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CONSULTANTS IN ACOUSTICS

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LECTURE NOTES

on

NOISE AND MANUFACTURING PLANTS

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CHAPTER I

INTRODUCTION TO ACOUSTICS

In this discussion of noise and vibration, it is intended to move quickly into the use of acoustical terms and to become acquainted with some of the elementary acoustical procedures without necessarily knowing or comprehending all the acoustics background that goes into the development of this material. Textbooks or reference books in acoustics* may be studied for a more detailed discussion and technical understanding of this material.

1. DECIBELS

Just as "inches" are used to measure distance and "degrees" are used to measure temperature, "decibels" are used to measure sound intensity. As in electrical engineering, decibels are used to express in logarithmic terms the ratio of two powers; i.e., if there are two electrical or acoustical powers P_1 and P_2, the ratio of those powers expressed in decibels would be

$$10 \log P_2/P_1 \quad .$$

If the power P_1 were some accepted standard reference power, such as a watt or some other basic unit of power, the decibels could be standardized to that reference value.

In acoustics, the decibel (abbreviated "dB") is used to compare both <u>sound power</u> and <u>sound pressure</u>. When describing the sound <u>power</u> of a sound source, the basic reference power is 10^{-12} watt (acoustic watts), and a particular sound source might be described as having a "sound power level" of, for example, 110 dB re 10^{-12} watt. When describing the sound <u>pressure</u> in a sound field, the basic reference pressure is 0.0002 microbar, and a particular area might be stated as having a "sound pressure level" of, say, 90 dB re 0.0002 microbar.

A microbar is equal to one dyne per sq cm or 0.1 newton per sq meter and is very nearly equal to one millionth of a standard atmosphere. It is likely that in a few years the reference pressure 0.0002 microbar will come to be known as $2\text{x}10^{-5}$ newton per sq meter. If this comes, it will be in the interest of international standardization of terminology and units.

In acoustics, the term "level" is used whenever a decibel quantity is expressed relative to a reference value, as in "sound pressure level" (referred to the reference pressure of 0.0002 microbar) and "sound power level" (referred to the reference power of 10^{-12} watt).

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*"Acoustics", Leo L. Beranek; McGraw-Hill Book Company (1954).

"Noise Reduction", Leo L. Beranek, Editor; McGraw-Hill Book Company (1960).

"NOISE AND VIBRATION ENGINEERING", Leo L. Beranek, Editor; McGraw-Hill Book Company (Planned for 1970 or 1971 Publication).

2. SOUND PRESSURE LEVEL

The ear is sensitive to sound pressure. Sound waves represent tiny oscillations of pressure just above and just below atmospheric pressure. These pressure oscillations impinge on the ear and "we hear the sound".

A "sound level meter" is also sensitive to sound pressure. When a sound level meter is properly calibrated, it relates the sound pressure of an incident sound wave to the standard reference pressure (0.0002 microbar) and it gives a reading in decibels relative to that reference pressure. "0 dB" on this scale means 0 dB above the reference pressure, which, of course, is the same as the reference pressure. This reference pressure, or 0 dB sound pressure level, represents approximately the weakest sound that can be heard by the average young human ear in the frequency region of highest sensitivity. (This definition came into existence when people were known to have maximum hearing sensitivity at youth; the truly damaging effects of too-loud music will change this for some of today's young people.)

A simple but expressive definition of "noise" is that it is "unwanted sound"; so "noise level" is often used synonymously with "sound pressure level". Both terms have the same reference pressure and are used interchangeably in this manual. The reference to 0.0002 microbar may be and frequently is omitted when it is clearly understood that the dB quantity is a sound pressure level. Hence one might say that "the noise level in the mechanical equipment room is about 85 dB".

Two abbreviations of the term "sound pressure level" are in fairly common use: "SPL" and "Lp". "SPL" is used in much of the literature and "Lp" is being used in some of the more recent literature. The abbreviation "SPL" is used throughout this manual, but it is completely interchangeable with "Lp" as found elsewhere.

3. ANALOGY BETWEEN LIGHT AND SOUND

Sound pressure and sound power can be illustrated simply with an analogy between light and sound. Suppose first that a room is illuminated with a bare 15-watt electric lamp. Even in a room with white painted walls and ceiling, this normally would be considered as a weak light source. If the room had only dark, unreflecting surfaces, the general room illumination would be very poor. Now a bare 150-watt lamp would give good general illumination if the walls are white, or light-colored, or highly reflecting (and depending, of course, on the size of the room and the distance to the lamp). However, the same 150-watt lamp might not give adequate room illumination if the walls and ceiling were black, or dark-colored or non-reflective. Thus, it is reasonably obvious that the intensity of the general room illumination depends not only on the power rating of the lamp, but also on the light-reflecting (or absorbing) properties of the room surfaces, on the size of the room, and on the distance to the light source. Further, if the lamp had a lamp-shade or if it were recessed in a flush-mounted ceiling receptacle, the light would be brighter in some directions than in others.

All the same factors apply to sound in a room! "Sound pressure level" is somewhat analogous to room illumination; "sound power level" is somewhat analogous to the power rating of the lamp. A "weak" sound source would produce low sound levels while a "stronger" sound source would produce higher sound levels. A constant sound source that would produce one sound level in a hard-walled bare room would produce a different sound level in the same room surfaced with a large amount of soft, fluffy acoustic absorption material.

The sound source would produce a higher sound level a few inches away than it would several feet away. It might radiate higher sound levels from one side than from another side. It would produce different sound levels in a large room than it would in a small room. Thus, the sound level in the room depends not only on the sound source (actually its "sound power"), but also on the sound absorption properties of the room surfaces, on the size of the room, the distance to the sound source, and also the directional characteristics of the sound source. In effect, the sound pressure levels heard by a person in the room are determined both by the sound power radiated by the source and by the "acoustic characteristics" of the room. All of this is merely leading up to the fact that (1) there is need for a way of rating a sound source that is independent of the environmental surroundings, and (2) there is need for a way of describing the "acoustic characteristics" of the room that is independent of the sound source. Then, with these two independently determined bits of information, any known, definable room or space and the sound field or "sound pressure level" ("SPL") about the room can be determined, remembering that it is the sound pressure level to which people respond in their living and working environments. Just as the 150-watt lamp may produce relatively poor to good illumination in a given room, so also will a sound source produce relatively low or high sound pressure levels in a given room. Further, just as electric lamps are rated by a power rating, so also sound sources are rated by a power rating.

4. SOUND POWER LEVEL

The quantity "sound power level" expresses, in decibels relative to the reference power of 10^{-12} watt, the total amount of sound power radiated by a sound source, regardless of the space into which the source is placed. As suggested above, if the power level of a sound source is known and if the "acoustic characteristics" of a space are known, it will then be possible to estimate or calculate the sound pressure level in that space. Ultimately it is the SPL that usually must be determined because it is on that basis that people judge an acoustic environment.

Two abbreviations of "sound power level" are in common use: "PWL" and "L_w". "PWL" is used throughout this manual, but it is completely interchangeable with "L_w".

The need for sound power level data has grown rapidly in recent years. Consider ventilation system diffusers as an example. In earlier years, one manufacturer might have published sound pressure levels for his diffusers measured at some named distance in his highly reverberant test room. Another manufacturer might have published sound <u>pressure</u> levels of his diffusers at another distance in his test room (undoubtedly of different size and acoustic characteristics than that of his competitor). Still another manufacturer might have published noise data that he measured in a particular mock-up of a room that was intended to represent a typical office of a large building. Well, each manufacturer might have felt justified in his procedure, but the same identical diffuser in all those different test conditions could have yielded variations as high as 5 to 10 dB in sound pressure level. To provide a more realistic rating of <u>diffusers</u> (and other noise sources as well) rather than the <u>test rooms</u> in which they were measured, the importance of sound <u>power</u> level has come to be realized as a true indicator of the quantity of noise radiated by a source regardless of the surroundings. This fact has been recognized by most manufacturers of equipment to be rated or selected in terms of noise output; and they are in the process of obtaining and providing sound <u>power</u> level data for their equipment. The test facilities are quite expensive and the tests are not always simple, but steps are being taken to provide PWL data to the designer and customer.

5. SOUND POWER REFERENCE 10^{-12} WATT

The reference power for sound power level data in present U.S. and international usage is 10^{-12} watt as stated above. This reference should <u>always</u> be quoted (as in "110 dB re 10^{-12} watt") so as not to be confused with SPL data or with earlier PWL data that used 10^{-13} watt as the reference power.

Most of the U.S. acoustics literature before about 1963-1966 (and even some current literature) uses 10^{-13} watt as the reference power. The 10^{-12} watt value is now accepted as the U.S. and international standard. A 10 dB error can result by not using the correct reference. If it is desired to use PWL data given in "dB relative to 10^{-13} watt", reduce those numerical values of PWL by 10 dB to convert them to PWL values in "dB relative to 10^{-12} watt". Conversely, if it is desired to convert from 10^{-12} watt reference to 10^{-13} watt reference, add 10 dB to the 10^{-12} watt PWL values to get "dB re 10^{-13} watt". In this manual and in most current literature, 10^{-12} watt is the reference power for PWL data.

6. FREQUENCY, HZ AND CPS

With the recent trend in U.S. and international standards to recognize the early men of science, many new names for old units are being adopted. The traditional unit for frequency in the U.S. has been "cycles per second", abbreviated "cps". The new international unit for frequency, recently adopted by U.S. standards groups, is "Hertz", abbreviated "Hz". Throughout this manual the new unit "Hz" will be used; it has the same meaning as "cycles per second".

7. "OVERALL" FREQUENCY RANGE AND OCTAVE BANDS OF FREQUENCY

In order to represent properly the total noise of a noise source, it is usually desirable or necessary to break the total noise down into its various frequency components; that is, how much of the noise is low frequency, how much high frequency and how much is in the middle frequency range. This is essential for any comprehensive study of a noise problem for two reasons: (1) people react differently to low frequency and high frequency noise (for the same sound pressure level, high frequency noise is much more disturbing and is more capable of producing hearing loss than is the case for low frequency noise); and (2) the engineering solutions to reduce or control noise are different for low frequency and high frequency noise (low frequency noise is more difficult to control, in general).

It is conventional practice in acoustics to determine the frequency distribution of a noise by passing that noise successively through several different filters that separate the noise into 8 or 9 "octaves" on a frequency scale. Just as with an "octave" on a piano keyboard, an "octave" in sound analysis represents the frequency interval between a given frequency (such as 300 Hz) and twice that frequency (600 Hz in this illustration).

The normal frequency range of hearing for most people extends from a low frequency of about 20 Hz up to a high frequency of 10,000 to 15,000 Hz, or even higher for some people. By virtue of U.S. adoption of a recent international frequency standard in acoustics, most octave-band noise analyzing filters now cover the audio range of about 22 Hz to about 11,200 Hz in nine octave frequency bands. These filters are identified by their geometric mean frequencies; hence 1000 Hz is the label given to the octave frequency band of 700-1400 Hz. The nine octave bands of the "new" international standard are as follows (the numbers are frequently rounded off):

Octave Frequency Range (Hz)	Geometric Mean Frequency of Band (Hz)
22-44	31½
44-88	62½
88-175	125
175-350	250
350-700	500
700-1400	1000
1400-2800	2000
2800-5600	4000
5600-11,200	8000

The term "overall" designates the full frequency coverage of all the octave bands, hence 22-11, 200 Hz, or in some cases, 44-11, 200 Hz when the 31 Hz band is omitted.

The frequency bands in use in the U.S. before adoption of the bands listed above are as follows: 20-75, 75-150, 150-300, 300-600, 600-1200, 1200-2400, 2400-4800 and 4800-10,000 Hz. Most of the literature in acoustics before about 1963 will refer to these "old" frequency bands. The "new" international standard frequencies (sometimes called "preferred frequencies" in current literature) are used in this manual. Essentially the "old" and "new" frequency bands may be considered as being equivalent, with a few exceptions that will not be significant to the material in this manual. A set of filters used to separate a complex sound into octave bands is commonly referred to as an "octave band analyzer".

When a sound pressure level or a sound power level includes all the audio range of frequency, the resulting value is called the "overall" level. When the level refers to the sound in just one specific octave frequency band, it is called an "octave band level" and the frequency band is either stated or clearly implied.

For some special situations, a noise spectrum may be studied in finer detail than is possible with octave frequency bands. In such cases one-third octave bands might be used or even narrower filter bands might be used, for example to separate one particular frequency from another one if it is desired to separate the causes of a particular complex noise. The bandwidth and the identifying frequency of the band should always be specified.

8. WEIGHTING NETWORKS: A-, B- AND C-SCALES

Sound level meters are usually equipped with "weighting circuits" that tend to represent the frequency characteristics of the average human ear for various sound intensities. Hence, "overall" readings are sometimes taken with "A-scale" or "B-scale" or "C-scale" settings on the meter. The "A-scale" setting of a sound level meter filters out as much as 20 to 40 dB of the sound below 100 Hz, while the "B-scale" setting filters out as much as 5 to 20 dB of the sound below 100 Hz. The "C-scale" setting is reasonably "flat" with frequency, i.e. it retains essentially all the sound signal over the full "overall" frequency range. A plot of the frequency response of the electrical system of a sound level meter meeting USASI (U.S.A. Standards Institute, formerly American Standards Association) standards for the A-, B- and C-scale weighting networks is shown in Figure 1 at the end of this chapter. For several years the A-scale and B-scale readings were held in disfavor because they do not provide any knowledge of the frequency distribution of the noise, but there is a revival in the use of A-scale readings as a single-number indicator of the relative loudness of a sound as heard by the human ear. It is very important, when reading A-, B- or C-scale sound levels, to positively identify the scale setting used. The resulting values are called "sound levels" and are frequently identified as dB(A), or dB(B) or dB(C) readings. Note that these readings do not represent true "sound pressure levels" because some of the actual signal has been removed by the weighting filters.

For most acoustic applications the octave frequency band readings are the most useful. It is always possible to construct A-, B- or C-scale readings from all the octave band readings, but it is never possible to exactly construct the octave band readings from the weighting scale readings.

9. ADDITION OF DECIBELS

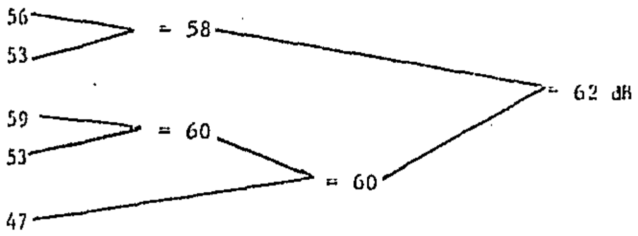
Since decibels are logarithmic values it is not proper to add them by normal algebraic addition. For example, 63 dB plus 63 dB does not equal 126 dB but only 66 dB.

A very simple, but adequate schedule for adding decibels is as follows:

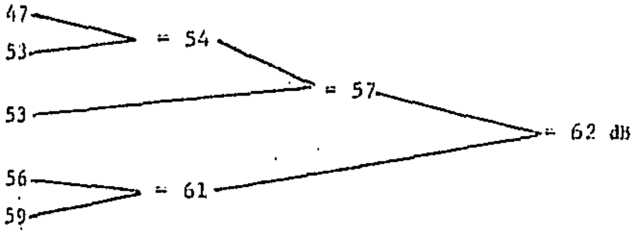
When two decibel values differ by:	Add the following amount to the higher value:
0 or 1 dB	3 dB
2 or 3 dB	2 dB
4 - 8 dB	1 dB
9 dB or more	0 dB

When several decibel values are to be added, perform the above operation on any two numbers at a time; the order does not matter. Continue the process until only a single value remains. A table repeating these rules is included in the section on noise sources.

As an illustration, add the following five noise levels:



Or, suppose the same numbers are arranged in a different order, as in



Sometimes, using different orders or adding may yield sums that might differ by 1 dB, but this is not too significant a difference in acoustics. In general, the above simplified summation procedure will yield accurate sums to the nearest 1 dB. This degree of accuracy is considered acceptable for the material given in these notes.

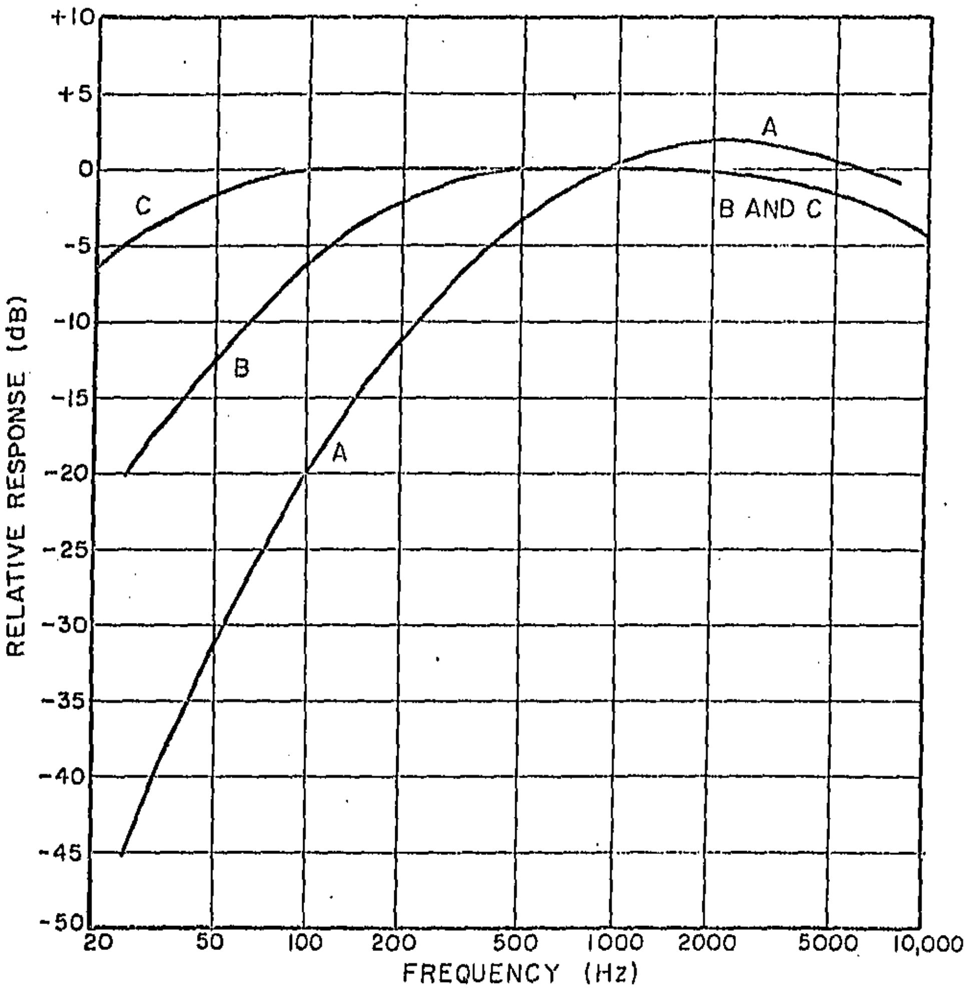


FIG. 1 APPROXIMATE ELECTRICAL FREQUENCY RESPONSE OF THE A-, B-, AND C-SCALE WEIGHTING NETWORKS OF USASI-APPROVED SOUND LEVEL METERS. (Taken from General Radio Company "Handbook of Noise Measurement")

CHAPTER 2

NOISE CRITERIA

The degree of disturbance or annoyance of an intruding unwanted noise depends essentially on three things: (1) the amount and nature of the intruding noise, (2) the amount of background noise already present before the intruding noise occurred and (3) the nature of the working or living activity of the people occupying the area in which the noise is heard. People trying to sleep in their quiet suburban homes would not tolerate very much intruding noise; while office workers in a busy mid-city office could have greater amounts of noise without even noticing it; and factory workers in a continuously noisy manufacturing space might not even hear a noisy nearby equipment installation.

It is common practice in acoustical engineering to rate various environments by "noise criteria" and to describe these criteria by fairly specific noise level values. Detailed discussions of noise criteria can be found in other literature*, and only a brief useful summary of that material is introduced here. In the interest of brevity, many important details and qualifications are omitted. Thus, in a complex problem, additional reading or acoustical assistance may be necessary.

1. NOISE CRITERION CURVES

From earlier studies of many types of noise environments that people have found either "acceptable" or "unacceptable" for various indoor working or living activities, a family of "Noise Criterion Curves" ("NC" curves) has been evolved. Figure 1 presents these curves. Each curve represents a reasonably acceptable balance of low frequency to high frequency noises for particular situations. These curves are also keyed-in to the "speech communication" conditions permitted by the noise. Thus, the lower NC curves prescribe noise levels that are quiet enough for resting and sleeping or for excellent listening conditions, while the upper NC curves describe rather noisy work areas where even speech communication becomes difficult and restricted. The curves within this total range may be used to set desired noise level goals for almost all typical indoor functional areas where some acoustic need must be served. For convenience in using the NC curves, the octave band sound pressure levels of Figure 1 are enumerated in Table 1.

In Table 2, a number of typical indoor living, working and listening spaces are grouped together into "categories" and each category is assigned a

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*For a quantitative discussion of noise criteria and noise levels, refer to a textbook or reference book on acoustics, such as "Noise Reduction", Leo L. Beranek, Editor; McGraw-Hill Book Company (1960) or "Handbook of Noise Control", C. M. Harris, Editor; McGraw-Hill Book Company (1954), or to the latest issue of the ASHRAE "Guide and Data Book", American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 346 East 47th Street, New York 10017 or to selected topics of the Journal of the Acoustical Society of America representative range of noise criterion values. Low Category Numbers indicate areas in which relatively low noise levels are desired; higher Category Numbers indicate areas in which relatively higher noise levels are permissible. Any occupied or habitable area not specifically named in Table 2 can be added under any appropriate Category Number as long as the acoustic requirements of the new area are reasonably similar to those of the areas already named under that category. A 5-10 dB range of NC values is given in Table 2 for each of the first five categories. In general, the lower limit of each range should be used for the more critical spaces or the more sensitive or criticaloccupants of an area, while the upper limit of each range may be used for the less critical spaces or occupants of an area. An exception to this generalization may occur when it is clearly known that the background noise of an area is so quiet and the walls between adjoining rooms have such low "transmission loss" that speech sounds or other clearly identifiable sounds may intrude from one office to another and be disturbing to occupants of either area. In this type of situation, "masking noise" may have to be introduced into the rooms in order to reduce some of the intelligibility of the intruding sounds, and the higher range of noise criterion values may actually be useful, as long as the mechanical equipment noise itself is relatively unobtrusive and not too identifiable. When properly controlled as to spectrum shape and sound level, ventilation system noise (the gentle "hissing" of diffusers, under-window induction units, dampers or air valves) sometimes provides some of this "masking noise". In more critical cases, where spectrum and level must be held under close control, electronic noise sources may be used.

A special note of concern is given for the Category 1 and 2 areas of Table 1. For a very quiet community area or for a quiet building with no internal ventilation system noise, the NC-20 noise criterion should be applied for indoor conditions. For a noisy city environment outdoors or for a building with a ventilation system known to fall in the NC-30 noise range, an NC-30 noise criterion can be applied to rooms other than bedrooms or auditoriums. For bedrooms or auditoriums or for situations that do not clearly fall at the NC-20 lower limit or NC-30 upper limit, NC-25 indoor noise criterion levels should be applied.

The reader may refer to the most recent issue of the ASHRAE Guide and Data Book for a listing of other typical situations and the associated range of NC values. The ASHRAE Guide usually lists a 10 dB range of NC values for each space, leaving it to the option of the user to select the specific NC value for his own particular situation.

For music or performing arts centers or concert halls, there is increasing evidence that a complete absence of noise is required in order to provide a full appreciation of the very low level sounds sometimes coming from the stage area. Thus, an NC-15 to NC-20 criterion should be applied as the goal for high quality concert halls. Acoustical assistance may be required to achieve these goals.

It is noted here that much of the known data on criteria do not extend down to the very low frequency band of 31 Hz. Some of the noise source data, however, include 31 Hz levels. For most ordinary noise problems, there will be no serious concern for the 31 Hz band so it can be ignored for most calculations. If it is known that a serious problem involves decision-making at 31 Hz, acoustical assistance should be obtained.

2. SPEECH INTERFERENCE LEVELS

A reasonably steady broad-band noise with moderate to high noise levels in the frequency bands of 500 to 2000 Hz will produce some degree of interference with speech, since most of the intelligibility of the human voice falls in this frequency range. The term "speech interference level" of a noise is now defined as the arithmetic average of the sound pressure levels of the noise in the three octave bands centered at 500, 1000 and 2000 Hz.* Table 3 gives the average "speech interference level" of a noise that will just barely permit reliable speech communication for a range of voice levels and distances. The data are based on tests performed out-of-doors where there are no reflecting surfaces to help reinforce the speech sounds, but the values can be used as approximations for indoor conditions as well. Also, to a first approximation (but not exactly), if a noise follows the shape of an NC curve, the "PSIL" value of the noise will nearly equal the NC curve number.

As a simple example of the use of Table 3, if the noise levels in a Mechanical Equipment Room average 62 dB in the 500, 1000 and 2000 Hz bands, barely reliable speech conversations could be carried on in that room by shouting at a 16-ft distance, by using a loud voice level at a distance of 8 ft, by using a raised voice at a distance of 4 ft or by using a normal voice level at a distance of 2 ft.

3. OUTDOOR BACKGROUND NOISE

People tend to compare an intruding noise with the background noise that was present before the new noise came into existence. If the new noise has distinctive sounds that make it readily identifiable or if its noise levels are considerably higher than the background or "ambient" levels, it will be noticeable to the residents and it might be considered objectionable. On the other hand, if the new noise has a rather unidentifiable, unobtrusive sound and its noise levels blend into the ambient levels, it will hardly be noticed by the neighbors and it probably will not be considered objectionable.

Thus, in trying to estimate the effect of a new noise on a neighbor, it is necessary to know or to estimate the background noise levels in the absence of the new noise. Since the equipment is probably planned for continuous day and night operation, and since people are less tolerant of an intruding noise at night, the nighttime ambient noise levels are important to the evaluation of the problem.

Where possible (and especially if a sensitive neighborhood is located nearby), the average minimum nighttime noise levels should be measured several times

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*"SIL" was originally defined in terms of the three formerly-used octave bands 600-1200, 1200-2400 and 2400-4800 Hz. With the acceptance of the new international frequency bands in the U.S., an adjustment of values has been made and the new values are being identified by the notation "PSIL" in order to designate that they are based on the now "preferred" frequencies.

during several typically quiet nights. Readings should be taken in octave bands and readings should be taken when there is no nearby truck or auto traffic that would give falsely high values.

If background measurements cannot be made, the ambient noise levels can be estimated approximately with the use of Tables 4 and 5. In Table 4, the condition should be determined that most nearly describes the community or residential area or the nearby traffic activity (which frequently helps set the ambient levels in an otherwise quiet neighborhood) that would exist during the quietest time that the equipment would be in operation. For the condition that is selected, there is an appropriate "Noise Code No." at the right-hand side of Table 4 that is used to enter Table 5. For that particular Noise Code No., Table 5 then gives an estimate of the approximate average minimum background noise levels for that area and traffic condition. This is not an infallible estimate but it will serve in the absence of actual measurements.

It is cautioned that these estimates should be used only as rough approximations of background noise and that local conditions can give rise to a wide range of actual noise levels.* It is, nevertheless, realistic to utilize a method such as this to help determine the amount of noise that a new noise can make without becoming noticeably louder than the general background.

4. NOISE REDUCTION PROVIDED BY A BUILDING

An intruding noise coming from an outdoor noise source or by an outdoor noise path may be heard by a neighbor who is either indoors in his own building or outdoors on his property. If he is outdoors he may judge the intruding noise against the more-or-less steady background noise due to other noises in the area. If he is indoors, he may tend to judge the noise by whether it is audible or identifiable or intrusive into his surroundings. If the noise, when heard indoors in the neighbor building, can be made to be no greater than the appropriate NC values that would normally apply there, it is quite likely that there will be no complaint against the noise.

When outdoor noise passes into a building it suffers some noise reduction, even if the building has open windows. The actual amount of noise reduction depends on building construction, orientation, wall area, window area, open window area, interior acoustic absorption, etc. For practical purposes, however, the approximate noise reduction values provided by a few typical building constructions are given in Table 6. If these amounts of noise reduction are added to the indoor NC values, one would obtain the outdoor sound pressure levels that would yield the indoor NC values, applicable when outdoor noise passes through the building wall and comes indoors. For convenience and identification, the listed wall constructions are

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*A procedure similar to this is given in the ASHRAE Guide. It is cautioned, however, that the actual curves and sound levels used in the ASHRAE Guide are not identical to those used in this manual, even though the ASHRAE material originally was developed from data first presented in an earlier Baltimore Aircoil Company Bulletin. The data presented here are recommended as being slightly more conservative and somewhat more specific than the equivalent data offered in the ASHRAE Guide.

labeled with letters A through G, and are described in the notes under Table 6. Note that Wall A represents no wall at all, hence no noise reduction; and the use of Wall A indicates that the selected NC curve would actually apply in this special case to an outdoor activity (such as for a screened-in sleeping porch, a drive-in theater, an outdoor restaurant, an outdoor terrace, and the like).

5. OUTDOOR NOISE CRITERION

From the foregoing material it is possible to estimate an approximate outdoor noise criterion for almost any type of neighbor situation. Two somewhat independent approaches should be tried, and the decision based on the results of those two approaches.

The first approach provides an "outdoor noise level criterion" that will essentially produce the desired indoor noise levels after the noise passes through the wall of the neighbor building. These outdoor noise levels are merely the arithmetic sum of the appropriate indoor noise criterion levels from Table 1 and the noise reduction values of the neighbor's building as taken from Table 6.

The second approach provides another "outdoor noise level criterion" that is essentially based on the possible "intrusion" of the new noise into the existing outdoor background noise, as determined from Tables 4 and 5. To be completely inconspicuous, the new noise, when extrapolated to the neighbor's location, should be kept at or below the outdoor background noise levels in all octave bands. (If a noticeable pure tone signal is present in the intruding noise, its octave band level must be 5-10 dB lower than the background level in that octave band in order not to be noticeable. It may be difficult or economically impractical to reduce the noise to such low levels that they are essentially undetectable in the background. In this case it may be necessary to permit a small amount of intrusion; this may be done at a risk of generating complaints against the noise. A noise excess of about 5 dB above the background (at night) may produce some annoyance but it probably will not lead to legal action. An excess of about 10 dB above background noise will generally produce mild to strong complaints, and an excess of 15 dB or more is almost certain to generate serious complaints and ultimately legal action.

When the outdoor noise criterion levels are obtained by these two approaches, a decision should be reached on the final levels to be used. The lower octave band levels from each approach will certainly yield a non-intrusive noise; the upper octave band levels from each approach may be acceptable if they do not produce the high noise level excesses mentioned above.

6. PROTECTION OF HEARING

When people are exposed repeatedly to high noise levels for long periods of time, hearing loss may result. The noise levels in mechanical equipment rooms ("MERs") or power plants in buildings are frequently high enough to constitute hazardous exposures for essentially continuous occupancy in those work areas.

Table 7 lists the maximum sound pressure levels recommended by two groups for protection of hearing for personnel exposed to these levels for essentially 8 hours per day for many years. Even these levels will produce some hearing loss to some individuals. For details, the reader should refer to the original sources of data.*

Table 8 lists the noise levels considered acceptable for single part-time exposures on a daily basis. Part A of Tables 7 and 8 applies for broad-band noise (no pure tones present), while Part B of each table applies for narrow-band or pure-tone noise.

The CHABA Report emphasizes the value of rest or recovery periods of relative quietness intermixed with periods of high noise levels. During these periods of "quietness" (which must be at least 10 dB quieter in all bands than the levels given in Table 7), the ears begin a recovery process from the previous noise exposure that somewhat helps prepare the listener for the next noise exposure. In effect, for situations where the steady-state noise levels are just marginally above the recommended noise levels of Tables 7 and 8, it is possible to reduce the effect of the higher noise levels by intentionally providing some scheduled periods of "quiet". Or, if the nature of the operator's work in the machinery room is somewhat intermittent, it would be possible to permit these higher noise level exposures, provided that intermittent periods of relative quiet are also assured. Certain generalizations can be given for the intermittent sequences of noise and quiet:

(1) for long intervals of noise exposure, relatively long periods of recovery are required;

(2) for short intervals of noise exposure, relatively short periods of recovery are required;

(3) the higher the noise level, the more beneficial is the short-term removal from the noise.

The CHABA Report provides data on various amounts of intermittent exposures to noise to show the value of these recovery periods. A representative condition is shown in Figure 2. This plot shows the noise levels considered acceptable for certain intervals of noise "on" when they are followed by 10-minute intervals of noise "off". For use of these plots, the operator should be exposed to noise levels at least 10 dB below the Table 7 values during the 10-minute recovery periods.

It is strongly recommended that a separate control room be provided for each MER that must be attended, so that operating personnel can be provided a relatively quiet environment that does not involve hearing-loss noise levels.

---

*"Noise and Conservation of Hearing," Department of the Army Technical Bulletin TB MED 251, 25 January 1965.

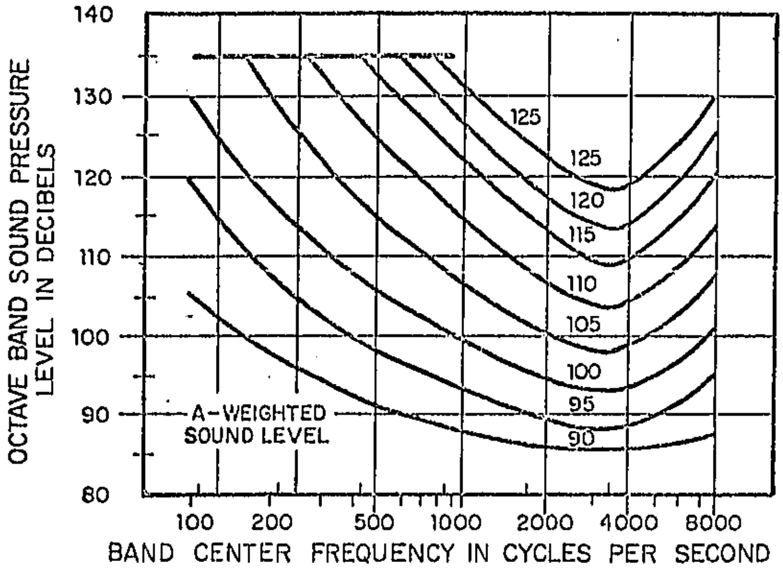
"Hazardous Exposure to Intermittent and Steady-State Noise," National Academy of Science and National Research Council, Committee on Hearing, Bioacoustics, and Biomechanics ("CHABA"), January 1965. (Also published in the Journal of the Acoustical Society of America, Vol. 39, No. 3, pp. 451-464, March 1966).

If the conditions of Tables 7 and 8 and Figure 2 cannot be met, ear protectors or a medically-supervised hearing conservation program are advised.

7. WALSH-HEALEY REGULATION

The following excerpts are taken from the Federal Register, Volume 34, No. 96, May 20, 1969 regarding U.S. Department of Labor Safety and Health Standards:

> Para. 50-204.1 Scope and Application
>
> (a) The Walsh-Healey Public Contracts Act requires that contracts entered into by any agency of the United States for the manufacture or furnishing of materials, supplies, articles, and equipment in any amount exceeding $10,000 must contain, among other provisions, a stipulation that "no part of such contract will be performed nor will any of the materials, supplies, articles, or equipment to be manufactured or furnished under said contract be manufactured or fabricated in any plants, factories, buildings, or surroundings or under working conditions which are unsanitary or hazardous or dangerous to the health and safety of employees engaged in the performance of said contract. Compliance with the safety, sanitary, and factory inspection laws of the State in which the work or part thereof is to be performed shall be prima-facie evidence of compliance with this subsection.
>
> Para. 50-204.10 Occupational Noise Exposure
>
> (a) Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown in Table 1 of this section when measured on the A scale of a standard sound level meter at slow response. When noise levels are determined by octave band analysis, the equivalent A-weighted sound level may be determined as follows:



Equivalent sound level contours. Octave band sound pressure levels may be converted to the equivalent A-weighted sound level by plotting them on this graph and noting the A-weighted sound level corresponding to the point of highest penetration into the sound level contours. This equivalent A-weighted sound level, which may differ from the actual A-weighted sound level of the noise, is used to determine exposure limits from Table I.

(b) When employees are subjected to sound exceeding those listed in Table I of this section, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of the table, personal protective equipment shall be provided and used to reduce sound levels within the levels of the table.

(c) If the variations in noise level involve maxima at intervals of 1 second or less, it is to be considered continuous. ~~In such cases, where the duration of the maxima are less than 1 second, they shall be treated as of 1-second duration.~~ delete

(d) In all cases where the sound levels exceed the values shown herein, a continuing, effective hearing conservation program shall be administered.

TABLE I

PERMISSIBLE NOISE EXPOSURES[1]

Duration per day, hours	Sound level dBA
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

[1] When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions: C1/T1+C2/T2. . . . Cn/Tn exceeds unity, then, the mixed exposure should be considered to exceed the limit value. Cn indicates the total time of exposure at a actual ~~specified~~ noise level, and Tn indicates the total time of exposure permitted at that level.

Exposure to impulsive or impact noise should not exceed 140 dBC peak sound pressure level (as read by an impact meter).

8. EAR PROTECTORS

Table 9 presents the approximate attenuation of a good, fitted ear plug (Air Force Type V-51R) and a reasonably comfortable softly-sealing ear muff (Air Force Type PRU-1/P) used singly or in combination. Other current models of well-fitted molded ear plugs and ear muffs will approximate these values, although poorly fitting protectors will have leakage and will fall short of these values by as much as 5 to 10 dB. In practice, ear plugs are more likely to be poor-fitting because they work loose with time. For most practical purposes the attenuation of either ear plugs or ear muffs may be taken to be about the same and to equal the lower values marked with an "*" in Table 9.

The details of fitting, maintaining and the need for persistent use of ear protection are not discussed here as that must fall to the Medical Director and ultimately to the user. It is merely emphasized that ear protectors have no equal for certain specific noise situations.

In the words of Dr. Arom Glorig, leading otologist in this field, "the best ear protector is the one that is worn!"

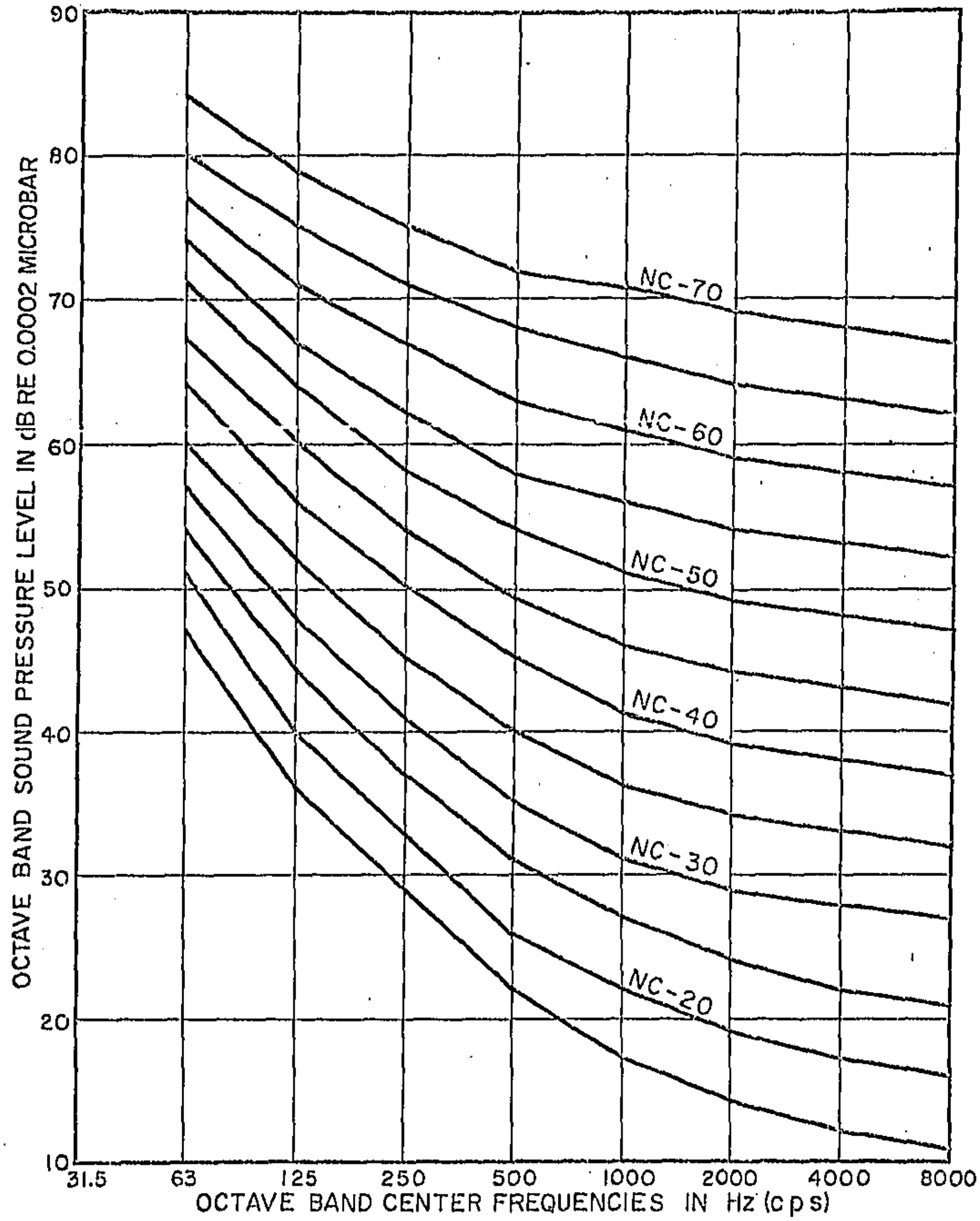


FIG.1 INDOOR NOISE CRITERION "NC" CURVES. REFER TO TABLE 1 FOR NUMERICAL VALUES OF SOUND PRESSURE LEVELS OF NC CURVES. REFER TO TABLE 2 FOR APPLICABLE AREAS.

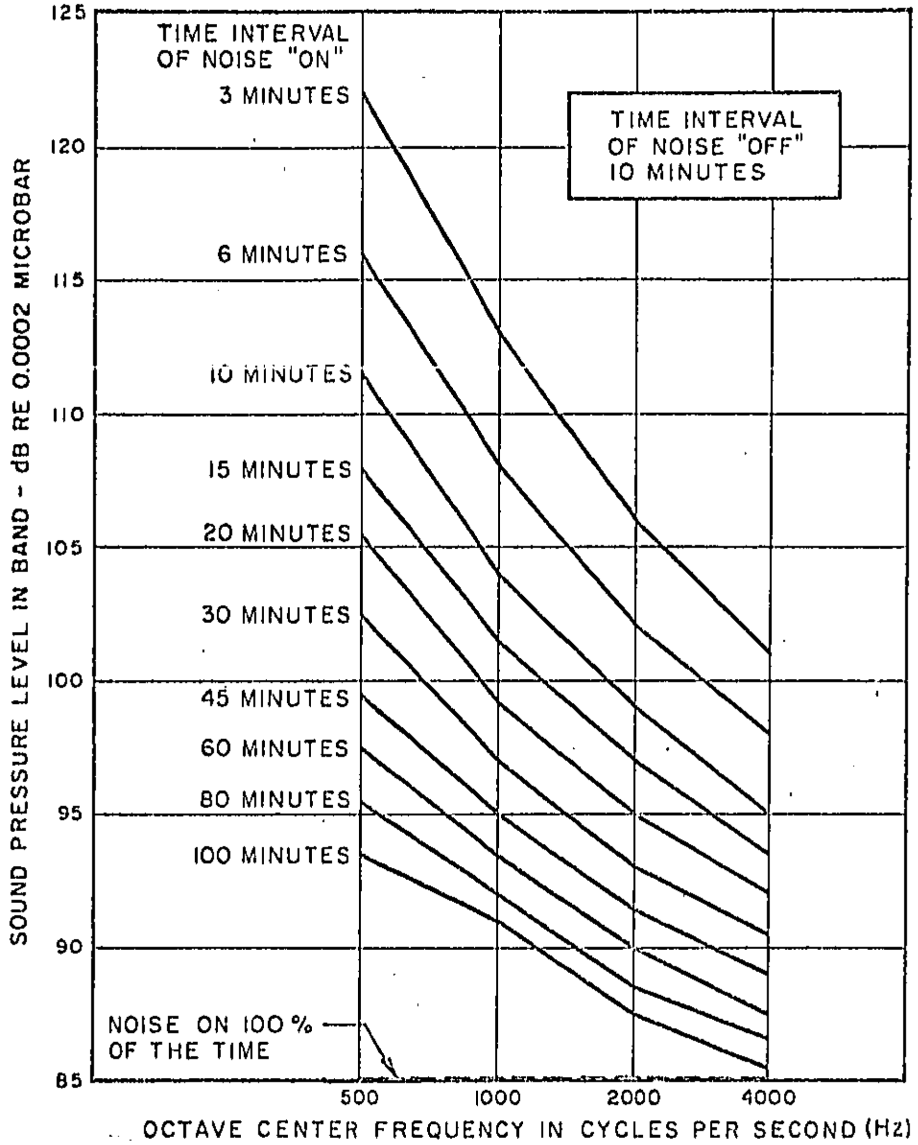


FIG. 2 HEARING PROTECTION CONTOURS FOR LONG-DURATION BROAD-BAND NOISE, WITH SYSTEMATICALLY SCHEDULED 10-MIN. ABSENCES FROM THE NOISE.

TABLE 1

OCTAVE BAND SOUND PRESSURE LEVEL (SPL) VALUES ASSOCIATED WITH THE NOISE CRITERION CURVES OF FIGURE 1 AND TABLE 2

NOISE CRITERION CURVES	63 HZ	125 HZ	250 HZ	500 HZ	1000 HZ	2000 HZ	4000 HZ	8000 HZ
NC-15	47	36	29	22	17	14	12	11
NC-20	51	40	33	26	22	19	17	16
NC-25	54	44	37	31	27	24	22	21
NC-30	57	48	41	35	31	29	28	27
NC-35	60	52	45	40	36	34	33	32
NC-40	64	56	50	45	41	39	38	37
NC-45	67	60	54	49	46	44	43	42
NC-50	71	64	58	54	51	49	48	47
NC-55	74	67	62	58	56	54	53	52
NC-60	77	71	67	63	61	59	58	57
NC-65	80	75	71	68	66	64	63	62

TABLE 2

CATEGORY CLASSIFICATION AND SUGGESTED NOISE CRITERION RANGE FOR INTRUDING MECHANICAL EQUIPMENT NOISE AS HEARD IN VARIOUS INDOOR FUNCTIONAL ACTIVITY AREAS

CATEGORY	AREA (AND ACOUSTIC REQUIREMENTS)	NOISE CRITERION
1	Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, etc. (for sleeping, resting, relaxing).	NC-20 to NC-30
2	Auditoriums, theaters, large meeting rooms, large conference rooms, churches, chapels, etc. (for very good listening conditions).	NC-20 to NC-30
3	Private offices, small conference rooms, classrooms, libraries, etc. (for good listening conditions).	NC-30 to NC-35
4	Large offices, reception areas, retail shops and stores, cafeterias, restaurants, etc. (for fair listening conditions).	NC-35 to NC-40
5	Lobbies, laboratory work spaces, drafting and engineering rooms, maintenance shops such as for electrical equipment, etc. (for moderately fair listening conditions).	NC-40 to NC-50
6	Kitchens, laundries, shops, garages, machinery spaces, power plant control rooms, etc. (for minimum acceptable speech communication, no risk of hearing damage).	NC-45 to NC-65

TABLE 3

SPEECH INTERFERENCE LEVELS ("PSIL"): AVERAGE NOISE LEVELS* (IN DB) THAT PERMIT BARELY ACCEPTABLE SPEECH INTELLIGIBILITY AT THE DISTANCES AND VOICE LEVELS SHOWN

Distance (ft)	Voice Level Normal	Raised	Very Loud	Shouting
½	74	80	86	92
1	68	74	80	86
2	62	68	74	80
4	56	62	68	74
6	53	59	65	71
8	50	56	62	68
10	48	54	60	66
12	46	52	58	64
16	44	50	56	62

---

*PSIL (Speech Interference Level in "Preferred" Octave Bands) is arithmetic average of noise levels in the 500, 1000 and 2000 Hz octave frequency bands. PSIL values apply for average male voices (reduce values 5 dB for female voice), with speaker and listener facing each other, using unexpected word material. PSIL values may be increased 5 dB when familiar material is spoken. Distances assume no nearby reflecting surface to aid the speech sounds.

TABLE 4

ESTIMATE OF OUTDOOR BACKGROUND NOISE BASED ON GENERAL TYPE OF COMMUNITY AREA AND NEARBY AUTOMOTIVE TRAFFIC ACTIVITY

(Determine the appropriate conditions that seem to best describe the area in question during the time interval that is most critical; i.e., day or night, probably night if for sleeping. Then refer to corresponding Noise Code No. in Table 5 for average minimum background noise levels to be used in noise analysis. Use lowest Code No. where several conditions are found to be reasonably appropriate.)

	CONDITION	NOISE CODE NO.
1.	Nighttime, rural; no nearby traffic of concern	1
2.	Daytime, rural; no nearby traffic of concern	2
3.	Nighttime, suburban; no nearby traffic of concern	2
4.	Daytime, suburban; no nearby traffic of concern	3
5.	Nighttime, urban; no nearby traffic of concern	3
6.	Daytime, urban; no nearby traffic of concern	4
7.	Nighttime, business or commerical area	4
8.	Daytime, business or commercial area	5
9.	Nighttime, industrial or manufacturing area	5
10.	Daytime, industrial or manufacturing area	6
11.	Within 300 ft of intermittent light traffic route	4
12.	Within 300 ft of continuous light traffic route	5
13.	Within 300 ft of continuous medium-density traffic	6
14.	Within 300 ft of continuous heavy-density traffic	7
15.	300 to 1000 ft from intermittent light traffic route	3
16.	300 to 1000 ft from continuous light traffic route	4
17.	300 to 1000 ft from continuous medium-density traffic	5
18.	300 to 1000 ft from continuous heavy-density traffic	6
19.	1000 to 2000 ft from intermittent light traffic	2
20.	1000 to 2000 ft from continuous light traffic	3
21.	1000 to 2000 ft from continuous medium-density traffic	4
22.	1000 to 2000 ft from continuous heavy-density traffic	5
23.	2000 to 4000 ft from intermittent light traffic	1
24.	2000 to 4000 ft from continuous light traffic	2
25.	2000 to 4000 ft from continuous medium-density traffic	3
26.	2000 to 4000 ft from continuous heavy-density traffic	4

TABLE 5

OCTAVE BAND SOUND PRESSURE LEVELS OF OUTDOOR BACKGROUND NOISE CODE NUMBERS OF TABLE 4

NOISE CODE NO. IN TABLE 4	OCTAVE BAND CENTER FREQUENCY IN HZ							
	63	125	250	500	1000	2000	4000	8000
1	40	37	32	27	22	18	14	12
2	45	42	37	32	27	23	19	17
3	50	47	42	37	32	28	24	22
4	55	52	47	42	37	33	29	27
5	60	57	52	47	42	38	34	32
6	65	62	57	52	47	43	39	37
7	70	67	62	57	52	48	44	42

TABLE 6

APPROXIMATE NOISE REDUCTION OF OUTSIDE NOISE PROVIDED BY TYPICAL EXTERIOR WALL CONSTRUCTION

OCTAVE FREQUENCY BAND (HZ)	A	B	C	D	E	F	G
63	0	9	13	19	14	24	32
125	0	10	14	20	20	25	34
250	0	11	15	22	26	27	36
500	0	12	16	24	28	30	38
1000	0	13	17	26	29	33	42
2000	0	14	18	28	30	38	48
4000	0	15	19	30	31	43	53
8000	0	16	20	30	33	48	58

A: No wall; outside conditions.

B: Any typical wall construction, with open windows covering about 5% of exterior wall area.

C: Any typical wall construction, with small open air vents of about 1% of exterior wall area, all windows closed.

D: Any typical wall construction, with closed but operable windows covering about 10-20% of exterior wall area.

E: Sealed glass wall construction, 1/4 in. glass thickness over approximately 50% of exterior wall area.

F: Approximately 20 lb/sq ft solid wall construction with no windows and no cracks or openings.

G: Approximately 50 lb/sq ft solid wall construction with no windows and no cracks or openings.

TABLE 7

A. MAXIMUM SOUND PRESSURE LEVELS RECOMMENDED FOR HEARING CONSERVATION FOR FULL-TIME EXPOSURE TO BROAD-BAND NOISE

Octave Frequency Band (Hz)	Sound Pressure Level in Band in dB re 0.0002 microbar	
	Recommended by TB MED 251	Recommended by CHABA
125	--	97
250	92	92
500	85	89
1000	85	86
2000	85	85
4000	85	85
8000	85	86

B. MAXIMUM SOUND PRESSURE LEVELS RECOMMENDED FOR HEARING CONSERVATION FOR FULL-TIME EXPOSURE TO NARROW-BAND NOISE OR PURE TONES

Octave Frequency Band (Hz)	Sound Pressure Level in Band in dB re 0.0002 microbar	
	Recommended by TB MED 251	Recommended by CHABA
125	--	92
250	87	87
500	80	84
1000	80	81
2000	80	80
4000	80	80
8000	80	81

TABLE 8

A. MAXIMUM SOUND PRESSURE LEVELS RECOMMENDED FOR HEARING CONSERVATION FOR PART-TIME EXPOSURE TO BROAD-BAND NOISE

Octave Frequency Band (Hz)	Sound Pressure Level (in dB) in Band for Single Exposure of Duration: 4 Hrs.	2 Hrs.	1 Hr.	½ Hr.	¼ Hr.
125	103	111	119	127	135
250	96	101	107	115	123
500	90	94	99	105	112
1000	88	91	95	100	106
2000	86	88	91	95	100
4000	85	87	90	93	98
8000	87	90	95	100	105

B. MAXIMUM SOUND PRESSURE LEVELS RECOMMENDED FOR HEARING CONSERVATION FOR PART-TIME EXPOSURE TO NARROW-BAND NOISE OR PURE TONES

Octave Frequency Band (Hz)	Sound Pressure Level (in dB) in Band for Single Exposure of Duration: 4 Hrs.	2 Hrs.	1 Hr.	½ Hr.	¼ Hr.
125	93	95	98	105	112
250	88	90	94	100	106
500	83	86	91	96	101
1000	82	85	89	93	97
2000	81	83	86	90	94
4000	80	82	85	88	92
8000	82	85	90	94	99

TABLE 9

APPROXIMATE ATTENUATION (IN DB) OF WELL-FITTED EAR PLUGS AND EAR MUFFS

(Poor fitting reduces attenuation significantly)

OCTAVE FREQUENCY BAND (HZ)	EAR PLUGS	EAR MUFFS	COMBINED
31	16	12*	20
63	18	14*	22
125	20	16*	24
250	22	19*	27
500	24	24*	30
1000	27*	30	34
2000	30*	30	40
4000	33*	35	45
8000	35	30*	40

---

*In practice, assume ear plugs and ear muffs to be equal and to have values shown by * when used alone (for both ears, of course).

CHAPTER 3
NOISE LEVEL DATA

Noise levels measured at several plants or equipment installations have been collected and are summarized in the enclosed Tables 1-3. These are divided roughly into various types of industries, and the levels given represent the approximate upper and lower limits found at various operator positions. This does not represent an exhaustive survey of plants or plant noise; the data merely indicate that hearing damage noise levels exist in many plant areas.

TABLE 1

SOME REPRESENTATIVE NOISE LEVEL RANGES
AT VARIOUS OPERATOR POSITIONS IN
VARIOUS INDUSTRIES

(MANY ACTUAL SITUATIONS INCLUDED,
BUT BY NO MEANS A COMPLETE LISTING)

	OCTAVE FREQUENCY BAND IN Hz								
	31	63	125	250	500	1000	2000	4000	8000
WOOD AND PULP PROCESSING									
	88	102	108	114	114	112	111	106	97
	72	79	81	90	91	86	81	76	67
POWER SAWS, MOLDERS, PLANERS									
	89	95	101	106	109	109	106	102	101
	60	65	69	71	73	74	73	72	70
PRINTING (INCL. NEWSPAPERS), BOOKBINDING									
	85	95	102	98	96	92	89	88	90
	68	73	73	72	73	73.	70	68	64
ROCK CRUSHING AND GRINDING									
	92	97	96	98	100	96	96	94	90
	80	88	86	85	84	82	80	74	70
ROCK DRILLS AND AIR COMPRESSORS									
	80	88	98	102	103	98	95	90	88
	70	80	88	88	84	85	80	80	75
COAL CAR SHAKE-OUT									
	100	119	115	111	108	105	104	103	98
	90	111	105	101	100	95	94	92	82

TABLE 2

SOME REPRESENTATIVE NOISE LEVEL RANGES
AT VARIOUS OPERATOR POSITIONS IN
VARIOUS INDUSTRIES

(MANY ACTUAL SITUATIONS INCLUDED,
BUT BY NO MEANS A COMPLETE LISTING)

	OCTAVE FREQUENCY BAND IN Hz								
	31	63	125	250	500	1000	2000	4000	8000
PETROLEUM PLANT									
	95	102	107	111	105	98	91	90	85
	75	80	78	75	73	70	66	61	54
PLASTICS PROCESSING									
	90	94	103	105	108	103	102	99	97
	72	77	77	84	82	81	80	74	64
TEXTILES									
	83	88	90	94	97	99	100	97	100
	58	60	62	67	66	71	71	65	56
LEATHER PROCESSING, SHOE MANUFACTURING									
	80	87	88	91	93	95	96	95	94
	70	75	75	72	76	78	75	74	72
MACHINE SHOPS (GRINDING, PUNCHING, RIVETING)									
	88	98	104	108	102	106	108	110	109
	70	76	74	78	78	74	70	71	66
BOTTLING AND CANNING PLANTS									
	88	95	101	102	98	95	91	90	92
	65	72	75	70	68	65	63	60	57

TABLE 3

SOME REPRESENTATIVE NOISE LEVEL RANGES AT VARIOUS OPERATOR POSITIONS IN VARIOUS INDUSTRIES

(MANY ACTUAL SITUATIONS INCLUDED,
BUT BY NO MEANS A COMPLETE LISTING)

	OCTAVE FREQUENCY BAND IN Hz								
	31	63	125	250	500	1000	2000	4000	8000
ELECTRIC GENERATING STATIONS									
	106	104	108	107	105	103	100	94	84
	82	86	89	82	81	80	84	72	62
GAS COMPRESSOR STATIONS									
	126	109	103	99	96	96	95	99	108
	85	83	85	90	84	76	76	77	73
MECHANICAL EQUIPMENT ROOMS									
	90	94	93	90	88	89	89	86	80
	70	72	75	76	73	68	65	62	53
ROAD MACHINERY, FARM TRACTORS									
	85	95	106	104	102	102	98	95	92
	68	72	78	79	75	72	70	63	58

CHAPTER 4

AIRBORNE SOUND DISTRIBUTION INDOORS AND OUTDOORS

A brief discussion is given here on sound transmission inside a room and in an outdoor situation. The objective of this discussion is to give the reader a basic understanding of the role of "acoustic absorption" inside a room and the various factors that influence sound propagation out-of-doors.

1. SOUND DISTRIBUTION IN A ROOM

a. SPL Variation with Distance. It is generally true that the sound pressure level (SPL) drops off as one moves away from the sound source. In an outdoor "free-field" situation (no reflecting surfaces except the ground), the SPL drops off at the rate of 6 dB for each doubling of distance from the acoustic center of the source (there are qualifications to this generalization that can be ignored for the present). In an indoor situation, all the enclosing surfaces of a room confine the sound waves so that they cannot continue spreading out indefinitely and become dissipated with distance. Instead, as the sound waves bounce around within the room, a certain amount of energy is absorbed at each reflection but, in general, there is a build-up of sound level because the sound energy is "trapped" inside the room and cannot escape (somewhat figuratively speaking). In a highly reverberant room, with walls that are hard, rigid and completely impervious, very little sound energy is absorbed at each reflection so the sound bounces around a long time before it ultimately is absorbed. In this type of room, the room becomes almost "saturated" with sound; and as one moves away from the sound source, the sound level drops off very slowly with distance (possibly only ½ to 1 dB per doubling of distance for some relatively small, but very reverberant rooms). In a highly absorptive room, however, a considerable amount of energy is absorbed at each reflection as the sound waves bounce around the room. There is less build-up of sound within the room; and as one moves away from the sound source, the sound level drops off more rapidly (possibly 2 to 4 dB per doubling of distance). Note that the walls would have to be 100% absorptive in order to have no reflected sound at all. This would then simulate the outdoor free-field condition, that requires no reflecting surfaces, and the sound level drop-off with distance would become the theoretical maximum of 6 dB per doubling of distance.

Thus, in a qualitative sense, it is seen that the reduction of sound pressure level indoors, as one moves across the room away from the sound source, is dependent on the degree of absorption and, of course, on the distance that one moves. The amount of absorption also involves surface areas of the room. All of this is expressed quantitatively by the curves of Figure 1 at the end of this chapter. As an example of the use of Figure 1, suppose a room has an amount of sound absorption that produces a "Room Constant, R" value of 1000 sq ft. At a distance of 2½ ft from the acoustic center of a non-directional sound source, the "RELATIVE SPL", as read off the left-hand side of the graph for the R=1000 curve, is -7½ dB. At a 5-ft distance, the REL SPL becomes -11 dB, indicating a reduction of 3½ dB as one doubles the distance in going from 2½ to 5-ft distance. Continuing, at a 10-ft distance, the REL SPL becomes

-13 dB, indicating a reduction of 2 dB as one doubles the distance from 5 ft to 10 ft. Then, at a 20-ft distance, the REL SPL becomes -14 dB, indicating a reduction of only 1 dB as one doubles the distance from 10 ft to 20 ft. The other curves for other values of Room Constant (related to room absorption) give other variations of SPL with distance away from the source. Only if a room has an infinite Room Constant (perfect sound absorption at all the side wall and ceiling surfaces), would the sound pressure level drop off indefinitely at the outdoor rate of 6 dB per doubling of distance.

It is seen that Figure 1 offers a means of estimating the amount of noise level reduction for a piece of mechanical equipment in a room as one moves from one distance to any other distance in the room, provided one knows the Room Constant of that room. Obviously, the next step is to calculate or estimate the value of the Room Constant.

b. Room Constant. A suitable acoustics textbook will give details of a fairly accurate calculation of the Room Constant for any specific room, knowing (1) all the room dimensions, (2) the wall, floor and ceiling materials, (3) the amount and type of acoustic absorption materials, and (4) the sound absorption coefficients of the acoustic materials at various specified frequencies. For the purpose of these notes, however, such a high degree of accuracy is not considered necessary, so a simplified estimating procedure is suggested. It must be recognized that this simplification yields a less accurate estimate than does the more detailed textbook procedure, but it is nevertheless considered acceptable for use here. The basic steps of the simplified procedure are listed as follows:

1. Determine the total interior surface area of the room.
2. Determine the total area of acoustic absorption material to be applied to the walls and/or ceiling of the room.
3. From steps 1 and 2, determine the percentage of total room surface covered with absorption material.
4. From Part A of Table 1 determine the "room label" associated with the percentage figure found in step 3 above.
5. Calculate the volume of the room, in cu ft.
6. From Figure 2 (at the end of this chapter), using the volume of step 5 and the "room label" of step 4, determine the approximate Room Constant (R in sq ft) for the room. This value applies for octave band frequencies of 500-8000 Hz.
7. Determine the corrected values of R for 31-125 Hz as given in Part B of Table 1. The values differ depending on the type of acoustic treatment used. See the footnotes of Table 1 regarding "NRC" values normally associated with 1 in. and 2 in. thick acoustic absorption materials.

c. Example. Assume a room 40 ft long, 30 ft wide and 15 ft high. The total interior surface area is 4500 sq ft and the volume of the room is 18,000 cu ft. Suppose 2 in. thick acoustic panels having an NRC of 0.80 are used over the full ceiling area and in a 5-ft wide band around all four walls. The total area of acoustic treatment is 1900 sq ft, giving 42% area coverage. In Table 1, 42% is seen to fall about midway between a "Medium-Dead Room" and a "Dead Room". In Figure 2, for a room volume of 18,000 cu ft and a room label between "Medium-Dead" and "Dead", the value of R is found to be approximately 2000 sq ft. This value would apply for 500-8000 Hz. At lower frequencies, the value of the corrected R would be (from Part B of Table 1):

0.2 R or 400 sq ft at 31 Hz,
0.3 R or 600 sq ft at 63 Hz,
0.5 R or 1000 sq ft at 125 Hz,
0.8 R or 1600 sq ft at 250 Hz.

Continuing this example, suppose it is desired to find the SPL reduction in this room while going from 3-ft to 20-ft distance from the noise source. In Figure 1, find the difference in REL SPL between 3 ft and 20 ft for R values of:

400 600 1000 1600 and 2000 sq ft.

These are as follows, in order:

3 dB 4 dB 5 dB 6 dB and 7 dB.

Thus, the 3-ft SPLs for the particular piece of equipment would be reduced by these amounts to obtain the 20-ft SPLs for the frequency bands, in order:

31 63 125 250 and 500-8000 Hz.

d. <u>SPL in a Room when PWL is Known</u>. In the event that the sound <u>power</u> level (PWL) of some piece of equipment is known, the same general procedure may be used, with one small exception. In Figure 1, the ordinate of the graph, "Relative Sound Pressure Level" (abbreviated to "REL SPL") is actually related to SPL and PWL by the equation

$$\text{SPL} = \text{PWL} + \text{REL SPL}$$

for any particular Distance D and Room Constant R. In this equation, SPL is given in the standard unit "dB re 0.0002 microbar", PWL is given in the standard unit "dB re 10^{-12} watt", and REL SPL is quoted in decibels and is the conversion term that relates SPL to PWL. In the above equation, the REL SPL is read directly off the curve of Figure 1 for a particular D and R value. Then, if the PWL is known, the SPL can be calculated.

e. <u>Example</u>. Suppose a machine is to be installed in the acoustically treated room described above and suppose it is desirable to find the SPL at a distance of 20 ft. For this example, suppose that the manufacturer submits PWL data for this unit. The PWL values are listed in Column 2 of the accompanying table. It was learned above that the Room Constant had the values 400, 600, 1000, 1600 and 2000 sq ft at the various frequencies. From Figure 1, REL SPL values can be determined for the particular Room Constant values at a 20-ft distance. These values are shown in Column 3 of the table below. Finally, since

SPL = PWL + REL SPL,

the SPLs can be calculated. These are listed in Column 4.

Col. 1 Octave Band (Hz)	Col. 2 PWL (dB re 10^{-12} w)	Col. 3 REL SPL (dB)	Col. 4 SPL at 20 ft (dB re 0.0002 microbar)
31	95	-10	85
63	93	-12	81
125	94	-14	80
250	95	-16	79
500	99	-17	82
1000	102	-17	85
2000	108	-17	91
4000	105	-17	88
8000	94	-17	77

f. Qualifications. There are two points that should be kept in mind in using the data of Figure 1. These are both suggested by the caption under the abscissa of the graph: "Equivalent distance from acoustic center of a non-directional source". Strictly speaking, very few noise sources in real life are completely non-directional sources, but in this write-up and in many conventional noise problems the assumption is made that the source is non-directional, that is, that it radiates sound equally in all directions. If the true directional characteristics are known, they may be used, but for the present purpose this is not required. The second point regards the "distance from the acoustic center." The acoustic center, as the term implies, is the location that would be occupied by a "point source" of equal sound power output. The acoustic center of a noise source may be at the nearest surface of the unit being measured, or it may be located somewhere near the geometric center inside the unit. For a strictly correct use of Figure 1, the distance should be referred to the acoustic center, but in practice the location of the center is not always obvious. Also, because most large machines cannot be replaced precisely by equivalent "point sources", the SPL that could be calculated for a very close distance (such as 1 or 2 ft from the machine) may not agree with the actual measured SPL at that very close distance.

g. Data Form 1. A copy of Data Form 1 is given at the end of Chapter 4. This form summarizes the step-by-step procedure for estimating the Room Constant of a room. Data Form 1 can be duplicated by the user for working on various specific situations.

h. Example. To illustrate the use of Data Form 1 and Table 1, the reader is given the following exercise. Suppose a given manufacturing space is 100 ft long, 50 ft wide and 20 ft high. Calculate the Room Constant for four conditions: (1) for Condition 1 there is no acoustic absorption material in the room; (2) for Condition 2 the entire ceiling area is covered with a 1 in. thick acoustic absorption ceiling panel (NRC = 0.65 to 0.74); (3) for Condition 3 the entire ceiling area and one-half the side wall area is covered with a 1 in.

thick acoustic panel (NRC = 0.65 to 0.74); and (4) for Condition 4 the entire ceiling area is covered with a 2 in. thick acoustic panel (NRC = 0.75 to 0.85). Assume that the noise level at the operator position of a machine in that room is 90 dB in all the octave bands when there is no room absorption; assume that the operator position is 3 ft from the "acoustic center" of the machine when using Figure 1. Next, determine the noise levels that would exist in that room at distances of 3 ft (the operator position), 10 ft and 50 ft from the acoustic center of the machine for the four conditions of acoustic absorption given above.

The answer to this problem is summarized in the table below.

Octave Frequency	Condition 1	Condition 2	Condition 3	Condition 4
SPLs at 3-ft distance:				
31	90	86	85	86
63	90	86	85	85
125	90	86	86	86
250	90	87	87	87
500-8000	90	88	88	88
SPLs at 10-ft distance:				
31	89	82	80	82
63	89	82	80	81
125	89	81	80	80
250	88	81	79	80
500-8000	87	81	80	81
SPLs at 50-ft distance:				
31	89	81	78	81
63	89	81	78	79
125	89	80	77	78
250	88	78	75	77
500-8000	85	77	74	77

The simplifications used in this procedure introduce possible errors of 1 or 2 dB (perhaps even 3 dB for some situations), so extreme accuracy should not be expected. However, a few obvious points from the above example should be noted. First, in the high frequency region (where hearing protection is usually most important), the use of acoustic absorption on the ceiling and side walls gives very little protection to the operator who works only 3 ft from his own machine. Also, in a completely non-absorbent room, the SPLs do not drop off very much with distance from the machine. With acoustic absorption present, however, noise levels drop off noticeably as one moves away from the noise source. Thus, when an operator is exposed to the combined noise of several machines in the room, at least some portions of that total noise can be reduced with an application of acoustic absorption.

Table 2 at the end of this chapter may be used to estimate the reduction of noise level at increasing distances from a noise source for a range of Room Constant values. These amounts of reduction are based on a "starting point" of 3 ft from the noise source, and merely represent a simplification of Figure 1 when 3 ft is the "normalized" starting distance. To illustrate the use of Table 2, suppose that a room has a Room Constant of 700 sq ft at a given frequency and it is desired to know the reduction in SPL in going from the normalized 3-ft distance out to 10 ft and 50-ft distances (these values were involved in the problem given at the beginning of this discussion). In Table 2 it is seen that the SPL reduction would be 3 dB at 10 ft and 5 dB at 50 ft, relative to the SPL at 3 ft. The values will be found to agree with the SPL data given in the tabulated answer above for Condition 1 at the 500-8000 Hz octave frequency bands.

2. SOUND DISTRIBUTION OUT-OF-DOORS

a. Effect of Distance. As a general rule, sound from an essentially localized source spreads out as it travels away from the source, and the sound pressure level (SPL) due to that source decreases at the rate of 6 dB per doubling of distance (referred to as "the inverse square law"). This effect is due to spreading only, and this is an effect common to all types of energy propagation originating from an essentially point source and free of any special focussing or beam-controlling devices. In addition, the air absorbs a certain amount of sound energy due to "molecular absorption". For short distances (less than a few hundred feet) this energy absorption can be ignored, but for sound propagation over a reasonably large distance it should be considered. Further, the "molecular absorption" effect is greater at high frequencies than it is at low frequencies.

In the present discussion, time does not permit a detailed quantitative treatment of plant noise that escapes to the neighbors, so it must be sufficient here to note merely that escaping plant noise will drop off at the rate of about 6 dB for each doubling of distance from the noise source. Thus, a noise level of 80 dB (in a specified octave band) at some measurement point, say 200 ft from the outdoor noise source, would, in general, yield a noise level of 74 dB at 400-ft distance, 68 dB at 800-ft distance, 62 dB at 1600-ft distance, and so on.

b. Effect of Atmospherics. Precipitation, wind, wind gradients (with altitude), temperature, temperature gradients (with altitude), and relative humidity are possible atmospheric factors in outdoor sound transmission.

Rain, mist, fog, hail, sleet and snow are the various forms of precipitation to consider. These have not been studied extensively in their natural state so there are no representative values of excess attenuation to be assigned to them. Rain, hail and sleet may change the background noise levels, and a thick blanket of snow provides an absorbent ground cover for sound traveling at grazing incidence near the ground. In practice, of course, precipitation or a blanket of snow are intermittent, temporary and of relatively short total duration, and they could not be counted on for steady-state sound control, even if they should offer noticeable attenuation.

A steady, smooth flow of wind, equal at all altitudes, would have no noticeable effect on sound transmission. In practice, however, wind speeds are slightly higher above the ground than at the ground, and the resulting wind speed gradients tend to "bend" sound waves over large distances. Sound traveling with the wind is bent down to earth, while sound traveling against the wind is bent upwards above the ground. There is little or no increase in sound levels due to the sound waves being bent down; in fact, there is additional loss at the higher frequencies and at the greater distances. There can be some reduction of sound levels at relatively long distances (beyond a few hundred yards) when the sound waves are bent upward, for sound traveling against the wind.

Irregular, turbulent or gusty wind provides fluctuations in sound transmission over large distances. The net effect of these fluctuations may be an average reduction of a few decibels per 100 yards for gusty wind with speeds of 15 to 30 mph. However, gusty wind or wind direction cannot be counted on for noise control over the lifetime of an installation.

Constant temperature with altitude produces no effect on sound transmission, but temperature gradients can produce bending in much the same way as wind gradients do. Air temperature above the ground is normally cooler than at the ground, and the denser air above tends to bend sound waves upward. With "temperature inversions" the warm air above the surface bends the sound waves down to earth. These effects are negligible at short distances but they may amount to several dB at very large distances (say, over a half-mile). Again, there is little or no increase, but there may be a decrease in sound levels. Temperature gradients should not be relied on as a noise control aid.

Very low relative humidity (10 to 20%) increases the effect of "molecular absorption" of sound energy. These low values of relative humidity are seldom found in most inhabited areas, however.

In summary, there are atmospheric effects which would seldom increase but could decrease sound levels at large distances from a source. These decreases are usually of an intermittent, short-time duration and they are usually beneficial to the receiver (in giving temporary noise reduction) when they occur, but it is best not to rely on them for long-time benefits in terms of noise control design.

<u>c</u>. <u>Attenuation Provided by Barriers</u>. A wall, a building, a large mound of earth, a hill or some other type of solid structure, if large enough, can serve as a partial "barrier" to sound and can provide a moderate amount of sound reduction for a receiver located within the "shadow" provided by the barrier.

Table 3 gives a sketch of a barrier and the excess attenuation that might be expected from the barrier as a function of certain dimensions. This attenuation is in addition to the distance effect of the "inverse square law". For a barrier to be effective, its lateral width should extend beyond the line-of-sight between the source and receiver by at least as much as the height of the barrier extends above the line-of-sight. Also there must be no nearby large reflecting surfaces that can reflect sound around the barrier into the shadow zone. The distance D in the sketch of Table 3 must be very large compared to the distance R and the height H. The attenuation values given in Table 3 will apply equally for the two conditions:

(1) Sound source at Point A and receiver at Point B, or
(2) Sound source at Point B and receiver at Point A.

The barrier loses effectiveness at very large distances because sound that passes over the top of the barrier may be bent back down to the ground by wind and temperature gradients. If D is greater than 1 mile, the attenuation values used should be only about one-half the values given in Table 3.

If a barrier wall is to be built or used as a noise control device, the "transmission loss" of the wall (or building) should exceed by at least 10 dB in all frequency bands the excess attenuation to be expected from the wall. This can usually be met with a solid wall (no cracks) having a surface weight of 10 to 20 lb per sq ft.

If the barrier is a large "thick" building, the distance R should be taken from Point A to the near wall of the building and the height H should be the height of the building at the near wall. There should be no large openings entirely through the building that would destroy the effectiveness of the building as a barrier. A few small open windows in the near and far walls would probably be acceptable, provided the interior rooms are large.

Caution: Note that a large reflecting surface, such as the barrier wall, may reflect more sound in the opposite direction than there would have been with no wall at all present. If there is no special focussing effect, the wall may produce at most only about 2 or 3 dB higher levels in the direction of the reflected sound.

d. <u>Attenuation Provided by Trees</u>. Heavy dense growths of woods provide a small amount of sound attenuation. To be effective both winter and summer, there should be a reasonable mixture of both deciduous and evergreen trees. Also the ground cover should be sufficiently dense that sound cannot pass under the absorbent upper portion of the trees. For dense woods of several hundred feet depth, the sound may pass over the tops of the trees, in which case the attenuation through the trees should never be considered greater than the excess attenuation over the trees, as determined from the application of Table 3.

Table 4 gives the approximate excess attenuation of sound through dense woods, where dense woods are taken as having an average "visibility penetration" of about 70 to 100 ft. Occasional trees and hedges give no significant attenuation. "Visibility penetration" is the average maximum distance in the woods at which some small portions of a large (3-ft square) white cloth can still be seen.

e. <u>Noise Reduction of a House or Building</u>. Outdoor noise normally suffers some noise reduction when it passes indoors into a house or building, even when the building has open windows. The amount of noise reduction (NR) varies with the building construction, orientation, wall area, window area, open window area, etc. Some estimated NR values for building constructions were given in Table 6 of Chapter 2.

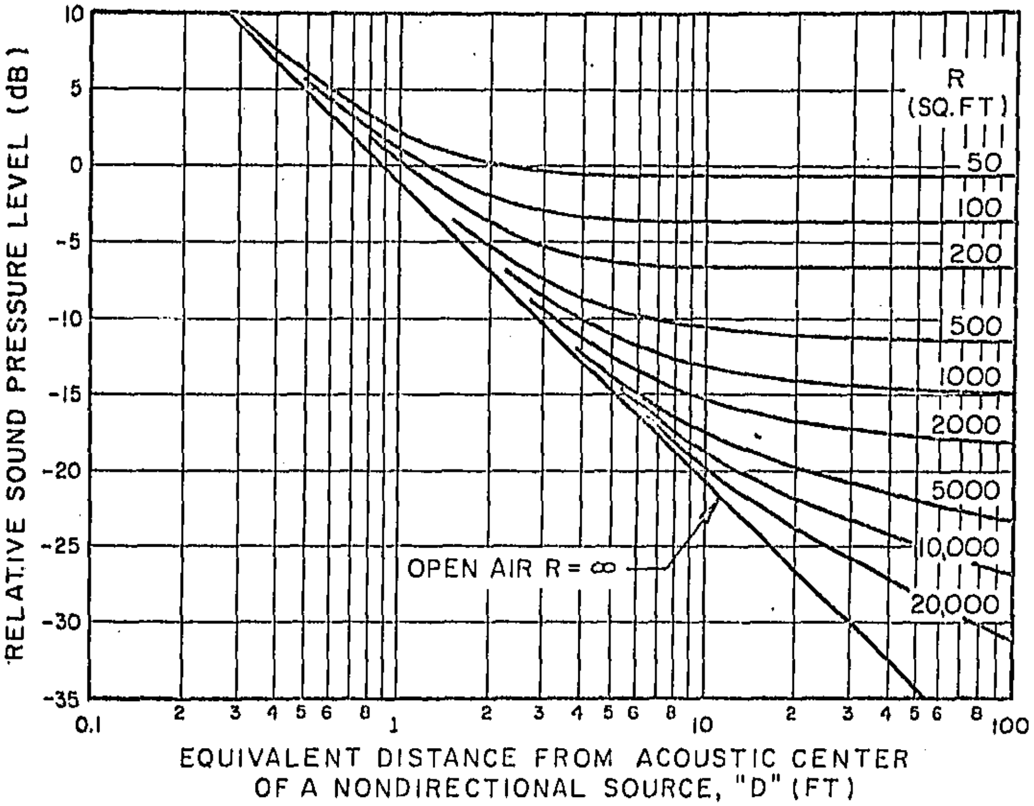


FIG. 1 APPROXIMATE RELATIONSHIP BETWEEN "RELATIVE SOUND PRESSURE LEVEL" AND DISTANCE TO A NOISE SOURCE FOR VARIOUS ROOM CONSTANT VALUES

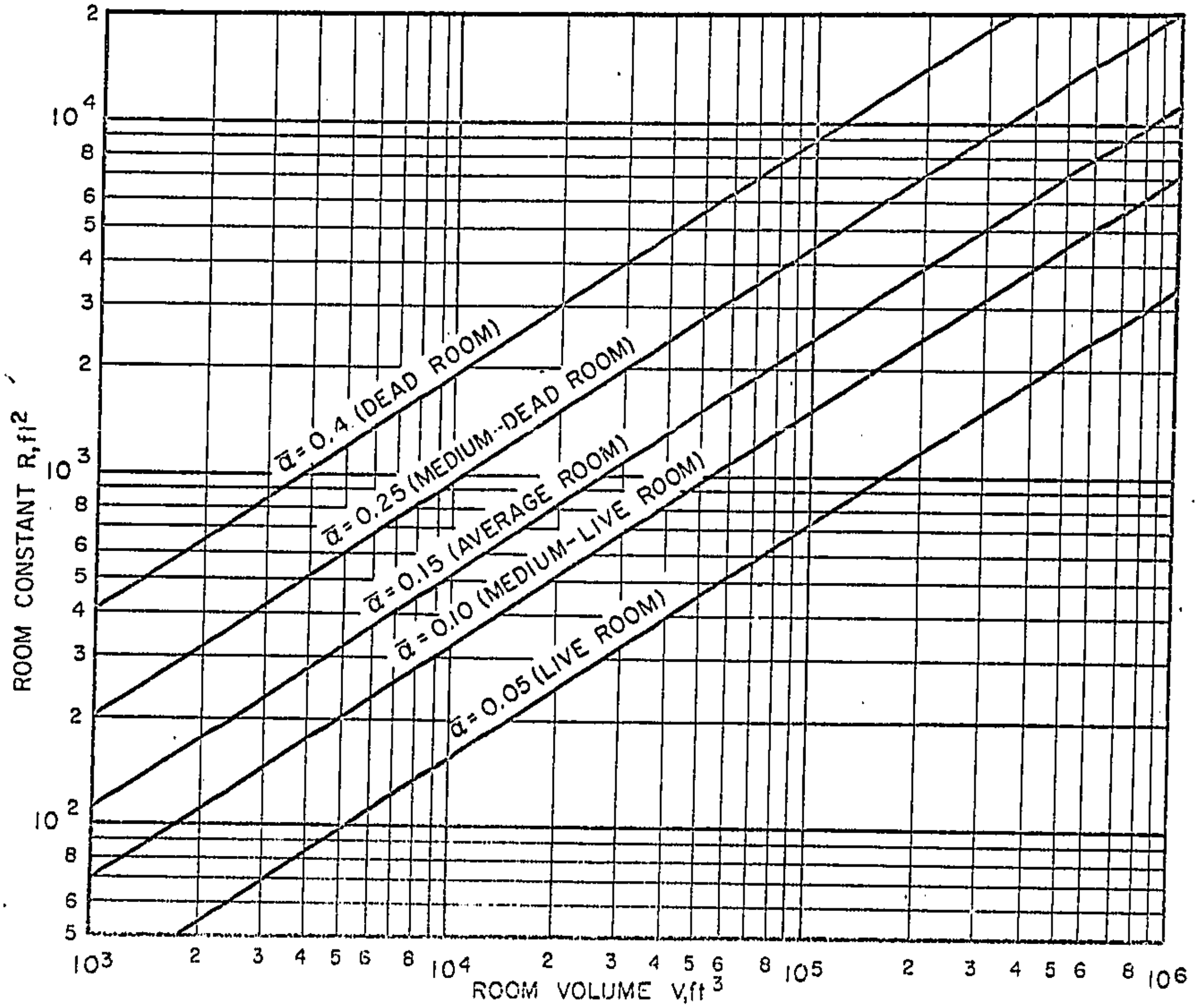


FIG. 2 APPROXIMATE RELATIONSHIP BETWEEN ROOM VOLUME AND ROOM CONSTANT FOR SPACES OF VARIOUS AVERAGE ACOUSTIC ABSORPTION (AT MID-FREQUENCY REGION OF 500-1000 cps)

TABLE 1

ACOUSTIC TREATMENT DETAILS FOR USE WITH FIGURES 1 AND 2 IN ESTIMATING ROOM CONSTANT

PART A. SURFACE COVERAGE OF ACOUSTIC MATERIAL

Percentage of Total Room Surface Area Covered with Absorption Material	Room Label on Figure 2 Curves
0%	"Live Room"
10%	"Medium-Live Room"
15-20%	"Average Room"
30-35%	"Medium-Dead Room"
50-60%	"Dead Room"

PART B. LOW FREQUENCY CORRECTION TO "R"

Octave Band (Hz)	Corrected R to be used in Figure 1 for NRC = 0.65 - 0.74 and if there is no acoustic absorption	NRC = 0.75 - 0.85
31	0.2 R	0.2 R
63	0.2 R	0.3 R
125	0.3 R	0.5 R
250	0.5 R	0.8 R

Note: NRC is "noise reduction coefficient". NRC values are published for all acoustical materials manufactured and distributed by members of the Acoustical Materials Association (or successor organization).

An NRC of 0.65 to 0.74 can be met by most perforated, fissured or textured acoustic tiles or panels of 3/4-in. or 1-in. thickness or by most perforated panels containing at least 1 in. thick layers of glass fiber or mineral wool.

An NRC of 0.75 - 0.85 can be met by most 2-in. thick layers of acoustic absorption material or by most 3/4-in. or 1-in. thick acoustic materials spaced at least 2 in. away from the wall or 10 in. away from the ceiling from which they are supported.

TABLE 2

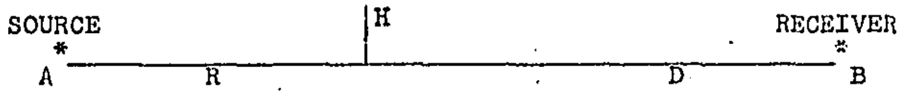
REDUCTION OF SPL (IN DB) IN GOING FROM NORMALIZED 3-FT DISTANCE TO A GREATER DISTANCE "D" IN A ROOM HAVING A ROOM CONSTANT "R"

ROOM CONSTANT "R" (in sq. ft)	DISTANCE "D" (IN FT) FROM EQUIPMENT				
	5	10	20	40	80
100	0	1	1	1	1
200	1	1	1	1	1
320	2	2	2	2	2
500	2	3	4	4	4
700	2	3	4	5	5
1000	2	4	5	6	6
2000	3	6	7	8	8
3200	4	7	8	10	11
5000	4	8	10	12	13
7000	4	8	11	13	15
10000	4	9	12	14	17
20000	5	10	14	17	20
50000	5	10	16	21	24
INFINITE	5	11	17	23	29

TABLE 3

APPROXIMATE NOISE REDUCTION (IN DB)
PROVIDED BY A SOLID BARRIER

(Do not go above 24 dB or below 0 dB attenuation in any bands. See text for discussion. Use one-half of attenuation for D greater than 1 mile.)



RATIO	NOISE REDUCTION IN FREQUENCY BAND							
H^2/R (ft)	63 HZ	125 HZ	250 HZ	500 HZ	1000 HZ	2000 HZ	4000 HZ	8000 HZ
0.3-0.4	0	0	3	6	9	12	15	18
0.5-0.8	0	2	5	8	11	14	17	20
0.9-1.2	1	4	7	10	13	16	19	22
1.3-1.9	3	6	9	12	15	18	21	24
2.0-3.1	5	8	11	14	17	20	23	24
3.2-4.9	7	10	13	16	19	22	24	24
5-8	9	12	15	18	21	24	24	24
9-12	11	14	17	20	23	24	24	24
13-20	13	16	19	22	24	24	24	24
over 20	15	18	21	24	24	24	24	24

TABLE 4

APPROXIMATE NOISE REDUCTION (IN DB) PROVIDED BY DENSE WOODS

(Mixed Deciduous and Evergreen trees; 20-40 ft height, visibility penetration of 70 to 100 ft)

OCTAVE FREQUENCY BAND (HZ)	EXCESS ATTENUATION (in dB per 100 ft. of woods)
63	1/2
125	1
250	1-1/2
500	2
1000	3
2000	4
4000	4-1/2
8000	5

Notes:

1. For average 10-20 ft height, use one-half the rate given in the table.
2. For sparse woods of 200-300 ft visibility penetration, use one-half the rate given in the table.

DATA FORM 1

ROOM CONSTANT OF SOURCE ROOM OR RECEIVER ROOM

ROOM NO. OR DESIGNATION ____________________

1. AVERAGE ROOM DIMENSIONS (IN FT.)
   LENGTH __________ WIDTH ______________ HEIGHT ______________

2. VOLUME OF ROOM ________________ CU. FT.

3. TOTAL INTERIOR SURFACE AREA OF ROOM __________________ SQ. FT.

4. AREA OF PLANNED ACOUSTIC TREATMENT* __________________ SQ. FT.

5. PERCENT AREA COVERED BY ACOUSTIC TREATMENT ____________ %
   (100 x Item 4/Item 3)

6. "ROOM LABEL" FOR ITEM 5 FROM TABLE 1A, CHAPTER 4
   ____

7. FOR ITEMS 2 AND 6, ROOM CONSTANT FROM FIG. 2, CHAPTER 4
   R = ______________ SQ. FT. FOR 500 - 8000 Hz

8. CHECK ACOUSTIC ABSORPTION TREATMENT:

	☐ NONE OR NRC = 0.65 - 0.74	☐ NRC = 0.75 - 0.85
THEN, FOR 31 Hz	0.2 R = __________	0.2 R = __________
63 Hz	0.2 R = __________	0.3 R = __________
125 Hz	0.3 R = __________	0.5 R = __________
250 Hz	0.5 R = __________	0.8 R = __________

9. ROOM CONSTANT FOR ALL OCTAVE BANDS, IN SQ. FT.#
   (Repeat appropriate values from Items 7 and 8)

OCTAVE FREQUENCY BAND IN Hz								
31	63	125	250	500	1000	2000	4000	8000

*Add 50% of floor area to Item 4 if floor is carpeted or has drapes or upholstered furniture. Treat this as NRC = 0.65 material.

#Add to all bands any area always open to the outside, i.e., having 100% absorption.

DATA FORM 1

ROOM CONSTANT OF SOURCE ROOM OR RECEIVER ROOM

ROOM NO. OR DESIGNATION ______________________________

1. AVERAGE ROOM DIMENSIONS (IN FT.)
   LENGTH __________ WIDTH ______________ HEIGHT _______________

2. VOLUME OF ROOM _________________ CU. FT.

3. TOTAL INTERIOR SURFACE AREA OF ROOM ____________________ SQ. FT.

4. AREA OF PLANNED ACOUSTIC TREATMENT* ____________________ SQ. FT.

5. PERCENT AREA COVERED BY ACOUSTIC TREATMENT ______________ %
   (100 x Item 4/Item 3)

6. "ROOM LABEL" FOR ITEM 5 FROM TABLE 1A, CHAPTER 4
   ____

7. FOR ITEMS 2 AND 6, ROOM CONSTANT FROM FIG. 2, CHAPTER 4
   R = _______________ SQ. FT. FOR 500 - 8000 Hz

8. CHECK ACOUSTIC ABSORPTION TREATMENT:

	☐ NONE OR NRC = 0.65 - 0.74	☐ NRC = 0.75 - 0.85
THEN, FOR 31 Hz	0.2 R = ____________	0.2 R = __________
63 Hz	0.2 R = ____________	0.3 R = __________
125 Hz	0.3 R = ____________	0.5 R = __________
250 Hz	0.5 R = ____________	0.8 R = __________

9. ROOM CONSTANT FOR ALL OCTAVE BANDS, IN SQ. FT.#
   (Repeat appropriate values from Items 7 and 8)

OCTAVE FREQUENCY BAND IN Hz								
31	63	125	250	500	1000	2000	4000	8000

*Add 50% of floor area to Item 4 if floor is carpeted or has drapes or upholstered furniture. Treat this as NRC = 0.65 material.

#Add to all bands any area always open to the outside, i.e., having 100% absorption.

CHAPTER 5

PRINCIPLES, METHODS AND EXAMPLES OF NOISE CONTROL IN MACHINE DESIGN

Although there still exist many questions on the psychological and physiological effects of noise on people, there is no question that too many people are currently exposed to too much noise. With this premise as an accepted fact, we wish to consider here briefly some of the basic methods of noise control that are available and that are in practical use in many places where people have agreed that some noise must be stopped.

Of course, it is highly desirable at the time of the original design to reduce the noise generated and radiated by a machine. Usually, however, a complex machine represents an evolutionary growth of one or more simpler machines, and as the size, speed, complexity and performance increase, concern for noise is lost along the way, if indeed there was ever any such concern in the first place. As a result, the completed machine may be noisy and it is probably so uniquely put together that it is virtually impossible to go back into the machine and simply insert a few noise-reduction treatments. As a result we rather seldom have the opportunity to change the "internal workings" of a complex machine; instead, we are usually restricted to working around the perimeter of the problem. This imposes rather serious limitations on the noise control that can be achieved.

Nevertheless, whether we can work on the inside or the outside of the machine, there are certain basic approaches to noise control. First, actual noise level goals or criteria are established for the work space in question. In most factory spaces, the goal is to achieve "safe" noise levels for the protection of hearing or to achieve low enough noise levels to carry on some degree of reliable speech communication. Next, we almost always include measurements of the noise and vibration of the machine that is to be quieted, in order to determine and to quantify the principal components and paths of noise. Then, we are in a position to design noise control treatments for the machine.

1. NOISE PRODUCING MECHANISMS

Let us first look briefly at a few of the typical mechanisms that produce noise. This is not a complete list; but it perhaps will begin to remind one of the basic noise sources of various types of machines.

Figure 1 illustrates some of the basic movements in machines that can give rise to noise or vibration. Incidentally, we can treat vibration almost synonymously with noise, because usually a vibration source either produces noise itself or causes something else to which it is attached to produce or radiate noise. Hence, the term "structure-borne noise" frequently describes this mixture of noise and vibration.

Figure 2 illustrates the mechanisms whereby high speed air movement can generate turbulence; and turbulence is almost synonymous with noise. Remember that sound is caused by the vibration of air particles, and turbulent air flow produces vibration of the air particles in the airflow. The noise radiated from the rear of a jet engine is a dynamic example of how turbulence produces noise.

Figure 3 illustrates one of the possible but usually less serious producers of noise. Motors and transformers are relatively simple examples of noise caused by electro-magnetic induction, but there are some industrial applications that involve tremendous amounts of noise and vibration.

Figure 4 may suggest "musical acoustics" but it is intended to highlight two mechanisms whereby a small amount of energy may produce an exaggerated amount of sound. A small amount of energy at the resonant frequency of a particular structure can produce large amounts of sound; the structure may be a gear, a subway wheel, a steel linkage in a machine, a panel of a cabinet enclosing a machine or even a special size and shape of an air space. The "sounding board" represents almost any structure to which a vibrating device is rigidly attached. The floor is a sounding board for a motor and pump, if you live on the floor under that motor and pump and if they are not properly vibration-isolated. The steel framing of a large machine may be the "sounding board" for a relatively small vibrator inside the machine.

The sources and paths of sound shown by Figures 1-4 are only fragmentary but they suggest the noise complexity of a machine that may be made up of many of these mechanisms simultaneously in operation, each performing its small but necessary function. A more complete, but still brief, discussion of noise sources and general approaches to noise reduction is given in the paper reproduced at the end of these notes: "Guidelines for Designing Quieter Equipment" by Clayton H. Allen. A reprint is also included that gives some general information on several aspects of the noise problem: "The Anatomy of Noise" by Leo L. Beranek and Laymon N. Miller (from Machine Design, September 14, 1967).

2. NOISE CONTROL APPROACHES

Some of the most vital basic steps to noise control are included in the following list. These steps must be taken, where applicable, if any noise source is to be quieted.

a. reduction of certain impact or acceleration effects,

b. reduction of unbalanced forces,

c. reduction of large radiating areas,

d. elimination of noise leakage paths,

e. use of acoustic enclosures to contain the noise or acoustic barriers to shield or deflect the noise,

f. use of acoustic absorption material to absorb sound energy inside confined spaces and in sound-control passageways,

g. use of mufflers or attenuators to reduce noise in gas flow paths,

h. use of vibration isolation mounts to isolate a vibration source from a noise radiator,

i. use of flexible connections between the isolated source and its base structure

j. use of vibration damping materials to reduce noise radiation from thin surfaces, and

k. use of alternate less-noisy methods for performing the same function.

3. EXAMPLES OF NOISE CONTROL

We can demonstrate the use of some of these noise control methods with actual examples from industry.

a. Quieted Stock Tubes for Automatic Screw Machines. One of the well-publicized noise control treatments of a few years ago was a quieted stock tube for automatic screw machines*. A layer of fabric webbing placed between the outer solid-wall tubing and the inner helically wound steel liner serves partially as vibration isolation and partially as vibration damping. Figure 5 gives measured noise levels in an aisle position about 5 ft from a six-spindle stock tube array for four different combinations of stock and stock tubes. The two lowest curves represent the noise levels for an operation involving round stock. The upper curve of this pair (shown by the letter "C" inside the circle) is for conventional stock tubes, and the lower curve of this pair (shown by the letter "S" inside the circle) is for the "silent" stock tubes. The more dramatic evidence of the effectiveness of the "silent" stock tube is shown by the upper two curves of Figure 5 where hexagonal stock is rotating, rattling and thrashing around inside conventional ("C" inside the hexagonal data points) and "silent" ("S" inside the hexagonal data points) stock tubes. In this comparison, the "silent" stock tubes range 10 to 20 dB quieter than the conventional stock tubes. This is not intended to represent a thorough evaluation of stock tubes, for we have not studied the effect of spindle speed, stock lengths, stock size or stock tube size; but this comparison does show a significant reduction of noise for the special quieted stock tubes, using vibration isolation and vibration damping techniques. (In the oral presentation, magnetic tape recordings are played for these four conditions.)

b. Vibration Damping Materials. Strategic use of vibration damping material on thin metal surfaces is used extensively on aircraft fuselage skins and frames. The actual reduction of radiated or shell transmitted noise may be as little as only 2 or 3 dB or as much as 5 to 10 dB, but there are situations where every decibel is vital. Damping materials or damping tape are frequently applied to thin structural members inside some machines to reduce the structure-borne transmission of sound from gears, bearings, cams, ratchets, relays, etc. Damping materials are also used on large thin panels that form the cabinet-like enclosures of some machines, notably on household appliances such as dishwashers, automatic washing machines, and refrigerators, on many of the office type duplicating or copying machines and on the interior surfaces of automobile doors, hoods, trunk lids and other large surfaces. Sometimes, sound absorption blankets pressed and held against a metal surface can provide this vibration damping action while also serving to reduce build-up of noise levels inside a machine cover.

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*Schweitzer, B. J.: "A Silent Stock Tube for Automatic Screw Machines", Noise Control, Vol. 2, No. 2, p. 14, March 1956.

c. High-Pressure Air Exhaust Muffling. Release of high pressure air is a typical noise in many plants. Each single brief spurt of escaping air may not be so troublesome all by itself, but in plants having many automatically controlled air-operated devices or systems there is an almost continuous chatter of air releases around the work area. In one shop recently we found over twenty air escape ports, each giving off a short blast every 5 to 30 seconds. The shop manager was amazed to hear and comprehend all these air discharges when it was brought to his attention. The high frequency pitch of the air escape noise contributes to speech masking and when an operator works near a few of these they may contribute to long-range hearing damage. Small inexpensive mufflers are commercially available or 6-12 in. lengths of piping filled on the inside with loosely packed glass or mineral fiber can reduce much of the air escape noise.

Figure 6 illustrates the noise levels generated by a blast of air released from an ordinary shop air nozzle when fed by a 130-160 PSI air supply. The middle solid curve represents the noise levels for normal discharge of the nozzle. The high frequency end of this noise spectrum is capable of masking speech. When the air blast is directed against an obstacle, the noise made by the disturbed air stream usually results in even higher noise levels, as shown by the upper dashed curve of Figure 6. In this example, the air discharge was merely directed against a finger at 6-in. distance. Where air is used to remove stock parts, such as laminations or stampings, from an automatic punch press, these noise levels could be produced. Such noise levels are potentially high enough to contribute to the hearing damage problem.

A simple homemade muffler produced the noise levels shown by the lower dotted curve of Figure 6. This muffler was produced by wrapping the discharge end of the air nozzle with a 3-in. layer of porous flexible plastic foam and recessing the wrapping into a large fruit-juice can. In the high frequency region, this simple arrangement yielded a noise reduction of 30 to 40 dB. (In the oral presentation, magnetic tape recordings are played to illustrate the noise levels of Figure 6.)

d. Plastic Pelletizing Machine. Several plants use a high speed, multiple-blade cutting drum to pelletize extruded plastic materials. Schematically the cutting operation may be illustrated simply by the sketch in Figure 7. Continuous length, spaghetti-like strands of extruded material are fed into the rotating cutting drum and are cut into small pellets of any desired dimension. The high speed rotation of the cutting blades past the cut-off edge of the anvil produces a siren-like sound of very high intensity, possibly reaching sound pressure levels of 110 to 120 dB a few inches from the cutting edge. The fundamental frequency of the sound is the "blade passage frequency" of the cutting blades and this can typically fall in the range of several hundred to a few thousand cycles per second. Higher harmonics of this fundamental frequency are also present.

In one particular noise reduction program, a special acoustic enclosure was devised for this type of cut-off machine. A thick-walled, acoustically-lined form-fitting housing was designed to enclose the cutter and its drive mechanism, and acoustically-lined openings were provided for the entry of the plastic strands and for the exit of the pelletized stock.

The approximate noise levels in the aisle beside one machine are shown in Figure 8, for the case of no enclosure and for the case of the acoustic enclosure. The overall effectiveness of such an enclosure is usually limited by the sound leakage paths through the openings by which stock material is fed and removed and by the air and sound leakage paths in the various joints around the enclosure and in some of the gasketed covers that give access into the machine. Where ventilation of a drive motor is required, acoustically lined ducts or passageways must be provided for cooling air. Also, for maximum noise reduction it is necessary that the enclosure make no physical contact with any part of the cutting assembly or its drive mechanism.

It should be pointed out that the machine was never used in normal production runs without a protective enclosure. The original enclosure, however, did not provide adequate noise control and it was for this reason that the special acoustic enclosure was designed and added. (In the oral presentation, a magnetic tape recording is played to illustrate the cutter noise.)

e. Motor Room. In one plant a bank of electric motors and gears produced high noise levels in an adjoining work area. The heat radiated by the motors also added to the discomfort of the area. A light weight enclosure having its own ventilation arrangement reduced both the noise and the heat in the shop area.

Figure 9 shows the noise levels in the work space "before" and "after" the enclosure was provided. The enclosure wall was made up of 1/2-in. thick gypsum board mounted on metal studs, with all air cracks sealed. When the enclosure was installed, the reduced noise levels in the shop space (the lower dashed curve in Figure 9) were actually due to the machines in the shop rather than the motors and gears inside the enclosure.

f. Automatic Punch Press. The average noise levels are shown in Figure 10 for a typical operator position of a punch press at one manufacturing plant. The upper curve shows the noise levels for the original machine and the lower curve shows the noise levels following completion of an initial noise reduction treatment. The shaded area shows the design goal range desired for the final total shop noise reduction program. The upper limit of this range is the CHABA criterion for hearing preservation in the presence of steady-state narrow-band noise and the lower limit of the range is the NC-75 curve.

The initial treatment to this first punch press consisted of placing acoustic covers of metal or safety glass over all openings from the impact area of the punch press. The machine still has the same accessibility as before this acoustic treatment was added, since in the original version several expanded metal guards were already used to protect the operator. The expanded metal guards have been replaced by sliding solid safety glass panels fitted with gasketed seals. Additional noise control work is still to be undertaken, but this example illustrates that even a punch press can be quieted.

g. Stamping Machine. The average noise levels for a typical operator position of a large impact-type machine are shown in Figure 11. This is a high-speed automatic stamping machine that is very massive and includes several thick large-area steel panels that radiate the noise of each impact blow. It would be desirable to reduce the noise levels at the operator position to achieve approximately those shown by the lower dashed curve.

Extensive sound measurements have been made all around the machine in order to estimate the approximate sound power contributions made by each panel, each exposed piece of massive framing, each opening near the actual die set and each ventilation opening into the interior of the machine. In addition, vibration measurements have been made on all important structural components of the machine in order to calculate the sound levels expected to be radiated by the structure. A comparison of the measured sound levels directly in front of a large structural member with the expected sound levels based on vibration data for that structure is an important step in the diagnosis of a complex machine. Suppose that the vibration measurements indicate that a heavy, stiff framing member will not radiate very much noise. On the other hand, suppose that high sound levels are measured directly in front of that framing member. This paradox suggests that the high sound levels are probably due to some other nearby sound source and attention should be focussed on locating and identifying the sound source. If both the measured sound levels and the sound levels that are calculated from the vibration data tend to support each other, then there is reasonably good assurance that the structural member is correctly diagnosed and that an appropriate noise control treatment might be applied.

This particular machine is so complex that it has not yet been fully treated acoustically by the manufacturer. Several steps of a complete treatment have been carried out and a few compromises have been considered, but it is not expected that the design goal can be reached with partial or compromise treatments.

h. Horizontal Punch Press. A few years ago, a horizontal-acting punch press was producing excessive noise levels in an IBM shop area*. The acoustics group at IBM produced a cover for this machine that produced a noise reduction of approximately 15 dB in the middle frequency bands and up to 20-25 dB in the high frequency bands. The acoustic features of the enclosure included:

(1) gasketed safety glass viewing windows,

(2) snugly fitting access ports,

(3) muffled inlet ports for feeding stock into the machine,

(4) muffled ventilation openings into the enclosure to provide cooling air,

(5) adequate thickness of steel stock,

(6) internal surface damping, and

(7) internal absorption to contain the noise.

Note that there is a build-up of noise levels inside an enclosure, compared to the close-in noise levels if there were no enclosure, so the enclosure wall material and weight must be adequate. The use of absorption material helps reduce the inside build-up.

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*Engstrom, J. R.: "Noise Reduction by Covers", Noise Control, Vol. 1, No. 2, March 1955.

i. Pencil Shaping Machine. The first step in making a batch of pencils is to take two thin strips of cedar, groove them, insert leads in the grooves, and then glue the strips together. Stacks of the glued strips are then fed into the hopper of the molding machine that shapes the pencils. The feed mechanism provides a continuous flow of these strips. The upper cutter assembly cuts out the upper profile of a line of 8 pencils, and the lower cutter assembly cuts away the remaining unwanted material. The cut pencils then drop onto a conveyor or into a bin.

The cutter blades of this particular molding machine rotate at 14,400 RPM. The noise levels at the operator position reach and sometimes exceed 110 dB. Although the machine is quite compact, there are many openings into the cutter area and the siren-like sound is free to escape to the room. An experimental program was carried out to determine how much noise reduction could be achieved by closing up many of the openings through which sound escapes. An experimental sealed enclosure produced nearly 30 dB noise reduction at the peak frequency of the cutter.

Much of this noise reduction could be achieved with simple add-on pieces to the existing machine; but to achieve all of this noise reduction (and even more, if desired), some design changes would have to be made. To our knowledge, no follow-up work was ever done by the manufacturer because, at that time, there was no incentive. No one was asking for quieter machines and he could sell all the noisy machines that he could produce. So, why change!

An inspection of many other molding machines would show that a small effort toward closing up the noise escape paths could easily achieve a large amount of noise reduction.

j. Sonic Pile Driver. One of the dramatic devices introduced into the building construction industry in 1961 was the sonic pile driver. The sonic pile driver consists of a mechanical arrangement that converts the energy of two 500-HP diesel engines into an alternating up and down force which is coupled to the top of the pile. The speed of the engine is locked onto the longitudinal resonance of the pile casing. As the casing compresses and elongates, not over one-fourth inch at the lower end for the resonant frequency of about 100 cps, the weight of the casing and the engine load clamped at the top serve to "push" the piling into the ground.

In some actual pile driving on one job, conventional steam pile driving required 30 minutes to sink a pile 40-ft deep and the sonic pile driver "pushed" a similar pile into the ground in 45 seconds. The sonic pile driver is less noisy and the noise is of much shorter duration than that for the impact type pile driver with its repeated blows at from one to two blows per second. The vibration in the earth is less severe as well, and static loading tests on two piles driven by each method on the job described here showed a more stable setting of the sonically driven piles.

In addition to demonstrating a positive use of resonance in a mechanical system, this example illustrates the use of an unusual and imaginative way to do a job by a new and possibly quieter method.

k. Barriers and Partial Enclosures. Almost any machine or area can receive some benefit from a barrier or partial enclosure that may deflect or reflect sound to less critical spaces or that may provide "shielded" areas of lower sound levels or that may actually absorb some of the sound energy. Slides of a few representative forms of partial enclosures are shown in the oral presentation.

Depending on the noise source, the dimensions, construction and geometry of the barrier, the layout of the room, the operator position, etc., these barriers may produce localized or general noise reduction ranging from 2 to 10 dB in the low frequency region up to 5 to 20 dB in the high frequency region. For any larger amounts of noise reduction, one would have to set out to provide a total enclosure rather than a partial enclosure .

One example shows the 20 dB noise reduction achieved between two adjoining rooms containing power hammers. Each room has acoustic absorption lining and a large front opening for easy access of large parts. The enclosure provides little benefit to the operator exposed to his own noise, but noticeable reduction for all other noises to which he might be exposed.

When estimating time exposures, it is sometimes the nearly steady-state condition of all the noises of other equipment that may be a major or controlling part of the exposure of one operator and his intermittent or marginal noise-producing equipment. Thus, it may be important to reduce the "other" noise to an operator when it is difficult or impossible to reduce the noise of his own machine.

4. "DO'S AND DON'TS" IN NOISE CONTROL

The following outline is offered as a starting point for pursuing a noise reduction program on a noise source. Be aware of good noise design; use good acoustic principles whenever possible. Build one unit; check the noise output, using appropriate noise and vibration equipment. Re-design and modify as required. Follow the outline below as a checklist both to establish good acoustic design in the first place and to guide remedial steps later if necessary.

A. Airborne vs. Structure-borne Noise and Vibration

1. Have to identify which type and which paths.
2. Both finally radiated to ear by air paths.
3. In general, sound from a machine can be "heard" at lower levels than vibration can be "felt". Therefore, reduce vibration till it can't be "felt", maybe even more, depending upon environment.

B. Air Sources and Solid Sources of Sound

1. Air Sources (pressure fluctuations in air due to air movement).
    (a) Jet action of air stream produces turbulence (air cleaning, air conveying, ventilation, etc.)

(b) Periodic interrupted flow produces discrete frequencies (fans, motor vents).

(c) Air movement around obstacles (turbulence).

(d) Secondary air sources:
cracks, openings in covers, open ends of ducts, close-coupling by air of structural parts.

2. Solid sources of sound

(a) Any solid member of a system that moves or is contacted by any other moving solid member.

(b) Solid member may oscillate, expand and contract, deform, bend, slide, rotate, hit or be hit, accelerate or decelerate from uniform motion.

(c) Solid member can be set into vibration by air coupling and then transmit vibration to other members or re-radiate it as sound energy.

C. Reduction of Noise and Vibration

1. Reduction of air source noise at the source.
2. Reduction of airborne noise and vibration.
3. Reduction of solid source noise at the source.
4. Reduction of structure-borne noise and vibration.

D. Reduction of Air Source Noise

1. Reduce air flow velocity.
2. Diffuse air exhaust stream to reduce turbulence at edge and in surroundings.
3. Reduce or eliminate periodic interrupted air flow (cooling vanes on motors, less air flow through rotating part of motor; vary fan blade cutoff).
4. Smooth flow in ducts or in necessary air streams; streamline obstacles in air streams.
5. Secondary air sources:
   cover holes, treat necessary open holes or ducts, break up close air coupling.

E. Reduction of Airborne Noise and Vibration

1. Reduce vibration amplitude of radiating member.
2. Reduce area of radiating member.
3. Reduce air coupling of radiating member (even drill holes to allow free flow of air to reduce pressure build-up).
4. Remove moving parts from large radiating surfaces (actual separation or by use of vibration isolation mountings).

5. Shift frequency of noise to lower frequency region (lower frequency noise less efficiently radiated from small sources, and people more tolerant at low frequencies).
6. Control the direction of radiation of sound away from the listener (good for high frequency only; barriers, baffles).
7. Provide mufflers for all required openings that can radiate noise.
8. Enclose or partially enclose the noise or noise radiator (as massive as necessary consistent with rest of system); cover all holes or cracks for air escape; gasket access doors; must have no rigid connections between noise source or radiator and the enclosure structure; consider relative stiffness of isolation mount for frequency to be controlled. For undamped enclosures, apply surface damping to reduce resonances.
9. Use acoustic absorption (glass fiber, etc.) to absorb contained sound (on inside surface of a wall or box, not on outside; porous material absorbs bouncing sound waves, does not take out much energy transmitted through the material).
10. Effectively increase distance from noise radiator to listerner, give chance for sound to spread out; same energy in the room but less intense if further away (baffles, lined ducts, directivity).

F. Reduction of Solid Source Noise

1. Change mode of operation to produce less force on the system; look for and avoid basic designs that serve as sound amplifiers.
2. Seek other ways of accomplishing the end objective or movement (electric vs. magnetic, mechanical vs. hydraulic, etc.).
3. Provide smooth finishes for sliding contacts and rolling parts (includes cams and cam followers, linkages on common shafts, gears, sliding parts); adequate lubrication to reduce stick-slip motion.
4. For rotating parts, provide maximum balance to insure uniform speed and minimum acceleration and deceleration; provide minimum clearances in shafts and mating bearings to prevent vibration.
5. For non-uniform motion, provide minimum acceleration to do the job properly but have uniform acceleration (avoid "jerk": rate of change of acceleration); use maximum available time to produce the necessary velocity change, avoid peak acceleration.
6. Reduce weight of accelerated parts, including rotating unbalanced parts; surface dampen remaining light weight surfaces.
7. Reduce accumulated backlash or clearances in a string of linkages to reduce "jerkiness" to the final action; provide spring loading to final action to give constant force to resist jerkiness.

8. Apply acceleration forces only as rapidly as parts can follow to reduce impact, overshoot, undue flexing or deformation.

9. Reduce impact force to minimum necessary; look for other ways to transmit force or information to a system than by impact.

10. Use "soft" surfaces where possible to reduce impact (cams, cam followers, hammers, gears); use soft inserts under impact surfaces when possible; reduce mass and area of impact parts; use damping material on impact parts.

11. Apply damping materials to eliminate resonances of rods, panels, linkages, gears.

G. <u>Reduction of Structure-borne Noise and Vibration</u>

1. Provide vibration isolation for mounting of a noise or vibration source to its base; have no short-circuiting rigid connections (flexible connection in pipes or wiring, free coil turn in wiring connection). If rigid connections required, isolate next larger assembly that includes the rigid connections. Isolation mounting stiff enough to transmit performance requirement or provide functional operation, soft enough to prevent transmission of high frequency vibrational forces. Caution that springs, as steel bars, transmit some high frequency noise. Use rubber pads with springs. Use rubber-in-shear or felt, cork or rubber pads for high frequency isolation.

2. Reduce the weight of a vibration assembly, attach it to heavy-weight base with isolation mounts. Always try to support a vibration source from a massive "inertia block" (with use of isolation mounts; design curves on transmissibility assume infinite mass and rigidity for base). Avoid vibration isolation of a heavy source on a light-weight flexible base; base may be as flexible as isolation mount.

3. Avoid resonance of isolation mount with driving frequency. Design mount resonance frequency at least 2 to 4 times above lowest driving frequency.

4. Reduce the radiating area of structural paths (drill holes).

5. Add vibration damping materials to structure paths that will transmit vibration to another point in the system or to parts that can vibrate at various resonances. Surface damping, "spaced damping". Effect of temperature and frequency. Effectiveness somewhat proportional to thickness. Most effective on thin stock and at regions of maximum bending.

6. Provide area, weight, and impedance "mismatches" at junctions of different parts. (Impedance mismatch: materials with large differences in values of density x velocity of sound)

7. Avoid close air coupling between large surfaces (air a good spring connection for large areas at close spacing; example Thermopane glass not much better acoustically than single glass of same total weight).
8. Avoid structural connections that amplify force (illustrate with "T" connection; slight flexing of base will amplify to large motion of top).

5. CONCLUSION

It would be dishonest to imply that noise reduction comes simply and at no cost. The treatment may not be simple to execute even though it may be simple in concept. The cost may involve changes in attitude by the user, the operator, or the shop foreman. Some compromises in machine speed, performance, accessibility, or convenience may be required. If noise reduction is a controlling requirement, some of these compromises may have to be made.

Most of the examples described here relate to noise reduction steps added to a machine without actually changing the "internal workings" of the machine. If design engineers can adapt some of these guide lines into their original designs, possibly some noise reduction can be built into a machine without having to add it on later. This, of course, is the real objective. There is no "magic" in acoustics. If noise reduction is wanted, noise reduction must be designed into a machine, not added onto it as an after-thought. Some of the basic noise reduction principles have been given in this discussion, but the real need facing all of us is the motivation to do something about it. Many of the methods, materials and knowledge are available.

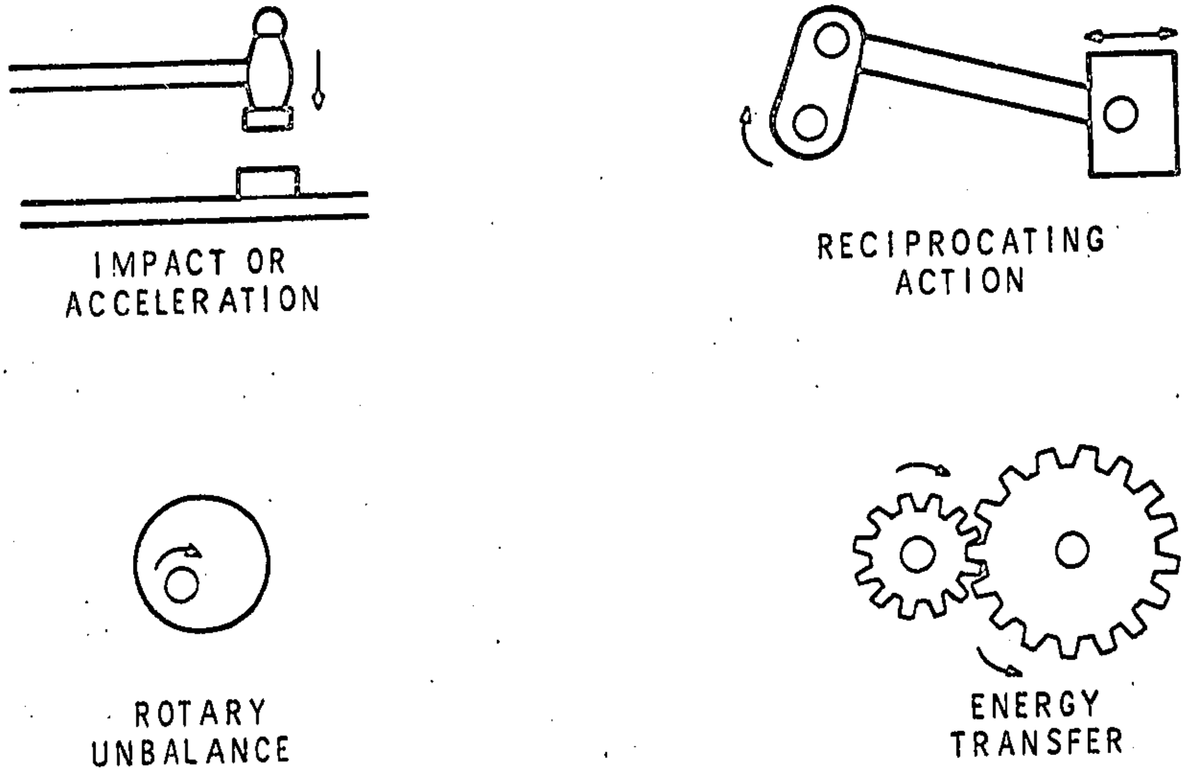
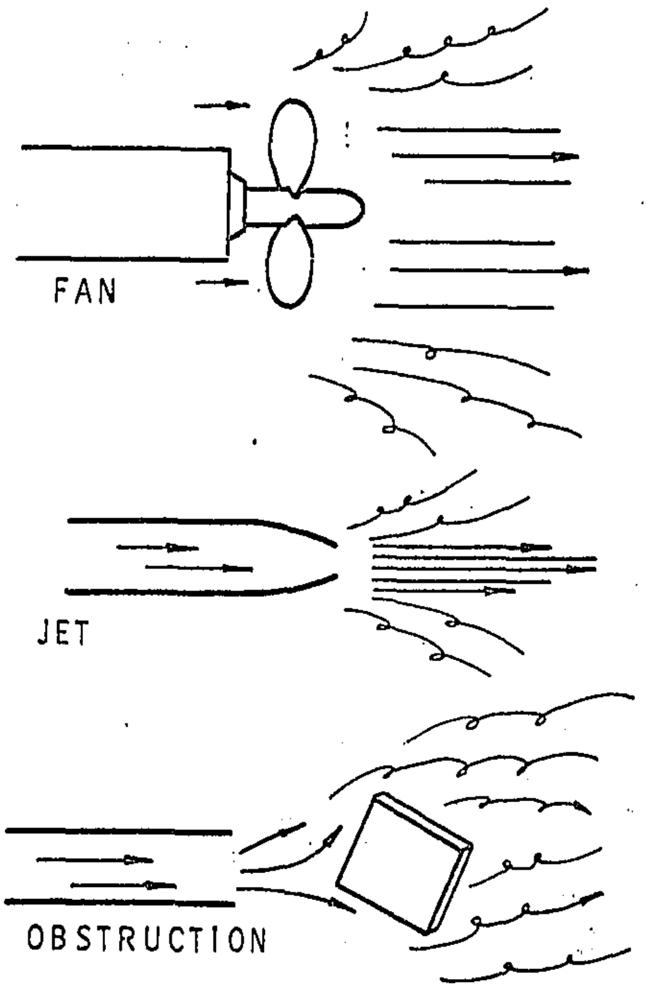


FIGURE 1
MECHANICAL NOISE EXCITATION

FIGURE 2
TURBULENCE
ASSOCIATED
WITH
MOVING
AIR



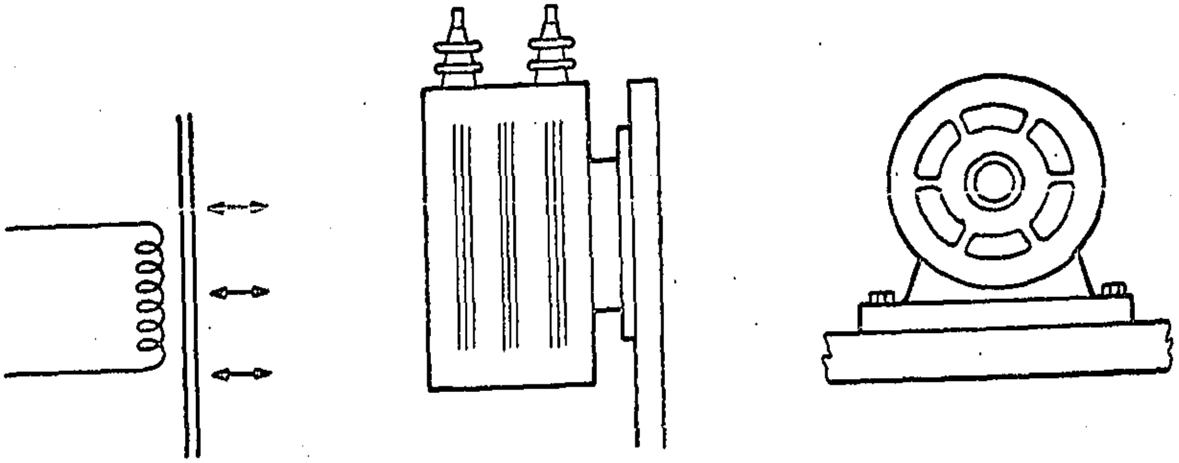
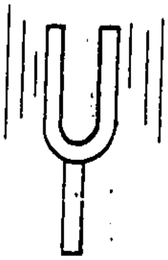
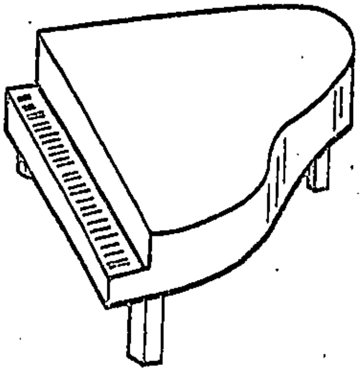


FIGURE 3
ELECTRO-MAGNETIC
INDUCTION



RESONANCE



"THE SOUNDING BOARD"

FIGURE 4

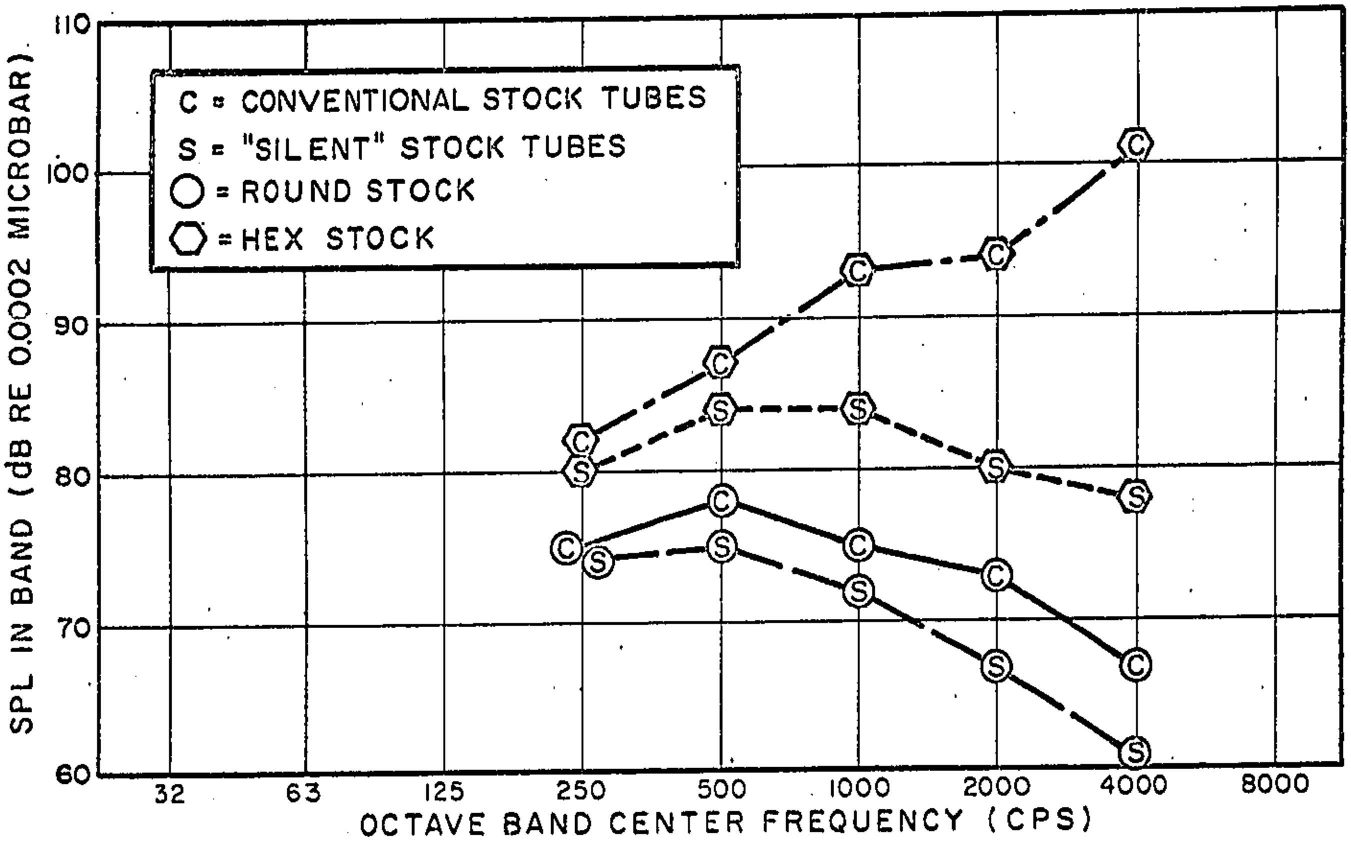


FIGURE 5
NOISE LEVELS 5 FT FROM VARIOUS STOCK TUBE ARRANGEMENTS OF AUTOMATIC SCREW MACHINE

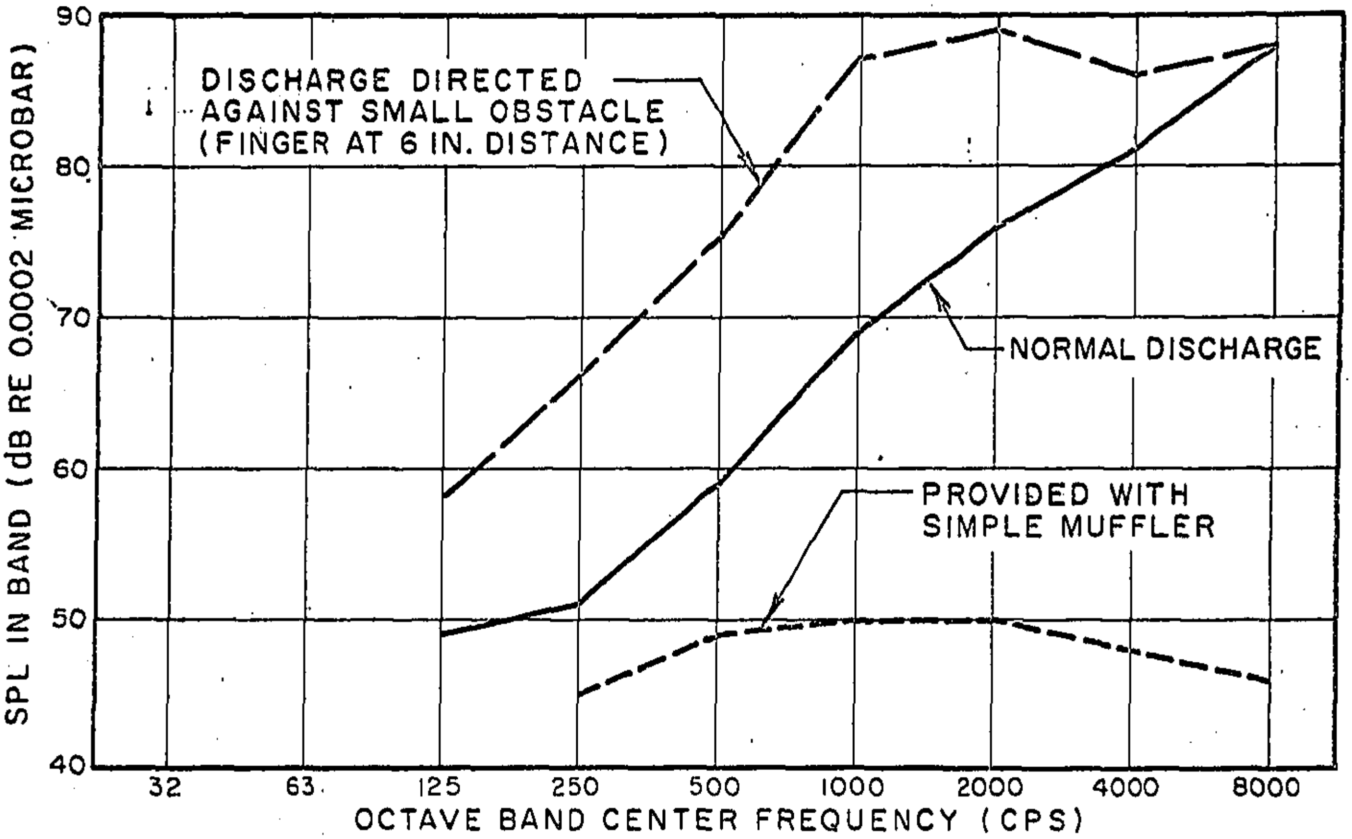


FIGURE 6
NOISE LEVELS 3 FT FROM SHOP AIR NOZZLE
DISCHARGING AIR FROM 130-160 PSI LINE

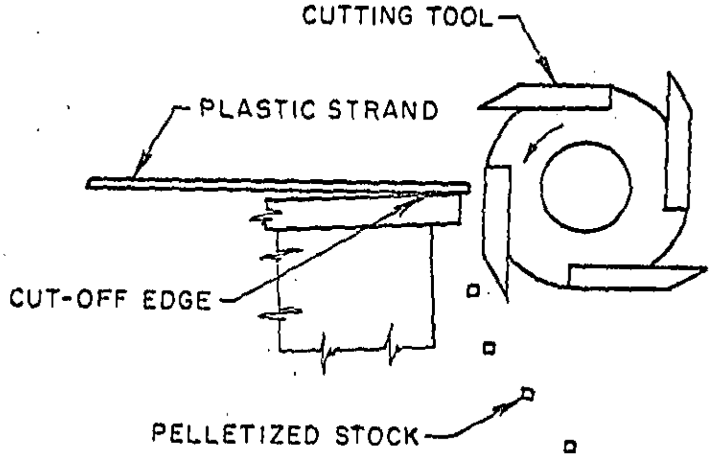


FIGURE 7
SCHEMATIC OF PELLETIZING MACHINE

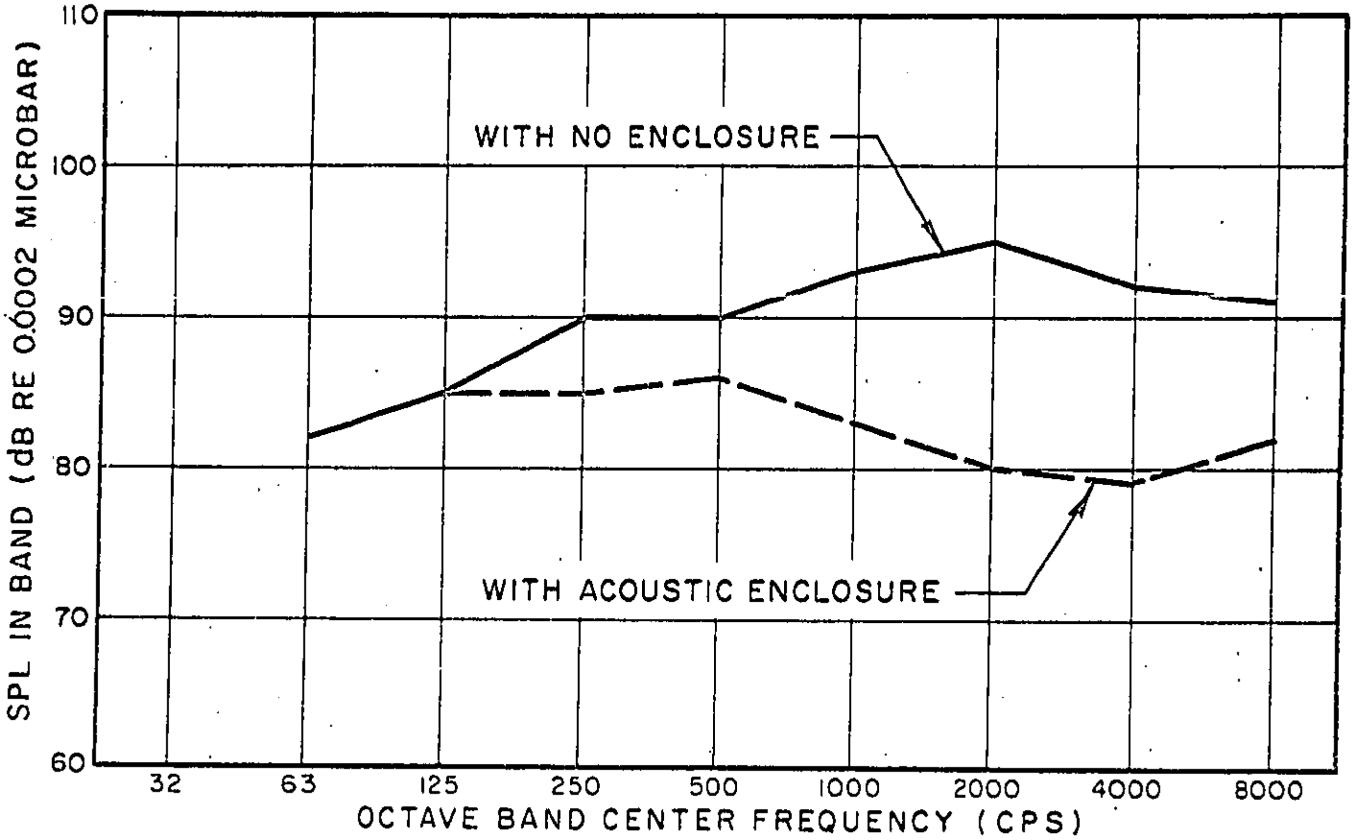


FIGURE 8
NOISE LEVELS IN AISLE POSITION
BESIDE PELLETIZING MACHINE

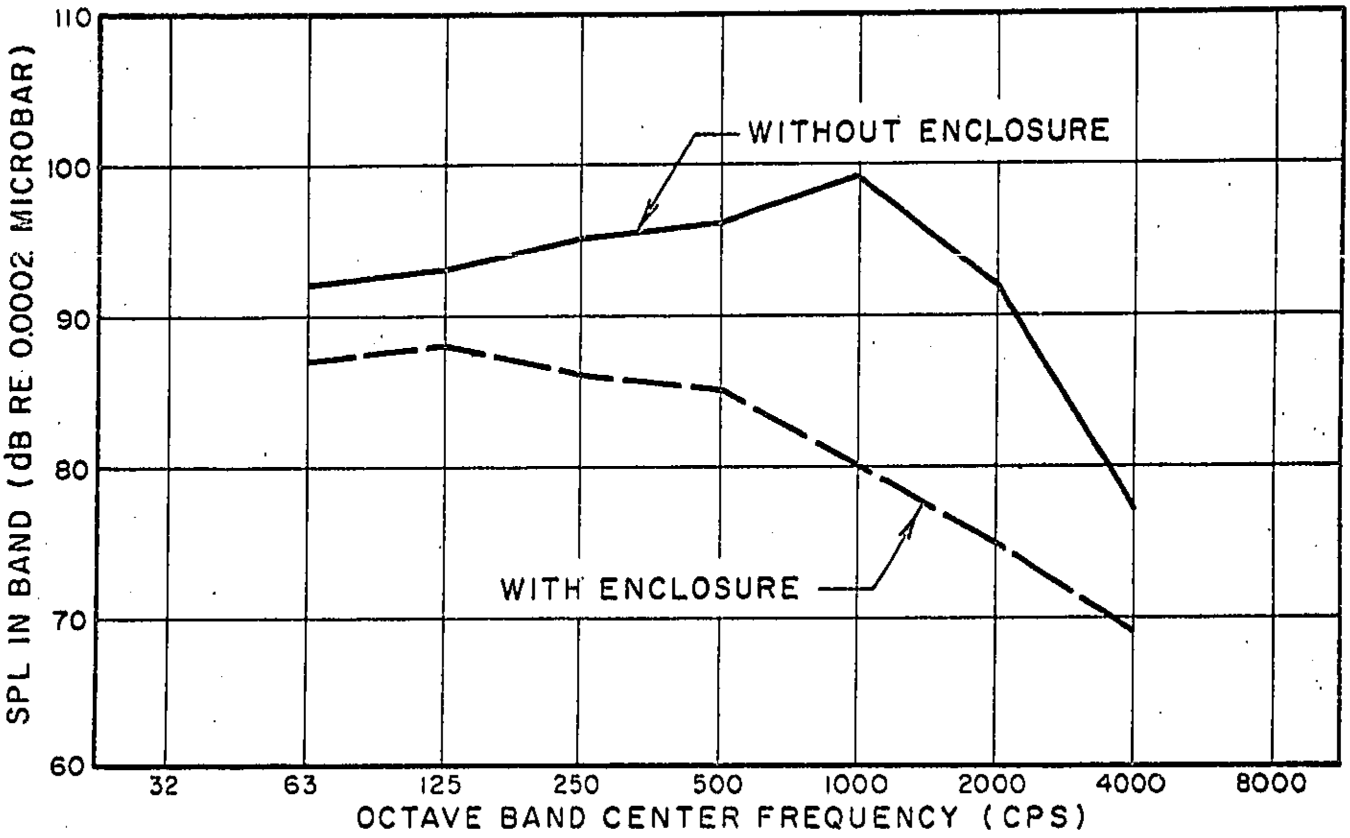


FIGURE 9
NOISE LEVELS IN FACTORY SPACE DUE TO
SEVERAL NEARBY MOTOR-GEAR DRIVES

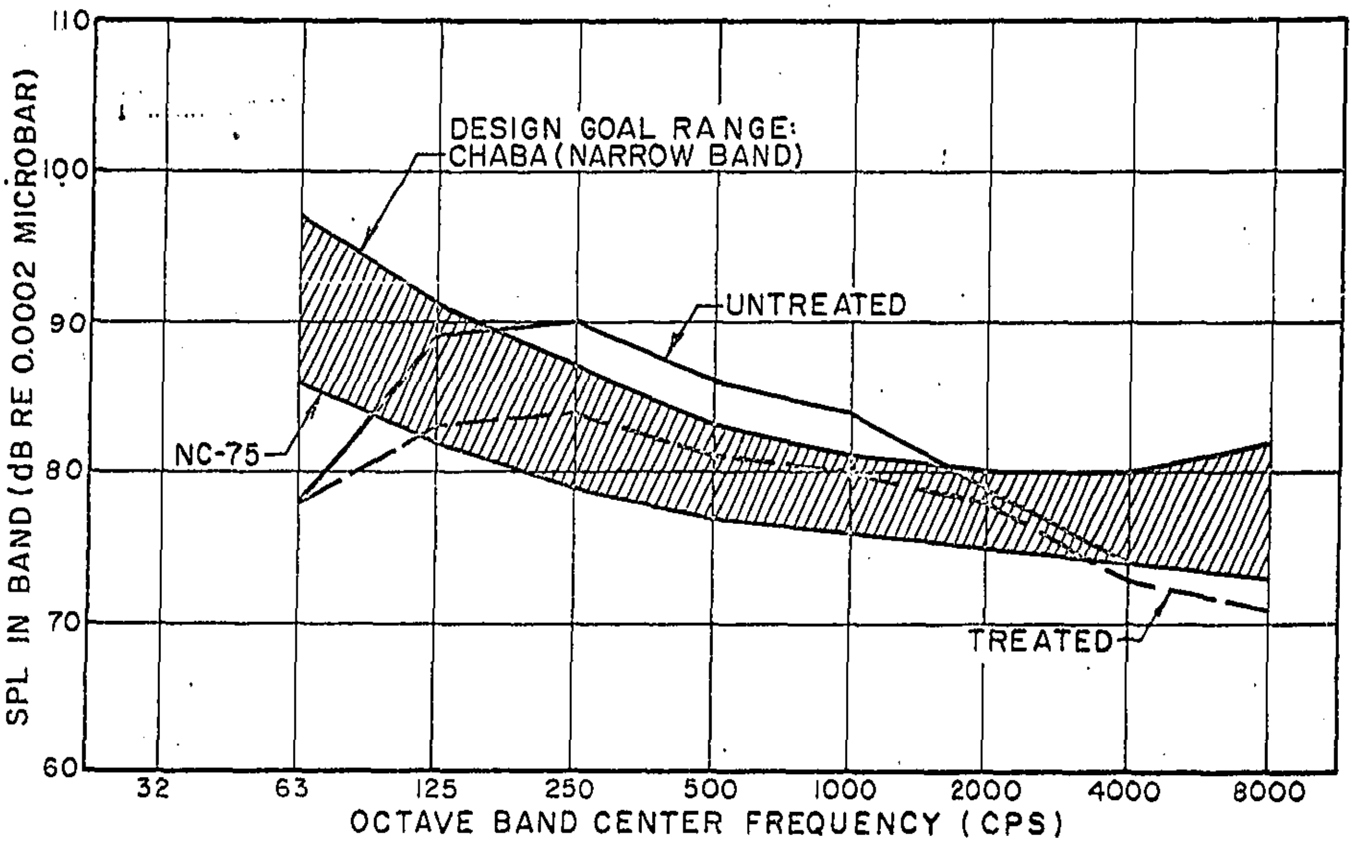


FIGURE 10
NOISE LEVELS AT OPERATOR'S CONSOLE OF PUNCH PRESS

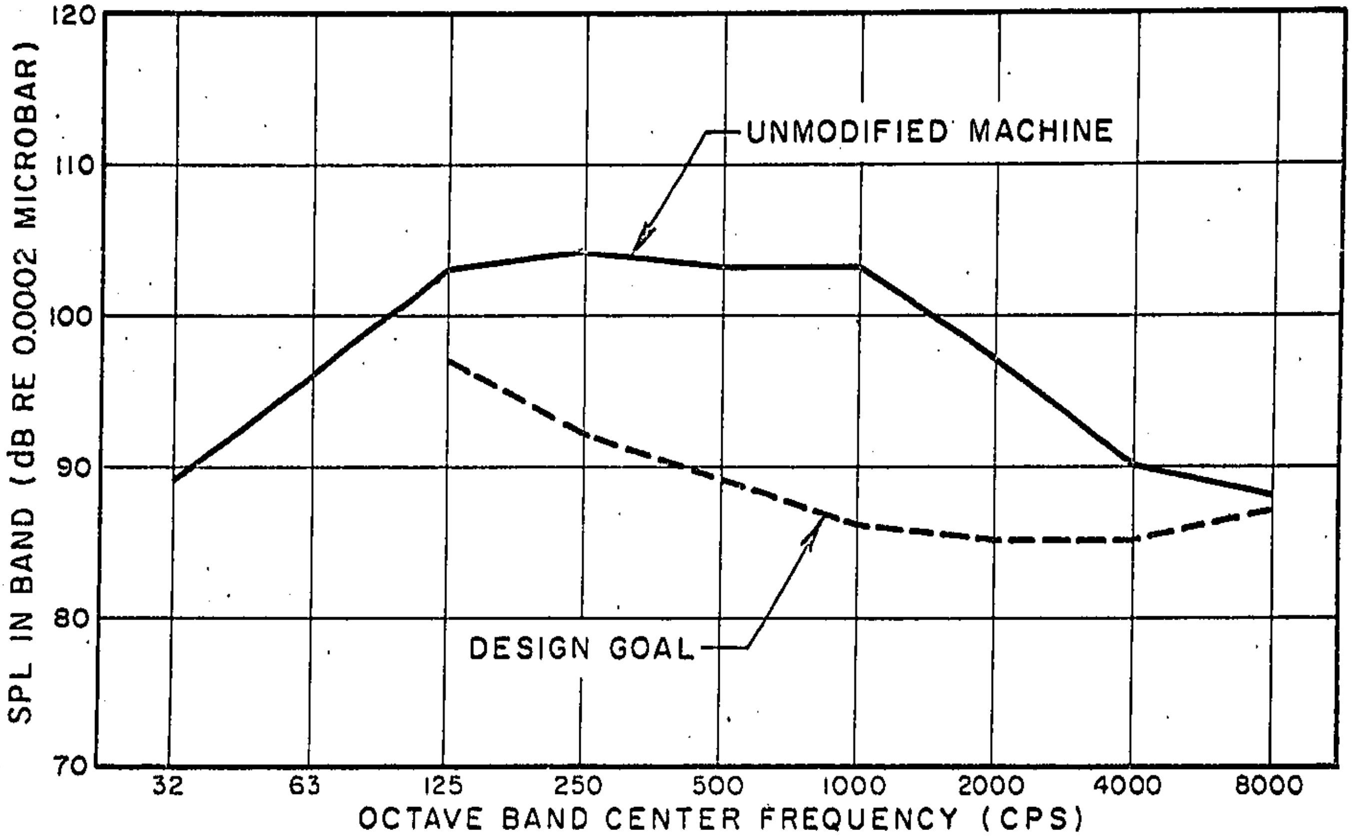


FIGURE 11
EXISTING AND DESIRED NOISE LEVELS AT OPERATOR POSITION OF HIGH-SPEED AUTOMATIC IMPACT-TYPE MACHINE