. L. and Wilson, K. E., Apparatus and Procedures for Predicting Ventilation System Noise, JASA, 25, 313, 1953.

97. Beranek, L.L. and the Staff of BBN, Office Noise Studies at Hill Air Force Base, WADC Tech. Doc. 56-58, ASTIA Doc. AD 110645, 1956.

98. Schultz, T., Community Noise Ratings, Applied Science Publishers, Ltd. London, 1972.

99. Beranek, L.L., Criteria for Office Quieting BAsed on Questionnaire Rating Studies, JASA, 28, 833, 1958.

100. Knudsen and Harris, Acoustical Designing in Architecture, Wiley & Sons, Inc., 1950.

101. ISO Recommendation R1996, Acoustics, Assessment of Noise with Respecc to Community Response, 1971.

102. Beranek, L. L., Blazier, W. E., and Figwer, J. J., Preferred Noise Criterion (PNC) Curves and Their Application to Rooms, JASA, 50, 1971, p. 1223.

103. Beranek, L. L., Noise and Vibration Control, McGraw Hill, 1971, Chapter 18.

104. Galloway, W. J. and von Gierke, H. E., Individual and Community Reaction to Aircraft Noise. Present status and standardization efforts paper presented at the London Conference on Reduction of Noise and Disturbance Caused by Civil Aircraft, Paper INC/C4/PG, 1966.

105. Noise, Final Report, HMSO London, England, CMND 2056, 1963.

106. Anderson, C.M.B., The Measurement of Attitude to Noise and Noises, NPL AC-52, Teddington, England, 1971.

107. Purkis, H. J., London Noise Survey No. 6/66, March 1966, BRS.

108. Second Survey of Aircraft Noise Annoyance Around London, HMSO, London, 1971.

109. Cedarlof, R., Jonsson, E. and Kajland, A., Annoyance Reaction to Noise from Motor Vehicles, Acustica, 13, 270, 1963.

110. Kilman, Tor, Lundquist and Nordlund, Report 38, 1968, SIB, Stockholm, Sweden.

111. Fog, Jonsson, Kajland, Nilson and Sorensen, Traffic Noise in Residential Areas, SIB, Sweden, 1968.

112. Cederlof, Jonsson, Sorensen, On the Influence of Altitudes of the Source on Annoyance Reactions to Noise, Nordick Hygienisk Tidskrift 46-59, Stockholm, Sweden, 1967.

113. Brukinayer, F. and Laug, L., Disturbance of the Population by Traffic Noise, Oostereiche Inger, 1967, H.8, 302-306, H.9, 338-344, and H.10, 376-385.

114. Bruckmayer, Judgment of Noise Annoyance by Reference to the Background Level, Oost. Ing.-Feit., 1963, 315.

115. Auzon, S. and Lamura, C., te bruit aux abords des autoroutes, CSTB, 78, 669, 1966.

116. Lamure, Auzon, les niveaux de bruit au voisinage des autoroutes degages, CSTB, 71, 599, 1964.

117. Lamure, Bacelon, la gene du bruit de la circulation automobile, CSTB, 88, 762, 1967.

118. Auzon and Rapice, Gene du bruit du a la circulation automobile in site urbain, CSTB, 1971.

119. Bitter, C., and Van Weeren, P., A Study of the Problem of Social Nuisance and Sound Insulation in Blocks of Dwellings, Report No. 24, UDC, 534.83-7:311.213.3, Research Institute for Public Health Engineering, T.N.O., September 1955, La Hague.

120. Tracor, Community Reaction to Airport Noise, NASA Report CR-1761, 1971.

121. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, Environmental Protection Agency, March 1974, Report No. 550/9-74-004.

122. Rosenblith, W. A., Stevens, K. N., Bolt, R. H., A Community's Reaction to Noise: Can it be Forecast?, Noise Control, 1, 63, 1955.

123. Galloway, W. J. and Bishop, D. E., Noise Exposure Forecasts: Evolution, Evaluation, Extensions and Land Use Interpretations, BBN Report No. 1862, December 1969.

124. FAA Regulations Part 36.

125. von Gierke, Task Group 111, Report of the Airport Study, 1974.

126. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, Environmental Protection Agency, March 1974, Report No. 550/9-74-004.

127. Population Distribution of the United States as a Function of Outdoor Noise Level, Report 550/9-74-009, Environmental Protection Agency, Washington, D.C., June 1974.