# 34. PREDICTION OF EFFECTS OF NOISE ON MAN

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## SUMMARY

The major basic deleterious effects of noise on man are (1) masking of speech, (2) damage to hearing, and (3) perceived noisiness or unwantedness. Present knowledge permits accurate quantitative prediction from spectral measures of a noise and the effects of the noise on the understandability of speech and on temporary and permanent deafness. Methods for the quantitative prediction from spectral measures of noise and the basic effects of noise on perceived noisiness and behavior of people have been developed to the point that standarization of these methods is perhaps possible.

## INTRODUCTION

In the standardized terminology of acoustics, "noise" is defined as unwanted sound. However, confusion sometimes results in the use of the word noise as an appellation for unwanted sound because there are two general classes of "unwantedness." In the first category the sound signifies or carries information about the sound's source which the listener has learned to associate with some unpleasantness not due to the physical sound but due to some other attribute of the source. For instance, the sound of the fingernail on the blackboard suggests perhaps an unpleasant feeling in tissues under the fingernail; the sound of an airplane suggests, to some persons, fear that the plane may be falling on their home; a baby's cry causes anguish in a mother; the squeak of a floorboard is frightening because it may indicate the presence of a prowler. In all these examples, it is not the sound as noise that is unwanted (although for other reasons it may also be unwanted), but the information it conveys to the listener. This information is strongly influenced by past experiences of each individual and, in the author's opinion, its effects cannot be quantitatively related to the physical characteristics of the sounds.

In the second category, the unwanted effects of sounds are related to physical characteristics of the sound in ways that are more or less universal and invariant for all people, These effects are both physiological and psychological; the effects are psychological only in the sense that man learns through normal experience of the relations between the characteristics of sounds and their basic perceptual effects. The effects referred to and to be discussed subsequently are (1) the masking of wanted sounds, particularly speech, (2) auditory fatigue, (3) loudness or perhaps some general quality of bothersomeness or distractiveness, and (4) possibly startle (although, because of man's ability to adapt to repeated stimulations, this effect will vary in time).

These effects presumably are (1) very similar for all people, (2) not dependent on learning nor can they for the most part be "unlearned," and (3) quantitatively related to the physical nature of sounds. Because of these characteristics, they deserve the attention of persons interested or involved in the design of devices that generate sound, in the control of the sound during its transmission, or in the protection of the health and well-being of people exposed to the sound. Indeed, nearly all measurement of sound by acoustical engineers is made for the immediate or ultimate purpose of evaluating the effects of the sound on man.

## MASKING OF SOUNDS

It is likely that the most disruptive, harmful, and widespread effect of noise is that of masking or interference with the perception of wanted auditory signals, in particular, speech. It is also an unfortunate fact that this masking effect is something for which there is no adaptation. Masking is primarily to be understood in terms of a competition that takes place in the inner ear or cochlea of man's auditory system for the attention of the receptor cells in the cochlea. These receptor cells respond solely on the basis of physical forces exerted upon them and cannot distinguish between sounds that the listener may want to hear and the sounds he may not want to hear.

Perhaps for present purposes only two particularly important features of masking need be mentioned here:

(a) The so-called spread of masking that occurs from low-frequency sounds upon higher frequency sounds

(b) The audibility of speech in the presence of a masking noise

### Spread of Masking

Figure 1, based on reference 1, illustrates the general amount of masking of one pure tone which occurs from the presence of another pure tone. For example, the curve labeled "20 dB" in figure 1 indicates the intensity required of a "probe" tone at frequencies between 80 and 1000 Hz to be just heard in the presence of a steady-state 200-Hz tone at an intensity of 20 dB. In the absence of the 200-Hz masking tone, any tone will be audible when its intensity, as plotted in figure 1, is at zero dB. Thus, the curves in figure 1 represent the increases in intensity required at a given frequency to make a tone audible in the presence of the 200-Hz masking tone.

There are two things to be noted in particular about figure 1: (1)the frequencies above the masking tone or sound are masked to a greater extent than are frequencies below the masking tone, and (2) as the intensity of the masking tone or sound is increased, the degree of upward spread of masking is increased.

### Masking of Speech

The masking effects of noise on speech are sufficiently known to permit the preparation of standardized procedures for predicting from these physical measurements of speech and noise the needed masking that will occur and its effects upon the understandability of the speech. This calculation procedure is called the "Articulation Index" and essentially reflects (a) the relation between the speech spectrum and the spectrum of the noise, **(b)** the variations in intensity of the speech spectrum, and (c) the relative contributions of different segments of the speech spectrum to the understanding of speech. Figure 2, derived from references 2 and **3,** illustrates the typical way in which an articulation index (AI) is calculated and the basis for the calculations.

## AUDITORY FATIGUE AND DAMAGE TO HEARING

Although masking of speech may be the most bothersome effect from work, sociological, and behavioral points of view, it should not be overlooked that the ear is subject to fatigue and damage as a result of exposure to noise. This damage to hearing tends to occur somewhat slowly and painlessly with continued exposure to noise so that the ear is often permanently damaged before people are aware of what is happening. It is partly for this reason that noise is an occupational health hazard in the military services and in many industries, including, of course, the aviation industry.

**As** with masking of speech, it is possible to depict certain general relations between noise exposure and auditory fatigue in terms of the spectrum of the noise and the duration of exposures. Figure **3** (from ref. **4)** shows a set of so-called equinoxious damage risk contours for exposure to noise. Any point on these curves is presumed to represent the same amount of damage risk to hearing as any other point. For example, a one-third octave band of noise with a center frequency (cf) of 200 **Hz,** an intensity of 105 dB, and a daily duration of 60 minutes will cause the same amount of auditory fatigue and eventual permanent damage to hearing as a one-third octave band of noise with a center frequency of 3000 **Hz,** a sound pressure level of 105 dB, and a daily duration of only **3** minutes. The damage risk exposures in figure **3** will, it is believed, cause in no more than 50 percent of the people a permanent threshold shift of no more than 10 dB at 1000 Hz or below, 15 dB at 2000 **Hz,** and **20** dB at 3000 Hz or above. These permanent threshold shifts will occur only after approximately 10 years of almost daily exposure to the noise conditions depicted. On the basis of present knowledge, such as that illustrated in figure **3,** it is possible to predict with reasonable accuracy the permanent threshold shift or damage to hearing that is likely to occur in given percentages of people for given years of exposure to a wide variety of noises of differing spectral and temporal patterns.

The noise from past and present aircraft is a hazard to hearing only to operational and maintenance personnel working in or close to the aircraft. However, the external noise from aircraft would not have to be increased too much beyond the present levels and/or durations before legitimate claims could be made that some small amount of damage to hearing occurs in some small percentage of the people living in communities near airports.

## LOUDNESS AND PERCEIVED NOISINESS

In general, the acceptability of noise to people has been evaluated in terms of its judged subjective annoyance value. Sometimes subjects have been asked to rate the loudness rather that the annoyance or unwantedness of the sounds on the presumption that the response of people to either of these questions would be about the same.

Psychological judgment tests have demonstrated that people will consistently judge among themselves the "unwantedness," "unacceptableness," "objectionableness," or "noisiness" of sounds that vary in spectral content and duration provided that the sounds do not differ significantly in their meaning. The subjects in these tests are asked to consider the terms in quotation marks as being synonymous when making their judgments. This general attribute or quality of sound is designated as "perceived noisiness." It is presumed that, for the judgment of perceived noisiness, the human auditor subconsciously combines the inherent effects of loudness, masking, auditory fatigue, and perhaps distractiveness and startle into a single overall reaction to a sound. It is to be emphasized that the effects the meaning of sounds have upon judgments as to acceptability are specifically excluded from or kept constant for this attribute of perceived noisiness.

The unit of perceived noisiness is called the "noy." A sound that is judged to be subjectively equal in noisiness to an octave band of random noise with a center frequency of 1000 Hz (referred to hereinafter as the standard reference band), a sound pressure level of 40 dB (re 0.0002 microbar), and a duration of 1/2 second is given a value of 1 noy. A sound that is judged to be twice as noisy as a sound of 1 noy has a value of 2 noys, four times as noisy a value of 4 noys, and so forth.

It has been customary to express acoustic and psychoacoustic measurements in terms of a decibel scale. For this reason the noy value of a sound that presumably reflects the magnitude in noisiness as perceived by a person is usually converted to the so-called PNdB scale. This conversion consists of referring to the sound pressure level of the standard band that has the same noy value as a given sound as the PNdB value of the given sound. For example, noise that has a noy value of 1 has a PNdB value of 40, the sound pressure level of the reference band at 1 noy. The relations between noy and PNdB values, band center frequency, and band sound pressure level for bands of sound of equal bandwidth and the same temporal pattern are shown in figure 4.

Although the noy and PNdB terminology and concepts are analogous to and based upon the sone and phon units used for loudness, some frequency bands of noise are slightly different when one judges loudness than when one judges unwantedness, as is shown by the difference between the 80-noy and 80-sone contours at the top of figure 4. Other differences, perhaps more important, to be found between judgments of loudness and perceived noisiness are described subsequently.

In figure 4, several functional relations are shown that perhaps require further explanation. The noy contours in this figure were obtained by having the subjects or the experimenters adjust the intensity of different frequency bands of noise until they sounded equally noisy or unwanted or unacceptable as a band of noise at 1000 Hz whose intensity was kept constant. For example, a band of noise with a center frequency of 1000 Hz and an intensity of 40 dB is equal subjectively to other frequency bands having the intensities indicated by the 1 noy contour. It is seen that bands of frequencies in the region from 2000 to 5000 Hz are judged to be the most unwanted at a given sound pressure level.

To help quantify the scale of perceived noisiness as the intensity of a sound is increased while the frequency content is kept constant, the number 1 was arbitrarily assigned to the reference or standard band with center frequency of 1000 Hz and set at a sound pressure level of 40 dB (re 0.0002 microbar). Subjects were then asked to adjust the 1000-Hz band until it sounded twice as unwanted as the reference band at an intensity of 40 dB. This intensity was assigned a value of 2 noys, which indicates that subjectively the sound was now twice as unwanted. The different intensities required to obtain additional doublings of the unwantedness were determined. It was found that, on the average, increasing the intensity by 10 dB resulted in a doubling in the subjective noisiness of sounds.

## CONCEPTS OF PERCEIVED NOISINESS

Starting with the relations shown in figure 4, or other somewhat similar relations, attempts have been made to build a general set of procedures for calculating from physical measures what is or will be the perceived noisiness to the average person of sounds, regardless of their source and exclusive of their meanings. Indeed, procedures have been developed for estimating the perceived noisiness of (a) single occurrences of sounds of different spectra but of like durations, (b) single occurrences of sounds of different spectra and of like or different durations, and (c) multiple daily occurrences of sounds of different spectra and of like as well as of different durations. These procedures are described subsequently.

### Single Occurrences of Noise That Differ in Spectral Shape, Bandwidth, and Tonal Complexity

In figure 4 it was observed that the perceived noisiness of a sound of a given bandwidth changed as its center frequency was varied. However, noises of common interest are much more complex in their spectral content and bandwidths. The effect of changing the bandwidth of sounds is taken into account in the calculation of the perceived noisiness (PN) or perceived noise level (PNL) in accordance with the following formulas and approximation methods:

$$\text{Perceived noisiness} = \left[\text{Noys (max. band)} + 0.15\left(\sum \text{All bands} - \text{Noys (max. band)}\right)\right]$$

$$\text{Perceived noise level in PNdB} = 40 + 10 \log_2 \text{PN}$$

$$\text{Approximation methods} \begin{cases} \text{PNL in dB(N), sound level meter, N weighting network} \\ \text{PNL in dB(A), sound level meter, A weighting network} + 13\,\text{dB} \end{cases}$$

These formulas, which were developed by S. S. Stevens (ref. 5) for the calculation of loudness, have been empirically derived and work very well for noises that are of a single temporal pattern and differ only in their general spectral shape and width.

However, it has been found that a sound that consists of a broadband spectrum plus steady-state pure-tone or line spectral components is more unacceptable or noisier than a sound without these components, even though the pressures in the different frequency bands are the same for the two sounds. The tone-to-noise ratio (T/N) can, when the tone and noise are measured separately, be evaluated from one-tenth or narrower to full-octave band levels. When, as is usually the case, the tone and noise are measured together, the presence of pure-tone or line spectral components is identified by the ratio of the tone-plus-noise in a band to the noise in adjacent bands (T + N)/AN. When this ratio is 3.0 dB or greater, it is presumed that significant pure-tone or line spectral components are present.

Figure 5, based on reference 6, illustrates the subjective penalty that is generally found when pure-tone or line spectral components are present. This penalty, which is read from the ordinate, means that the band containing a pure-tone or line spectral component has an apparent subjective intensity equal to the actual measured sound pressure level in the band in question plus the number of decibels read from the ordinate in the figure. It is seen that the penalty earned by pure-tone or line components depends upon their frequency and the degree to which they exceed the background noise. The results of new tests of the pure-tone penalty are discussed in reference 7.

### Single Occurrences of Noises of Differing Temporal Pattern

Although loudness tends to remain constant if the intensity remains constant, the perceived noisiness of a sound increases as the noise is continued in time. To a first approximation it is found that the perceived noisiness of a sound is equal to the integrated, on an energy basis, PNdB values that are found in successive 1/2-second intervals during the occurrence of a noise. For practical purposes, an occurrence of a noise is said to extend between the times the noise is within 10 dB of its maximum level. The formula for calculating the effective perceived noise level (EPNL) of a sound is as follows:

$$\text{Effective perceived noise level in EPNdB} = \left(\sum_{0.5} \log_{10}^{-1} \text{PNdB}/10\right) - 12$$

$$\text{Approximation methods} \begin{cases} \text{EdB(N)} = \left(\sum_{0.5} \log_{10}^{-1} \text{dB(N)}/10\right) - 12 \\ \text{EdB(A)} = \left(\sum 0.5 \log_{10}^{-1} \text{dB(A)}/10\right) + 1 \end{cases}$$

where 0.5 is 1/2-second interval of time, and -12 is based on a reference duration of 8 seconds. It would appear, on the basis of present data, that the most accurate and general way of measuring or calculating from physical measurements the true unwantedness or noisiness of a sound is to determine tone-corrected PNdB values every 1/2 second during the sound and from these values to calculate their total or effective value. PNdB units that are calculated with tone corrections are usually designated $\text{PNdB}_t$.

Several units have been proposed for measuring or estimating the perceived noisiness of sounds. The most widely used or proposed measurements are summarized in table I. Several additional variations of these basic units are also in use or being evaluated, as are briefly discussed in reference 8.

## COMPOSITE NOISE RATING

One prime goal of noise evaluation is to determine the acceptability of a total noise environment present day after day in a given community or neighborhood. Research data collected to date indicate that the equal energy assumption used in calculating the EPNL of a sound apparently works reasonably well for the determination of the reaction of people to multiple sounds occurring during a day; that is, two sounds of equal EPNL have the same effect as one sound having an EPNL 3.0 dB higher than that of the individual sounds. In addition, it has been found that people react or complain more about noises occurring late at night (presumably because of interference with sleep and perhaps because the environment is, in general, quieter during that period and, therefore, more noise is noticeable). It has been proposed that a 10-dB penalty be placed upon noises that occur at night.

The sum of these ideas – that response to noises occurs on an energy basis and that there is a 10-dB greater sensitivity during the night than the day to noise – has been called the Composite Noise Rating (CNR). K. N. Stevens, A. C. Pietrasanta, and staff members of Bolt Beranek and Newman developed the Composite Noise Rating procedure for the U.S. Air Force (ref. 9). This procedure is used in the Department of Defense Land Use Planning Guide (ref. 10) and is also to be found in various technical reports prepared for the Federal Aviation Administration. The general formulas for *CNR* are as follows:

For noises of equal duration per occurrence but of differing spectra and/or numbers of occurrences,

$$CNR = \underbrace{\text{EPNL} + (10 \log_{10} N) - 12}_{\text{7 a.m. - 10 p.m.}} \oplus \underbrace{\text{EPNL} + (10 \log_{10} N) - 2}_{\text{10 p.m. - 7 a.m.}}$$

where N is number of occurrences of sounds and $\oplus$ is addition on $10 \log_{10}$ antilog basis.

For noises of equal or unequal durations per occurrence and of differing spectra and/or numbers of occurrences,

$$\text{CNR} = 10 \log_{10} \left[ \underbrace{\sum_{0.5} \left( \log_{10}^{-1} \text{PNdB}_{0.5}/10 \right) - 24}_{\text{7 a.m. - 10 p.m.}} \right] \oplus \left[ \underbrace{\sum_{0.5} \left( \log_{10}^{-1} \text{PNdB}_{0.5}/10 \right) - 14}_{\text{10 p.m. - 7 a.m.}} \right]$$

Originally, and during use, different units of measurement of the noise other than the EPNL units were used; also, from time to time, various "correction factors" have been applied to the units of noise measurement to account for presumed effects of the socioeconomic status of a neighborhood, that is, whether a neighborhood was close to heavy industry, rural, and so forth. There is obviously a need for standardizing the units of measurements and corrections to be used for the calculation of CNR.

As described previously, calculated PNL, EPNL, and CNR are based on the concept of a general reaction to sound that is the conglomerate effect of the attributes of loudness, masking of speech, auditory fatigue, and perhaps distractiveness and startle independently of any meaning the sound may have. It is to be noted that the behavioral reactions of most practical interest are those typically observed after months or years of daily or almost daily exposure to the respective noise environments. In that regard, it is estimated that there is an initial adaptation or familiarization over a period of the first several months of exposure to a given noise environment that reduces reactions to the noise by an amount equivalent to a reduction of about 10 CNR.

Figure 6 summarizes the general relations between CNR and various human reactions to sound. These relations are extrapolated from and consistent with laboratory and field research and actual "real-life" behavior of people in communities. (See ref. 11.) It is presumed that the range in reactions of people to a given noise environment as illustrated in figure 6 is a joint function of (a) individual personality differences, (b) individual and group differences in attitudes toward and abilities in the expression of complaints and other related behavior, and (c) variations in CNR exposure conditions between and in rooms in homes and buildings and areas in a community. Some new data on the problem of noise in communities are presented in references 12 and 13.

Unfortunately, one cannot really know the true EPNL or CNR received by individual people in their homes, or even on the streets in their communities, inasmuch as noise surveys depict only the noise present during some period of time at one point, or at most several points outdoors in a neighborhood. The actual noise in individual rooms and individual yards within that neighborhood must vary tremendously. Nevertheless, it is reasonable to believe that controlling noise in terms of EPNL and CNR must provide the most efficient and adequate criterion for reducing, by purely physical and operational means, the long-term reaction of people to noise in or at their homes and places of work.

## CONCLUDING REMARKS

Perhaps the most beneficial and practical applications of effective perceived noise level, and when possible Composite Noise Rating, are not with respect to present-day noises or noise environments but (1) as guides for the design and operation of so-called quiet engines, (2) in the forecasting of noise environments for neighborhoods and communities as new airports, roadways, and industries are developed and used, and (3) as guides for setting acoustical standards for new housing.

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TABLE I.- PROCEDURES THAT HAVE BEEN PROPOSED FOR ESTIMATION OF JUDGED PNL FROM OBJECTIVE SOUND MEASUREMENTS

[Within each class of sounds the units of measurement are rank ordered in accordance with relative accuracy with which usually they predict the judged perceived noisiness or unacceptability of sounds. (See ref. 6)]

| Class of sound | Sound measurement equipment | |
|---|---|---|
| | 1/3- or full-octave band filters and sound level meter, slow meter action | Sound level meter with frequency-weighting networks, slow meter action |
| Sounds of same temporal but different spectral patterns: | | |
| Broadband spectra, no pure tones or line spectra | 1. Peak PNdB<br>2. Max. PNdB | 3. dB(N)<br>4. dB(A) + 13 |
| Broadband spectra, with pure tones or line spectra | 1. Peak $\text{PNdB}_t$<br>2. Max. $\text{PNdB}_t$ | |
| Sounds of differing temporal and spectral patterns: | | |
| Broadband spectra, no pure tones or line spectra | 1. EPNdB<br>2. EEPNdB | 3. EdB(N)<br>4. EdB(A) + 13<br>5. EEdB(N)<br>6. EEdB(A) + 13 |
| Broadband spectra, with pure tones or line spectra | 1. $\text{EPNdB}_t$<br>2. $\text{EEPNdB}_t$ | |

## THRESHOLD SHIFT DUE TO A 200-HZ MASKING TONE

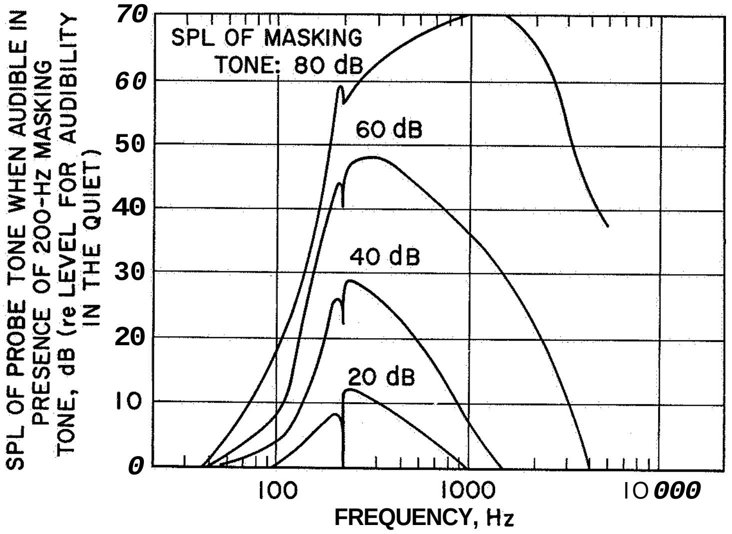
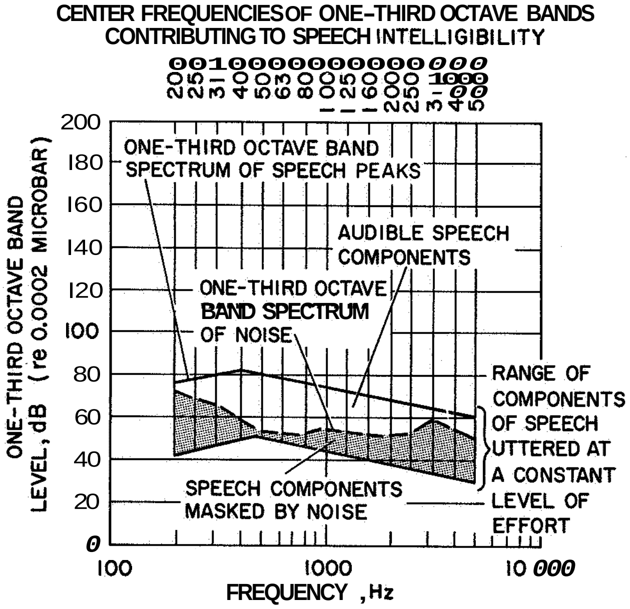


Figure 1

## PROCEDURE FOR CALCULATION OF THE ARTICULATION INDEX



| BAND cf, Hz | SPEECH PEAKS MINUS NOISE, dB | WEIGHT | COL 2 X C013 |
|---|---|---|---|
| 2001 | 4 | 0.0004 | 0.00 16 |
| 250 | 10 | 0.0010 | 0.0100 |
| 315 | 13 | 0.0010 | 00 130 |
| 400 | 24 | 0.0014 | 0.0336 |
| 500 | 26 | 0.0014 | 0.0364 |
| 630 | 26 | 0.0020 | 0.0520 |
| 800 | 24 | 0.0020 | 0.0480 |
| 1000 | 21 | 0.0024 | 0.0504 |
| 1250 | 18 | 0.0030 | 0.0540 |
| 1600 | 18 | 0.0037 | 0.0666 |
| 2000 | 15 | 0.0037 | 0.0555 |
| 2500 | 15 | 0.0034 | 0.051 0 |
| 3150 | 6 | 0.0034 | 0.0204 |
| 4000 | 8 | 0.0024 | 001 92 |
| 5000 | 12 | 0.0020 | 0.0240 |
| | | | AI = 0.5357 |
| AI OF 0.54 = 75 % WORDS CORRECT | | | |

Figure 2

EXPOSURES TO BANDS OF NOISE THAT WILL CAUSE ABOUT 10 dB THRESHOLD SHIFT AT 1000 Hz OR BELOW, 15 dB AT 2000 Hz, OR 20 dB AT 3000 Hz AND ABOVE

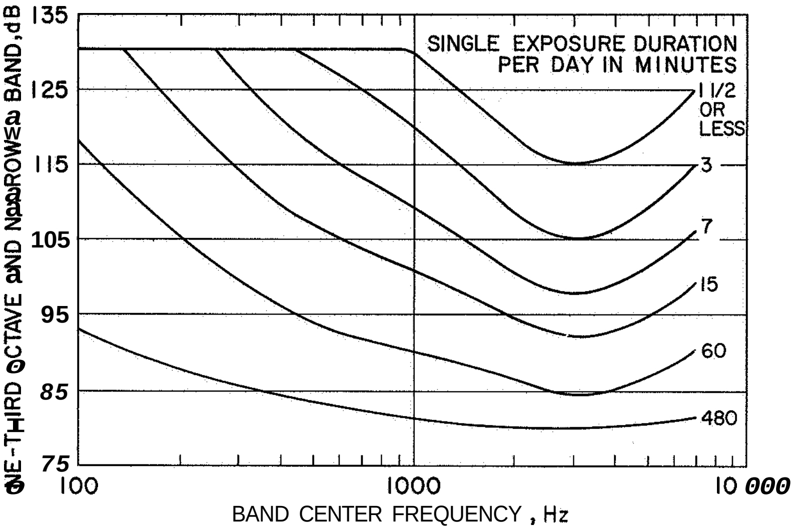


Figure 3

NOISINESS OF BANDS OF SOUND

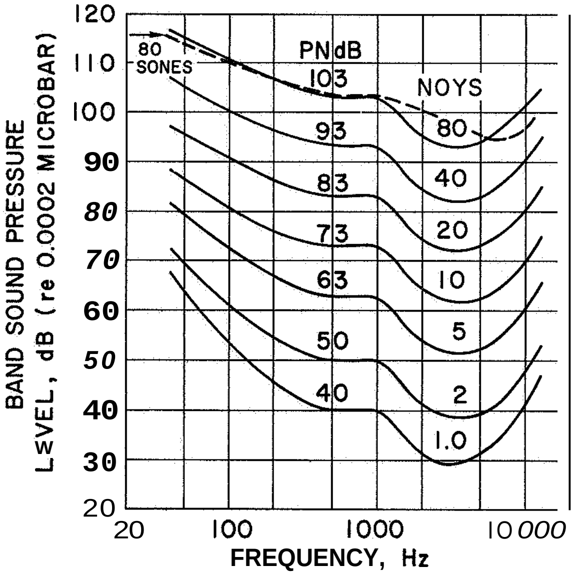


Figure 4

PENALTY FOR PURE TONES OR LINE SPECTRA

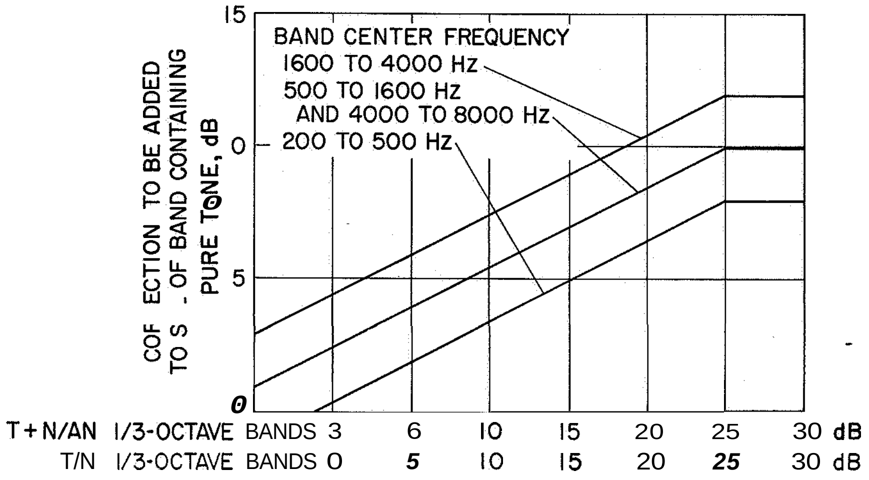


Figure 5

TOLERABLE LIMITS OF NOISE EXPOSURE FOR DIFFERENT AREAS AND PLACE OF MEASUREMENT

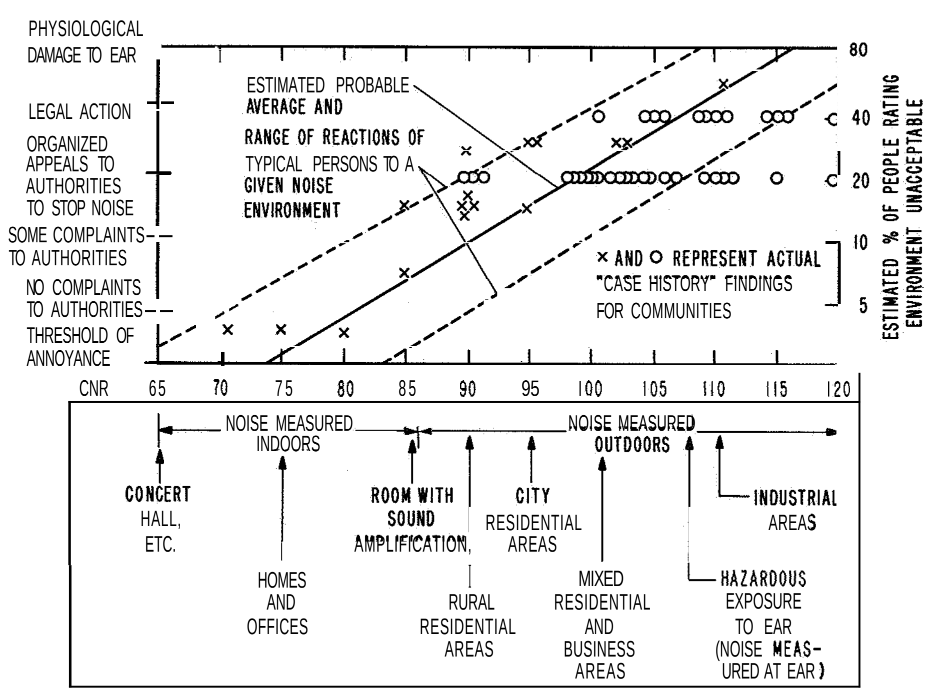


Figure 6