

IEEE Std 640-1985

IEEE Guide for Power Station Noise Control



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IEEE Guide for Power-Station Noise Control



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IEEE Guide for Power-Station Noise Control

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Foreword

(This Foreword is not a part of IEEE Std 640-1985, IEEE Guide for Power-Station Noise Control.)

Recognizing the need for guidance on various aspects of a comprehensive noise-control program for power generation plants, an IEEE Working Group on Power-Station Audible Noise Control was formed. Membership was composed of representatives from a cross section of utility companies, architect-engineering firms, and power-plant equipment suppliers. The working group held its organizational meeting in January 1972. Individual reports on power-station noise by the working group members became the basis for development of this guide. This guide reviews alternative noise-control methods for identifying and controlling noise-emission problems in existing and planned fossil and nuclear power plants.

Suggestions for improvement of this guide will be welcomed.

The IEEE wishes to acknowledge its indebtedness to those who have so freely given of their time and knowledge and have provided experimental or field-data work.

This guide was prepared by the Mechanical and Electrical Noise Working Group of the Station Design Subcommittee of the IEEE Power Generation Committee. At the time this guide was approved the working group had the following membership:

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Comments on standards and requests for interpretations should be addressed to:

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IEEE Guide for Power-Station Noise Control

1. Introduction

Environmental noise and occupational noise exposure are a matter of increasing public concern. Legislation requiring assessment, control, and abatement of noise has been enacted on all governmental levels. This guide provides guidance to control electric power-plant noise emissions to acceptable limits.

There has been an increase in the noise emissions from power plants with the use of larger, more intensely used, machinery. To reduce this noise emission, power-plant engineers need to become familiar with noise-control principles. Noise control for new plants is usually expensive and may cost up to 4% of the total cost of the plant. It is necessary that noise-control planning be done prior to constructing a new plant or to modernizing an existing plant so as to eliminate or minimize excessive retrofit costs.

A typical noise-control program consists of the following subsections:

1.1 Establishment of Noise-Control-Design Objectives. Noise-control objectives are dictated by

- (1) Community noise requirements
- (2) The Occupational Safety and Health Administration (OSHA) limits inside the plant
- (3) Speech interference levels in offices, control rooms, etc

These requirements are discussed in Section 3. The considerations in establishing these objectives are discussed in Section 8.

For new plants these objectives provide a starting point in specifying the equipment sound levels. For existing plants they help in determining the noise reduction necessary. Noise levels permitted inside the plant by OSHA are governed by the accumulated noise-exposure dose, not by the levels alone. Hence, the feasibility of administrative controls should be included in setting the permitted levels or the necessary noise reduction for hearing protection purposes.

1.2 Prediction/Determination of Power-Station Noise. Once the design objectives have been established, the next step is to predict for new plants or determine for existing plants the power-station noise.

In the case of an existing plant this means a sound survey inside the plant and in the surrounding community. The sound survey is discussed in Section 7.

There are two ways of predicting the noise from a new plant. If a similar plant is operating, one can conduct a sound survey and then modify the sound levels obtained for any differences which may exist between the two plants, such as topography of the surroundings and location, and orientation of the plant with respect to the nearby community. In the absence of a similar operating plant one can extrapolate the noise levels of a plant of smaller size but of a similar nature. There are no definite rules available for such an extrapolation. The manufacturers of the new plant equipment should provide sound data, measured or predicted, which will help in the extrapolation. These ideas are discussed in detail in Sections 6 and 7. If the manufacturers offer any modifications to their equipment to lower the noise levels, these should be considered in predicting the plant noise levels. The option of retrofitting to reduce the noise should also be kept in mind. Both have their advantages and disadvantages.

1.3 Specifications of Equipment Sound Levels and Noise Reduction. Some of the inputs that should be considered in preparing equipment specifications are discussed in Section 7. Design approaches to meet the desired levels are also discussed in Section 7.

To achieve the amount of noise reduction that may be required inside and around an existing power plant, the major sources of noise should be identified. Section 7 discusses the identification of noise sources in detail. Examples of frequency spectra of power-plant noise sources are described in Section 5. These spectra provide the necessary information needed in the selection of noise-reduction schemes in relation to the characteristics of the noise source. Noise-reduction schemes are discussed in Section 7. A list of the possible sources of noise and methods of noise reduction are also included in Section 7.

1.4 Evaluation of the Noise-Control Measures. Once the new plant, designed with noise-control considerations, is in operation or the noise-control measures are installed in an existing plant, a follow-up sound survey should be made to evaluate the noise-control program. If the noise levels fail to meet the selected design objectives, the reasons should be traced and corrected. See Section 7. This guide supports the program and addresses alternate noise-control methods for noise-emission problems generally encountered in fossil and nuclear power plants.

The noise-control techniques reviewed in this guide are not intended to be applicable to other power generating facilities such as combined cycle, diesel, gas turbine, hydro-electric, and solar power plants.

Information presented in this guide was obtained from published national standards, technical papers, and the experience from the installation and evalua-

tion of noise-control equipment. Terminology used conforms to ANSI S1.1-1960 (R1976) [2]¹.

It is not the intent of this guide to adopt any noise compliance limits or to design a specific series of noise-control devices to solve individual power-plant noise problems. Such an undertaking is somewhat impractical because of the numerous variations in regulation requirements, personnel exposure, plant siting, noise sources, equipment ratings, background levels, environmental conditions, and individual plant operational requirements. This guide provides the power-plant engineer with the tools necessary to identify potential noise problem areas and alternate control methods which may be required to comply with applicable limits.

1.5 Definitions. The following definitions apply to the subject matter presented in this guide.

absorption coefficient. The ratio of the energy absorbed by the surface to the energy incident upon it.

decibel. 10 times the logarithm to base 10 of a ratio of two powers.

sound intensity. The average rate of sound energy transmitted through a unit area normal to the direction of sound.

sound power. The total sound energy radiated by a source per unit time.

sound pressure. The instantaneous pressure measured in a sound wave, that is, the variation in atmospheric pressure.

1.6 References. When the following American National Standards referred to in this standard are superseded by a revision approved by the American National Standards Institute, the latest revision shall be used.

[1] AMCA STD 300-67, Test Code for Sound Rating—Air-Moving Devices.²

[2] ANSI S1.1-1960 (R 1976), American National Standard Acoustical Terminology (Including Mechanical Shock and Vibration).³

[3] ANSI S1.4-1983, American National Standard Specification for Sound Level Meters.

[4] ANSI S1.8-1969 (R 1974), American National Standard Preferred Reference Quantities for Acoustical Levels.

¹Numbers in brackets correspond to those of the references in 1.6 of this guide.

²AMCA publications are available from Air Movement and Control Association, 30 West University Drive, Arlington Heights, IL 60004.

³ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

- [5] ANSI S1.11-1966 (R 1976), American National Standard Specifications for Octave, Half-Octave, and Third-Octave Band Filter Sets.
- [6] ANSI S1.13-1971 (R 1976), American National Standard Methods for the Measurement of Sound Pressure Levels.
- [7] ANSI/ASC S1.6-1984, American National Standard Preferred Frequencies, Frequency Levels, and Band Numbers for Acoustical Measurements.
- [8] IEEE Std 85-1973 (R 1980), IEEE Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery.⁴
- [9] NEMA TR 1-1980, Transformers, Regulators, and Reactors.⁵
- [10] NUREG 4.2, Nuclear Regulatory Guide for Preparation of Environmental Reports for Nuclear Plants.⁶
- [11] Noise Ordinance of Chicago, 1971.⁷
- [12] Rules of Procedure—Certification for Major Steam Electric Generating Noise, 1973, Part 75, New York State, Albany, NY.
- [13] State and Local Noise Regulations, 1973, ch 8. Illinois Pollution Control Board.
- [14] *Sound and Vibration* (Magazine).
- [15] 24 CFR 51 HUD, Environmental Criteria and Standards for Housing and Urban Development.⁸
- [16] 29 CFR 1910.95 OSHA, Occupational Noise Standards.⁹
- [17] 29 CFR Bulletin 334, Guidelines to the Department of Labor's Occupational Noise Standards.¹⁰
- [18] 40 CFR 1 POE, Environmental Protection Agency—Public Health and Welfare Criteria for Noise.

⁴IEEE publications are available from IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08854.

⁵NEMA publications are available from National Electrical Manufacturers Association, 2101 L Street, NW, Suite 300, Washington, DC 20037.

⁶NUREG publications are available from Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

⁷This publication is available from Department of Environmental Control, Chicago, IL.

⁸HUD publications are available from Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

⁹OSHA publications are available from Occupational Safety and Health Administration, US Department of Labor, Washington, DC 20210 or from the nearest regional or area office of the United States Department of Labor.

¹⁰CFR publications are available from Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

[19] 40 CFR 1 POE, Environmental Protection Agency—Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety.

[20] US Department of Transportation, Federal Highway Administration Fundamentals in Abatement of Highway Traffic Lanes. Report on Contract no DOT-FH-11/7976, 1976.

2. Fundamentals

2.1 Introduction. Sound waves are a form of elastic waves that can be propagated through any medium exhibiting mass and elasticity. Mass, or inertia, enables displaced particles of the medium to transfer energy. Elasticity enables the disturbed particles to return to their original position, somewhat similar to a spring.

Air has mass and elasticity and therefore can transmit sound waves. A noise source sets adjacent air molecules in motion. This movement produces a variation in atmospheric pressure and this disturbance is propagated from molecule to molecule. The instantaneous variation in atmospheric pressure is called sound pressure. The speed of sound in a particular medium is defined as the product of frequency and wavelength

$$c = f\lambda \quad (\text{Eq 1})$$

where

c = speed of sound

f = frequency

λ = wavelength

In air the speed of sound is dependent only on the temperature of air. At 70 °F, the speed of sound in air is 1128 ft/s.

Sound may consist of a pure tone (a single frequency) where the instantaneous sound pressure is a sinusoidal function of time, or it may consist of a complex combination of many tones. The sound energy of a source may be distributed over a range of frequencies. The frequency distribution of sound is usually referred to as sound spectrum.

2.2 Characteristics of the Noise Source. A noise source is characterized by its frequency spectrum, variation of the spectrum with time, and the sound radiation pattern. Directivity, which is an index of the sound radiation pattern, is important in determining the number of measurement locations for the calculation of the sound power level of the source. The noises usually encountered in practice are classified as steady or nonsteady noise.

2.2.1 Steady Noise. The level of a steady noise remains essentially constant (that is, fluctuations are negligibly small) during the period of observation. The frequency spectrum can be broad band (prominent discrete components and narrow bands of noise are absent) or can have one or more discrete frequency components which have significantly greater amplitudes than those of the adjacent spectrum. The spectral distribution of sound, with or without discrete tones, remains constant.

2.2.2 Nonsteady Noise. If a noise level varies during the period of observation (as determined by listening), the noise is classified as nonsteady. This type may or may not contain audible discrete tones. Depending upon the variation in spectrum the noise is classified as fluctuating, intermittent, or impulse. See Table 1 for an example of different types of noise.

Table 1
Examples of Sources of Different Types of Noise

Steady	Nonsteady
Without audible discrete tones	Fluctuating
Distant city	Heavy traffic (nearby)
Waterfall	Pounding surf
Air-conditioning system	
With audible discrete tones	Intermittent
Circular saw	Aircraft fly-over
Transformer	Automobile passing by
Turbojet engine	Train passing by
Automobile horn	
Siren	
	Impulsive
	Isolated bursts
	Drop forge hammer
	Dog barking
	Pistol shots
	Door slamming
	Electrical circuit breaker
	Quasi-steady noise
	Riveting
	Pneumatic hammer
	Machine gun

2.2.3 Directivity. Directivity is a measure of the radial asymmetry, in three dimensions, of the sound radiation pattern of the source. A numerical measure of the directivity of a sound source is the directivity factor Q , a dimensionless quantity, defined in 2.4.2.2.

2.3 Sound Power, Sound Intensity, and Sound Pressure. Consider a point source of noise suspended in free space. Sound waves will emanate as spherical waves from this source. As the wave front progresses further from the source, its area increases as the square of the distance since the area of a sphere is $4\pi r^2$. If the energy of the noise source remains constant, it is evident that the sound power per unit area shall decrease. Thus, for a doubling of distance, the available energy is spread over four times the area, or the *sound intensity* is one fourth of its original value. This reduction in intensity with distance is known in physics as the *inverse square law*. See 1.5, **sound power** and **sound intensity**.

Measurements have shown that a soft whisper may produce a sound power of 10^{-9} W. A jet engine at its exhaust can develop 10^4 W. This indicates the wide range of sounds (10^{13} to 1) which can occur in our environment. To avoid use of such large numbers, acoustical engineers have borrowed a term from electrical engineering, that is, the decibel. See 1.5, **decibel**.

Electrical engineers have long used the decibel to describe the gain of amplifiers.

Thus, assume that an amplifier has an input of W_1 and an output of W_2 . The gain of the amplifier can be expressed as shown in Eq 2.

$$\text{Gain} = 10 \log \frac{W_2}{W_1} \quad (\text{Eq 2})$$

where

$$W_1 = 1 \text{ mW}$$

$$W_2 = 10 \text{ mW}$$

$$\text{Gain} = 10 \log \frac{10}{1} = 10 \text{ dB}$$

From Eq 2 it can be noted that the decibel is a relative quantity. When used to express noise level, a reference quantity is usually stated or implied.

In acoustics, the reference power is taken as 10^{-12} W . Thus, the term sound power level (PWL) can be defined as in Eq 3.

$$\text{PWL} = 10 \log \frac{W}{10^{-12}} \text{ dB (ref } 10^{-12} \text{ W)} \quad (\text{Eq 3})$$

where

PWL = sound-power level

W = sound power, watts

This power level is conveniently computed from Eq 4.

$$\text{PWL} = 10 \log W + 120 \quad (\text{Eq 4})$$

For example, if

$$W = 10 \text{ W}$$

$$\text{PWL} = 10 \log 10 + 120$$

$$= 10 + 120$$

$$= 130 \text{ dB (ref } 10^{-12} \text{ W)}$$

It is also convenient to use the decibel scale to express the ratio between any two sound pressures. Sound-pressure level (SPL) is defined in Eq 5.

$$\text{SPL} = 10 \log \frac{P^2}{P_{\text{ref}}^2} = 20 \log \frac{P}{P_{\text{ref}}} \quad (\text{Eq 5})$$

For airborne sounds, the reference sound pressure P_{ref} is $20 \mu\text{Pa}$, where

$$1 \mu\text{Pa} = 1 \mu\text{N/m}^2 = 10^{-5} \mu\text{bar}$$

Therefore

$$\text{SPL} = 20 \log \frac{P}{20 \mu\text{Pa}} \text{ dB (ref } 20 \mu\text{Pa)} \quad (\text{Eq 6})$$

where

SPL = sound-pressure level

P = sound pressure, Pa

NOTE: See Figs 1 and 2 for typical sound power and sound-pressure levels for various acoustic sources.

The instrument used to measure sound-pressure level consists of a microphone, attenuator, amplifier, and indicating meter. This instrument shall have an overall response that is uniform (*flat*) as a function of frequency, and the instrument is calibrated in decibels according to Eq 6.

The position of the selector switch of the instrument for this measurement is often called *flat* or 20–20 000 kHz to indicate the wide frequency range that is covered. The result of a measurement of this type is also called the overall sound-pressure level.

2.3.1 Sound Level. The apparent loudness that we attribute to a sound varies not only with the sound-pressure level but also with the frequency (or pitch) of the sound. If this effect is taken into account to some extent for pure tones, by *weighting* networks included in an instrument designed to measure sound-pressure level, then the instrument is called a sound-level meter. ANSI S1.4-1983 [3] requires that three alternate frequency response characteristics be provided in instruments designed for general use (see Fig 3 and Table 2). These three responses are obtained by weighting networks designated as A, B, and C. Responses A, B, and C selectively discriminate against low and high frequencies.

Whenever one of these networks is used, the reading obtained should be described as

- (1) The A-weighted sound level is 45 dB
- (2) Sound level (A) = 45 dB
- (3) SLA = 45 dB

In a table, the abbreviated form L_A with the unit dB is suggested, or where exceptional compactness is necessary, dB(A). The form dBA has also been used, but this notation implies that a new unit has been introduced and is therefore not recommended. Note that when a weighting characteristic is used, the reading obtained is said to be the *sound level*. Only when the overall frequency response of the instrument is flat are sound pressure levels measured. Since the reading obtained depends on the weighting characteristic used, the characteristic that was used shall be specified or the recorded level may be useless.

It is often recommended that readings on all noises be taken with all three weighting positions. The three readings provide some indication of the frequency distribution of the noise. If the level is essentially the same on all three networks, the frequencies of the predominate sounds are probably above 600 Hz. If the level is greater on the C network than on the A and B networks by several decibels, much of the noise is probably below 600 Hz.

POWER (WATTS)	ACOUSTIC POWER		SOURCE
	POWER LEVEL dB (ref 10^{-12} W)		
25–40 MILLION	195		SATURN ROCKET
100 000	170	}	RAM JET
			TURBO-JET ENGINE WITH AFTERBURNER
10 000	160		TURBO-JET ENGINE, 7000 lb THRUST
1000	150		
			4-PROPELLER AIRLINER
100	140		
10	130	}	75-PIECE ORCHESTRA } PEAK RMS LEVELS IN PIPE ORGAN } $\frac{1}{8}$ SECOND INTERVALS
			SMALL AIRCRAFT
1	120		LARGE CHIPPING HAMMER
			PIANO }
0.1	110		TUBA } PEAK RMS LEVELS IN BLARING RADIO } $\frac{1}{8}$ SECOND INTERVALS
0.01	100		CENTRIFUGAL VENTILATING FAN (13 000 ft ³ /min) 4 ft LOOM AUTO ON HIGHWAY
0.001	90		VANEAXIAL VENTILATING FAN (1500 ft ³ /min) VOICE-SHOUTING (AVERAGE LONG-TIME RMS)
0.0001	80		
0.00001	70		VOICE—CONVERSATIONAL LEVEL (AVERAGE LONG-TIME RMS)
0.000001	60		
0.0000001	50		
0.000 000 01	40		
0.000 000 001	30		VOICE—VERY SOFT WHISPER

NOTE: These levels bear no simple relation to the sound levels of Fig 2

Fig 1
Typical Power Levels for
Various Acoustic Sources

AT A GIVEN DISTANCE FROM NOISE SOURCE	dB(A)	ENVIRONMENTAL
	dB (ref 20 μ Pa)	
	140	
50 HP SIREN (100 ft)	130	
JET TAKEOFF (200 ft)	120	
RIVETING MACHINE	110	CASTING SHAKEOUT AREA
CUTOFF SAW PNEUMATIC PEEN HAMMER	100	ELECTRIC FURNACE AREA
TEXTILE WEAVING PLANT SUBWAY TRAIN (20 ft)	90	BOILER ROOM PRINTING PRESS PLANT
PNEUMATIC DRILL (50 ft)	80	TABULATING ROOM INSIDE SPORT CAR (50 mi/h)
FREIGHT TRAIN (100 ft) VACUUM CLEANER (10 ft) SPEECH (1 ft)	70	
	60	NEAR FREEWAY (AUTO TRAFFIC) LARGE STORE ACCOUNTING OFFICE
	50	PRIVATE BUSINESS OFFICE LIGHT TRAFFIC (100 ft) AVERAGE RESIDENCE
	40	MIN LEVELS – RESIDENTIAL AREAS IN CHICAGO AT NIGHT
SOFT WHISPER (5 ft)	30	STUDIO (SPEECH)
	20	STUDIO FOR SOUND PICTURES
	10	
THRESHOLD OF HEARING { YOUTHS — 1000 Hz – 4000 Hz }	0	

NOTE: These values are taken from the literature. Sound-level measurements give only part of the information usually necessary to handle noise problems, and are often supplemented by analysis of the noise spectra.

Fig 2
Typical A-Weighted Sound Levels
Measured with a Sound-Level Meter

Table 2
A, B, and C Electrical Weighting Networks
for the Sound-Level Meter*

Frequency (Hz)	A-Weighting Relative Response (dB)	B-Weighting Relative Response (dB)	C-Weighting Relative Response (dB)
10	-70.4	-38.2	-14.3
12.5	-63.4	-33.2	-11.2
16	-56.7	-28.5	-8.5
20	-50.5	-24.2	-6.2
25	-44.7	-20.4	-4.4
31.5	-39.4	-17.1	-3.0
40	-34.6	-14.2	-2.0
50	-30.2	-11.6	-1.3
63	-26.2	-9.3	-0.8
80	-22.5	-7.4	-0.5
100	-19.1	-5.6	-0.3
125	-16.1	-4.2	-0.2
160	-13.4	-3.0	-0.1
200	-10.9	-2.0	0
250	-8.6	-1.3	0
315	-6.6	-0.8	0
400	-4.8	-0.5	0
500	-3.2	-0.3	0
630	-1.9	-0.1	0
800	-0.8	0	0
1000	0	0	0
1250	+0.6	0	0
1600	+1.0	0	-0.1
2000	+1.2	-0.1	-0.2
2500	+1.3	-0.2	-0.3
3150	+1.2	-0.4	-0.5
4000	+1.0	-0.7	-0.8
5000	+0.5	-1.2	-1.3
6300	-0.1	-1.9	-2.0
8000	-1.1	-2.9	-3.0
10 000	-2.5	-4.3	-4.4
12 500	-4.3	-6.1	-6.2
16 000	-6.6	-8.4	-8.5
20 000	-9.3	-11.1	-11.2

* These numbers assume a flat, diffuse-field (random-incidence) response for the sound-level meter and microphone.

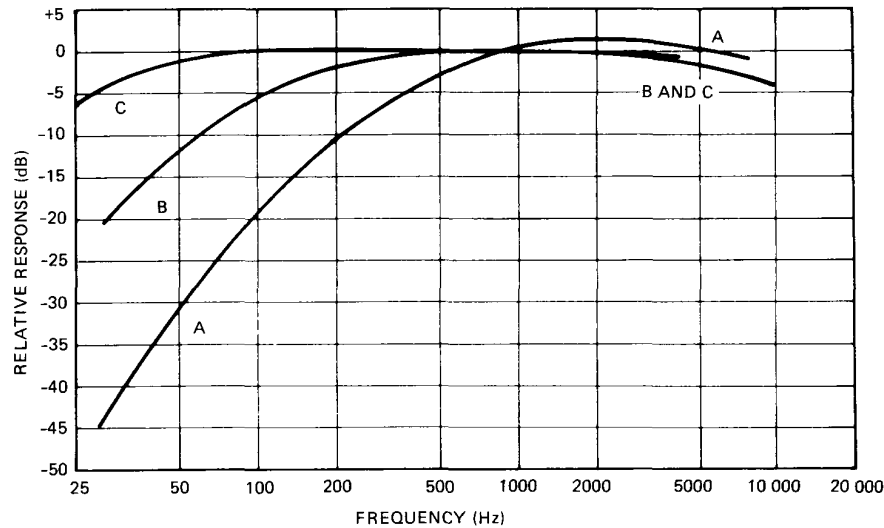


Fig 3
Frequency-Responses for SLM Weighting Characteristics
See ANSI S1.4-1983 [3]

2.3.2 A-Weighted Sound Level as a Single Number Rating. For simple ratings or screenings of similar devices, the A-weighted sound level at a specified distance is widely used. It is useful in preliminary ratings of similar noises for the human reactions that may occur. Measurement of the A-weighted sound level has been adopted for checking compliance with many ordinances and regulations, including the evaluation of personnel noise exposure.

2.3.3 Some Limitations of A-Weighted Sound Level. When only a single-weighted sound level is measured, the usefulness of the measurement is restricted.

The spectrum should almost always be measured, especially when noise control measures may be required. The spectrum is needed for efficient noise control, because the effects of sound isolation, acoustic treatment, vibration reduction, and other forms of noise control are frequency dependent. In addition, the reaction to the noise is frequency dependent, and the spectrum can show us the frequency region where the noise energy is most important in determining the effects. The source of an excessive noise and the spectrum often provide the most important clues for identifying and reducing the noise.

If a noisy machine is to be used in a room, the acoustic characteristics of the room as a function of frequency and the radiated sound-power level of the machine also as a function of frequency need to be known so as to estimate the noise level at some distance from the machine.

The spectra will help in providing data for later comparisons when conditions change or if better evaluation techniques are developed.

The limitations of the simple, weighted measurement should be recognized when plans for sound measurements are made.

2.3.4 Analysis in Frequency Bands. To make an analysis in the frequency domain, the signal energy is electrically separated into various frequency bands, for example, octave bands, each of which covers a 2:1 range of frequencies. The analysis yields a series of levels, one for each band, called *band levels*, or for octave bands, *octave band levels* or *octave band sound-pressure levels*. Here it is apparent that the band in which a reading of level is obtained shall be specified if the information is to be of value.

2.3.5 Octave Bands. The preferred series of octave bands for acoustic measurements [ANSI/ASC S1.6-1984 [7]] covers the audible range in ten bands. The center frequencies of these bands are 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz, and 16 000 Hz. The actual nominal frequency range of any one of these bands is 2:1; for example, the effective band for the 1000 Hz octave band extends from 707 Hz to 1414 Hz (see Table 3).

Another series of octave bands has been widely used in the past. The older bands were a 75 Hz low-pass filter, and the octave bands of 75 Hz to 150 Hz, 150 Hz to 300 Hz, 300 Hz to 600 Hz, 600 Hz to 1200 Hz, 1200 Hz to 2400 Hz, 2400 Hz to 4800 Hz, and a 4800 Hz high-pass filter, but these are no longer preferred. This older series is still specified in a number of test codes and the published data obtained with this series is extensive.

NOTE: For a method of converting octave-band levels measured with this older series to levels for the new series, see ANSI S1.11-1966 (R 1976) [5] and Appendix A. It should be noted that this conversion method applies only to broadband noise.

When a graph is made of the results of octave-band pressure-level measurements, the frequency scale is commonly divided into equal percentage intervals (a logarithmic frequency scale). The level for each octave band is plotted as a point at the center frequency of the octave band. Adjacent points are then connected by straight lines. An example of a plot of this type is given in Fig 4. Graph paper conforming to ANSI S1.13-1971 (R 1976) [6] is available commercially.

2.3.6 Narrower Bands. For a more detailed analysis of the distribution of sound energy as a function of frequency, narrower frequency bands are used. For certain analyses involving steep sloped spectra, the octave bands are divided into three parts, called one-third octave bands (see Table 3). Still narrower bands called one-tenth octave bands are also in widespread use for detailed analysis.

Calculated dB(A) values obtained by using octave-band center-frequency weighting values (from Table 2 to 4) cannot be exact because the distribution of sound pressure within each octave band of frequency is not known and the actual weighting varies continuously with frequency. The error can become substantial with certain steeply-sloped spectra and spectra containing discrete tones; however, it can be minimized by using one-third octave-band resolution.

Table 3
Center and Approximate Cutoff Frequencies for
Standard Set of Contiguous-Octave and One-Third Octave
Bands Covering the Audio-Frequency Range

Band	Frequency (Hz)					
	Octave			One-Third Octave		
	Lower Band Limit	Center	Upper Band Limit	Lower Band Limit	Center	Upper Band Limit
12	11	16	22	14.1	16	17.8
13				17.8	20	22.4
14				22.4	25	28.2
15	22	31.5	44	28.2	31.5	35.5
16				35.5	40	44.7
17				44.7	50	56.2
18	44	63	88	56.2	63	70.8
19				70.8	80	89.1
20				89.1	100	112
21	88	125	177	112	125	141
22				141	160	178
23				178	200	224
24	177	250	355	224	250	282
25				282	315	355
26				355	400	447
27	355	500	710	447	500	562
28				562	630	708
29				708	800	891
30	710	1000	1420	891	1000	1122
31				1122	1250	1413
32				1413	1600	1778
33	1420	2000	2840	1778	2000	2239
34				2239	2500	2818
35				2818	3150	3548
36	2840	4000	5680	3548	4000	4467
37				4467	5000	5623
38				5623	6300	7079
39	5680	8000	11 360	7079	8000	8913
40				8913	10 000	11 220
41				11 220	12 500	14 130
42	11 360	16 000	22 720	14 130	16 000	17 780
43				17 780	20 000	22 390

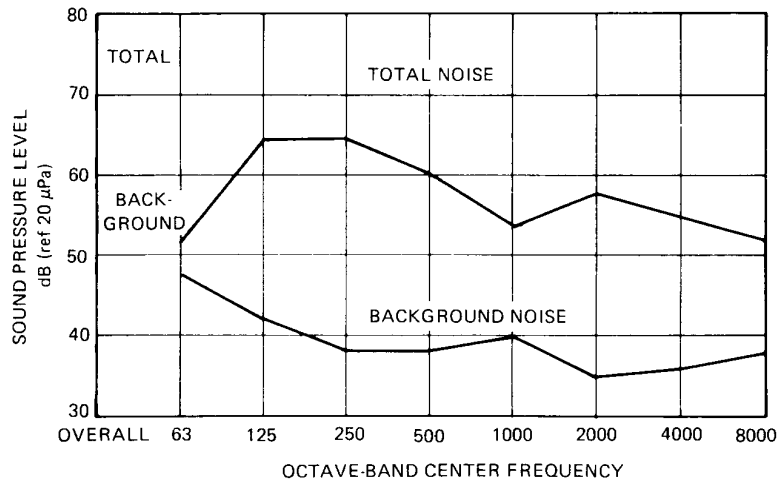


Fig 4
A Plot of the Octave-Band Analysis of
Noise from a Calculating Machine

Also, in these cases, to minimize cumulative amplitude errors, values should be calculated to 0.1 dB resolution, with only final answers rounded to the nearest integral decibel (dB) values.

2.3.7 Combining Decibels. Assume that it is desired to combine three decibel readings to obtain a total sound-pressure level, for example, 90 dB(A), 88 dB(A), and 85 dB(A). The complete mathematical solution is

$$\begin{aligned}\text{Antilog } 90/10 &= 10.0 \cdot 10^8 \\ \text{Antilog } 88/10 &= 6.3 \cdot 10^8 \\ \text{Antilog } 85/10 &= 3.16 \cdot 10^8 \\ &19.45 \cdot 10^8\end{aligned}$$

$$\text{SPL total} = 10 \log 19.45 \cdot 10^8 = 92.9 \text{ dB(A)} \quad (\text{Eq 7})$$

A much simpler method is to use the curve shown in Fig 5.

Difference(dB)	Increment	Interim Answer
90.0 -- 88 = 2.0	2.1	90.0 + 2.1 = 92.1
92.1 -- 85 = 7.1	0.8	92.1 + 0.8 = 92.9

Thus, the same answer, 92.9 dB(A), is obtained with much less work.

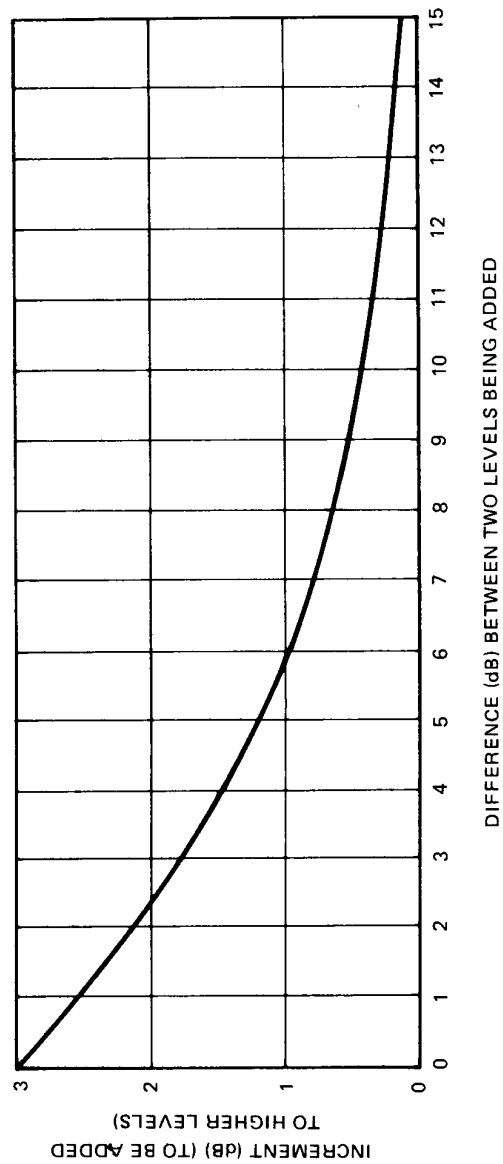


Fig 5
Chart for Combining Noise Levels

2.3.8 Combining Octave-Band Readings. Assume that an octave-band analysis in dB(C) is available, but no overall A-weighted reading was taken. The dB(A) value can be calculated as follows:

Octave Band	Band SPL dB(C)	Correction*	Corrected SPL dB(A)
31.5	88	-36	52
63.0	88	-26	62
125.0	88	-16	72
250.0	94	-9	85
500.0	96	-3	93
1000.0	96	0	96
2000.0	92	+1	93
4000.0	89	+2	91
8000.0	76	+2	78

*From Table 4

Difference(dB)	Increment*	Interim Answer
62.0 - 52.0 = 10.0	0.4	62.0 + 0.4 = 62.4
72.0 - 62.4 = 9.6	0.5	72.0 + 0.5 = 72.5
85.0 - 72.5 = 12.5	0.3	85.0 + 0.3 = 85.3
93.0 - 85.3 = 7.7	0.7	93.0 + 0.7 = 93.7
96.0 - 93.7 = 2.3	2.1	96.0 + 2.1 = 98.1
98.1 - 93.0 = 5.1	1.2	98.1 + 1.2 = 99.3
99.3 - 91.0 = 8.3	0.6	99.3 + 0.6 = 99.9
99.9 - 78.0 = 21.9	0.0	99.9 + 0.0 = 99.9

*From Fig 5

If these values are combined by the more rigorous method, the answer will also be 99.9 dB(A).

As a practical consideration, sufficient accuracy can be obtained by dropping any correction due to a difference of 10 dB or more. A similar procedure may be used to convert *flat* octave-band data to equivalent A-weighted values. See Table 4.

Table 4
Conversion to Equivalent A-Weighted Values

	Center Frequency (Hz)								
	31.5	63	125	250	500	1000	2000	4000	8000
Correction (dB) (C-to-A)	-36	-26	-16	-9	-3	0	+1	+2	+2
Correction (dB) (Flat-to-A)	-39	-26	-16	-9	-3	0	+1	+1	-1

Frequently, reference is made to A-weighted octave bands. The weighting networks and octave-band filter sets on some older instruments are arranged so that the input signal is passed through the weighting network and subsequently through the filter set. This will allow A-weighted octave-band sound levels to be measured. Alternatively, octave-band sound-pressure levels may be adjusted by the factors given in Table 4 to obtain the equivalent A-weighted values.

Care shall be taken when analyzing octave- (or narrower) band readings to ascertain whether they were first passed through a flat network or a weighted network. As will be noted from Fig 6, serious errors in interpretation can occur if an incorrect assumption is made.

2.4 Sound Fields. To better understand the propagation characteristics of sound waves it is necessary to investigate their behavior in various environments.

2.4.1 Free Field

2.4.1.1 Point Source. The simplest form of source is a sphere that vibrates uniformly over its entire surface. We can think of this source as a round balloon with air in it. This source radiates sound equally in all directions from an apparent center, which is the center of the balloon. It is a *point source* insofar as sound radiation is concerned.

If such a point (or spherical) source is in the air far from other objects, including the ground, the sound pressure produced by the source is the same in every direction at equal distances from the point source. Furthermore, the sound pressure is halved for each doubling of distance from the point. This change is usually expressed as a decrease in sound-pressure level of 6 dB. The sound field produced under these idealized conditions is called a free sound field or a free field because it is uniform, it is free from all bounding surfaces, and it is undisturbed by other sources of sound.

2.4.1.2 Power Level in Free Field. Under free-field conditions, a single measurement of the sound-pressure level at a known distance from a point source is enough to tell us all about the sound field radiated by the source. For example, we can predict the level at any other point, since the sound pressure varies inversely as the distance from the source. We can also compute the total sound power radiated by the point source as shown in Eq 8.

$$\text{PWL} = \text{SPL} + 20 \log r + 11 \text{ dB} \quad (\text{Eq 8})$$

where

PWL = sound power, dB (ref 10^{-12} W)

SPL = sound pressure (ref $20 \mu\text{Pa}$)

r = distance (meters) from the point source to the point where the sound-pressure level is measured

For example, measure a sound-pressure level of 73.5 dB (ref $20 \mu\text{Pa}$) at a distance of 20 m from a point source; then

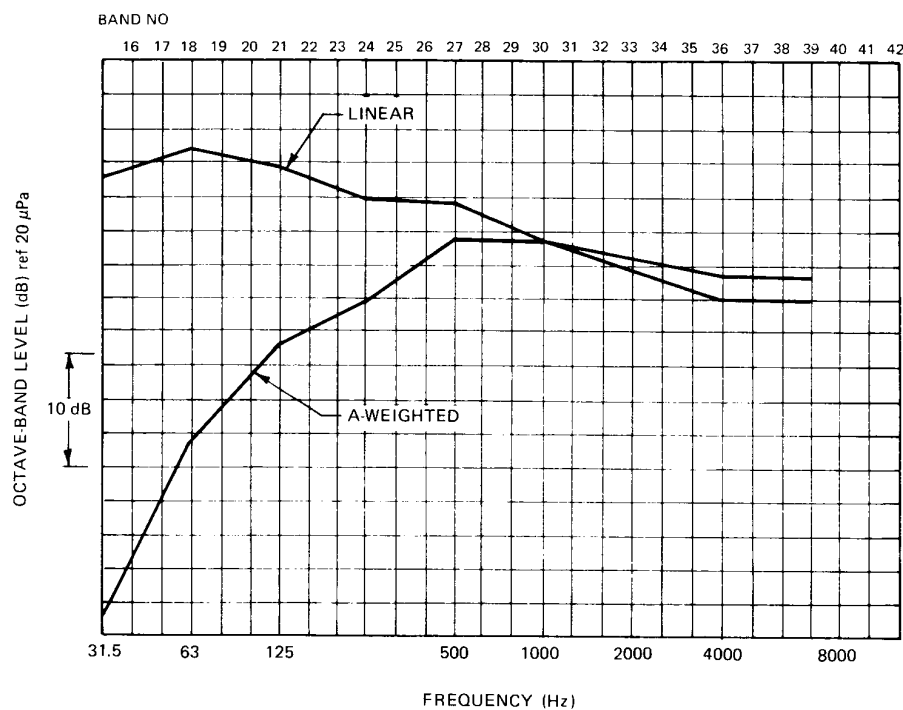


Fig 6
Comparison of Linear Versus A-Weighted
Octave Bands for Pulverizers—Bowl Mills

$$\begin{aligned}
 \text{PWL} &= 73.5 + 20 \log 20 + 11 \text{ dB} \\
 &= 73.5 + 26 + 11 \\
 &= 110.5 \text{ dB (ref } 10^{-12} \text{ W)}
 \end{aligned}$$

NOTE: The concept of a point source is an idealized one. It is unreasonable to assume that an actual source is a true point source, so that one should never be content with a single measurement.

2.4.1.3 Power Level in Hemispherical Space. For the more usual case, the source may be located far from other objects but close to the ground or floor. In this case, the sound source will radiate into hemispherical space as defined by the area above the ground plane. Since the intensity of the sound source radiating into a hemisphere is twice as great as that radiating into a sphere (see 2.4.1.2), the SPL measurement will be greater by 3 dB. In this idealized case, the sound-power level for hemispherical space is given by Eq 9.

$$\text{PWL} = \text{SPL} + 20 \log r + 8 \quad (\text{Eq 9})$$

where

PWL = sound power, dB (ref 10^{-12} W)

SPL = sound pressure (ref $20 \mu\text{Pa}$)

r = distance (meters) from the point source to the point where the sound-pressure level is measured.

2.4.2 Directional Source. In actual practice, noise sources are not as simple as point sources. The sound is not radiated uniformly in all directions, either because the shape of the sound source is not spherical, or because the amplitude and time phase of the vibrations of the different parts are not uniform, or both. The net result is that more sound is radiated in some directions than in others. In other words, the sound-pressure level for a given distance is different in different directions.

When such a directional sound source is far from any other object it behaves in some ways like a point source. For example, the sound-pressure level decreases 6 dB for each doubling of distance, provided measurements are started at a distance away from the source that is several times the largest dimension of the source, and moved directly away from the source. In actual practice this idealized behavior is upset by the effects of variation in terrain, atmospheric conditions, and the interference of nearby objects.

2.4.2.1 Near Field and Far Field. At locations close to a directional source equal sound-level contours are different in shape from those at a distance. Furthermore, there is no apparent center from which the 6 dB drop for each doubling of distance is found. Consequently, this *near-field* behavior cannot readily be used to predict the behavior at a distance. For the near-field effect to be minimized, the location should be at least one wavelength away from the source. This dimension should be determined on the basis of the lowest frequency of interest. For example, if the lowest frequency of sound of interest is 120 Hz, the wavelength is approximately 10 ft.

Another factor that enters into the differences between the near-field and far-field behavior is the way the sound waves spread out from a source. The sound waves from a large source vary with distance differently from waves produced by a small source. But at a distance of several (three to four) times the largest dimension of the radiating source, *spherical spreading* is said to exist, and the behavior is then nearly independent of the size of the source.

2.4.2.2 Directivity Factor. When we are interested in sound-pressure levels beyond the immediate vicinity of the source, any sound can be treated as a point source, provided we introduce a directivity factor. This factor takes into account the variation in sound-pressure level with direction to the source. This directivity factor, which is a function of direction and frequency, is usually labeled Q . It can be expressed as

$$Q = \text{antilog} \frac{DI}{10} \quad (\text{Eq 10})$$

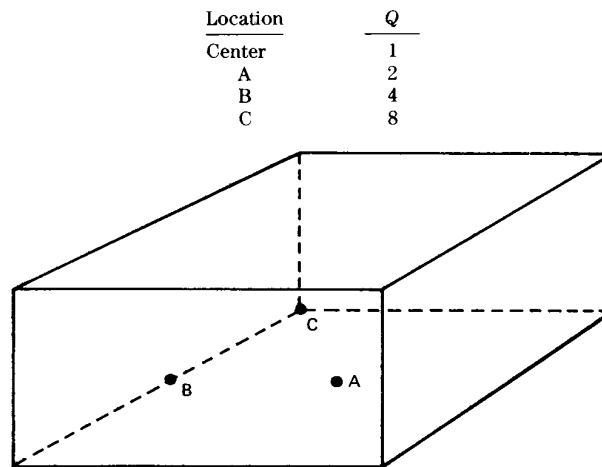
where

Q = directivity factor

DI = directivity index

For a point source located in the center of a large room, $Q = 1$ since the sound radiates uniformly in all directions. For other typical values of Q , refer to Fig 7.

Fig 7
Typical Values of Directivity Factor Q for
Different Locations of a Sound Source in a Large Room



Directivity index in any particular direction is defined as the sound-pressure level in that direction minus the mean sound-pressure level around the source. All these measurements are assumed to have been taken at a fixed distance r from the source.

$$DI = \text{SPL} - \overline{\text{SPL}} \text{ dB} \quad (\text{Eq 11})$$

where

DI = directivity index

SPL = sound-pressure level at a distance r in the desired direction

$\overline{\text{SPL}}$ = mean sound-pressure level around the source at distance r

2.4.2.3 Directivity in Hemispherical Space. The directivity index of a sound source on a rigid plane in a given direction from the source is given by

$$DI_H = \text{SPL} - \overline{\text{SPL}}_H + 3 \text{ dB} \quad (\text{Eq 12})$$

where

SPL = octave-band sound-pressure level at a distance r in the desired direction

$\overline{\text{SPL}}_H$ = average octave-band sound-pressure level measured on a test hemisphere around a source at distance r

The 3 dB in Eq 12 is added to the $\overline{\text{SPL}}_H$ because the measurement was made over a hemisphere instead of a full sphere.

2.4.2.4 Mean Sound-Pressure Level. The accurate method for obtaining the mean sound-pressure level requires making a set of measurements uniformly distributed on the hemisphere (sphere in the true free field) centered about the acoustic center of the source. The mean sound-pressure level is then determined from Eq 13.

$$\overline{\text{SPL}} = 10 \log \frac{1}{n} \left(\text{antilog} \frac{\text{SPL}_1}{10} + \text{antilog} \frac{\text{SPL}_2}{10} + \dots + \text{antilog} \frac{\text{SPL}_M}{10} \right) \text{ dB} \quad (\text{Eq 13})$$

where

$\overline{\text{SPL}}$ = mean sound-pressure level

$\text{SPL}_1 \dots \text{SPL}_M$ = level in dB of each measurement

n = number of measurements

A simple, though not precise, method to approximate the mean of a number of decibel readings is to take an arithmetic average. The following rules should be observed:

(1) For summing decibels which differ by 5 dB or less, take the arithmetic average directly

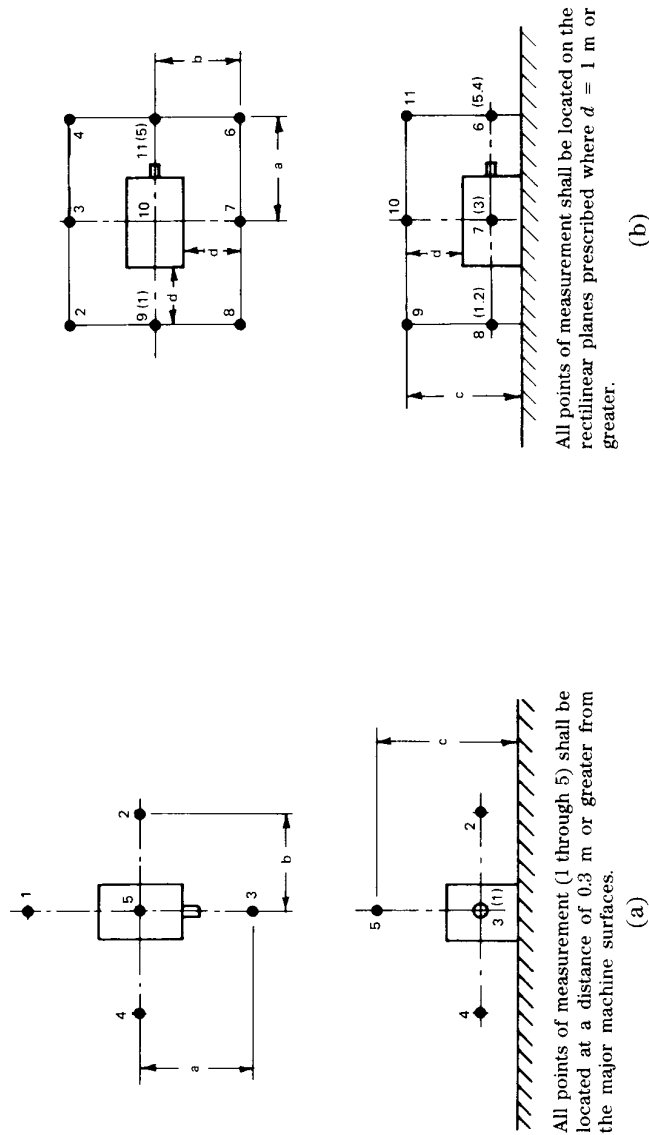


Fig 8
(a) Prescribed Points, Small Machines (b) Prescribed
Points, Medium Machines

(2) For summing decibels which differ by 5 dB to 10 dB, take the arithmetic average and add 1 dB

2.4.2.5 Equivalent Radius. Instead of making measurements on a true hemispherical surface, see IEEE Std 85-1973 (R 1980) [8], 2.6 and 2.7, which proposes that measurements be made on a *prescribed surface* surrounding the machine. Also see Figs 8(a), (b), and (c) which show the prescribed measurement points.

2.4.2.6 Sound-Pressure Level for a Directional Source. When we know the directivity factor for the direction of interest, we can use it as a multiplying factor on the power. Expressed in terms of level, Eq 14 is as follows:

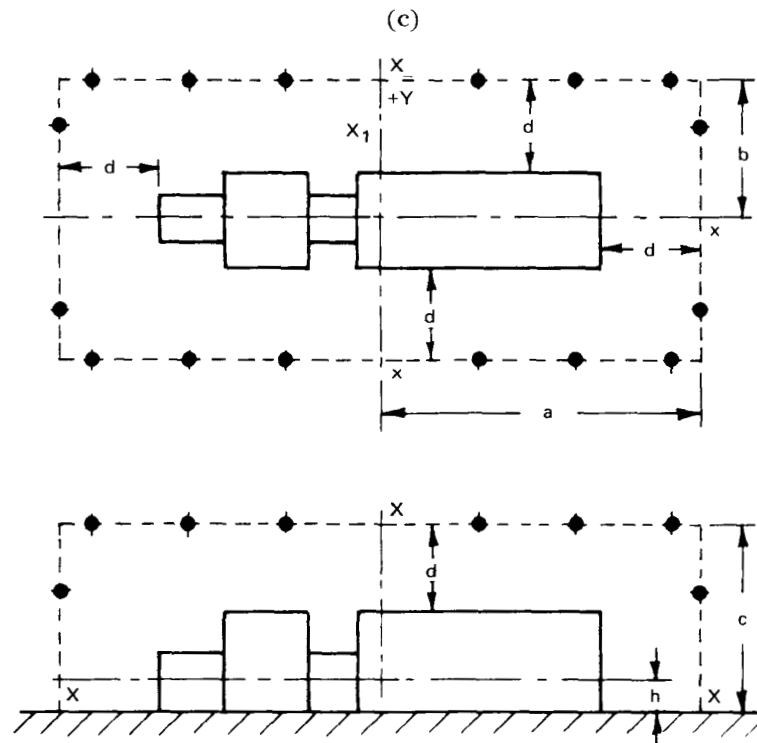
$$\text{SPL} = \text{PWL} + 10 \log Q - 20 \log r - 11 \text{ dB} \quad (\text{Eq 14})$$

In terms of the directivity index Eq 15 is as follows:

$$\text{SPL}_H = \text{PWL} + DI - 20 \log r - 11 \text{ dB} \quad (\text{Eq 15})$$

Fig 8
(c) Prescribed Points, Large Horizontal Machines

h = shaft height or 0.3 m, whichever is greater
 X = key measuring points
 O = measuring points marked off at intervals of $1 \text{ m} \pm 0.25 \text{ m}$ from key points
 d = 1 m or greater from major machine surfaces



Equation 15 relates the power level of the source, the sound-pressure level in a given direction at a distance r meters from the source, and the directivity index for that direction.

2.4.3 Effect of Reflections in a Room. The sound that a noise source radiates in a room is reflected by the walls, floor, and ceiling. The reflected sound will again be reflected when it strikes another boundary, with some absorption of energy at each reflection. The result of these reflections is that the sound-pressure level measured at a distance from the source is different from that predicted by Eqs 8 and 9.

Close to the source of sound there is little effect from these reflections, since the direct sound dominates. But far from the source, unless the boundaries are very absorbing, the reflected sound dominates, and this region is called the reverberant field. The sound-pressure level in this region depends on the acoustic power radiated, the size of the room, and the acoustic absorption characteristics of the materials in the room. These factors and the directivity characteristics of the source also determine the region over which the transition between reverberant and direct sound occurs.

A second effect of reflected sound is that measured sound does not necessarily decrease steadily as the measuring position is moved away from the source. At certain frequencies in a room with hard walls, marked patterns of variations of sound pressure with position can be observed. These patterns are called standing waves. They are noticeable mainly when the sound source has strong frequency components in the vicinity of one of the very many possible resonances of the room. They also are more likely to be observed when a frequency analysis is made; and the narrower the bandwidth of the analyzer, the more marked these variations will be.

The acoustical boundary conditions of ordinary rooms are extraordinarily complicated, and most sound sources are also complicated. The result of this complexity is that without advanced computer methods, only an average type of description can be used. Even a rough approximation can be useful, however, and we shall review briefly some of the work on room characteristics as it applies to the sound produced by a source in a room.

2.4.4 Effective Room Absorption and Absorption Coefficient. To simplify the analysis of the effect of the room, it is assumed that enough measurements are made so that any standing wave patterns can be averaged. A number of other assumptions are made, and then a relation of the form shown can be developed.

$$\text{SPL} = \text{PWL} + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{R} \right) \quad \text{dB} \quad (\text{Eq 16})$$

where

Q = directivity factor

r = distance from the sound source, m

R = effective room absorption (room constant), square meters or metric sabins and defined by Eq 17.

$$R = \frac{S \bar{\alpha}}{1 - \bar{\alpha}} \quad (\text{Eq 17})$$

where

S = room area (m^2)

$\bar{\alpha}$ = average absorption coefficient

The average absorption coefficient is given by Eq 18.

$$\bar{\alpha} = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \dots + \alpha_n S_n}{S_1 + S_2 + \dots + S_n} \quad (\text{Eq 18})$$

where

$\alpha_1, \alpha_2, \alpha_n$ = absorption coefficients of all materials in the room

S_1, S_2, S_n = corresponding areas of various materials

When a sound wave strikes a surface, a certain portion of the incident energy is absorbed. The sound-absorbing ability of a material is called the absorption coefficient. By definition true absorption coefficients range from 0 to 1. When $\alpha = 0$ all the energy is reflected, when $\alpha = 1$ all the energy is absorbed.

Absorption coefficients vary with material, frequency, and angle of incidence of the sound. Typical values are shown in Table 5. At frequencies above approximately 2000 Hz, the sound absorption in the air in a very large room is often

Table 5
Absorption Coefficients of Various Materials
Used in Acoustical Wall Treatment

Wall Treatment		Center Frequency (Hz)						
Facing*	Core**	125	250	500	1000	2000	4000	NRC***
None	1 in FW	0.06	0.20	0.65	0.90	0.95	0.98	0.70
None	3 in FW	0.53	0.99	0.99	0.99	0.99	0.99	0.95
None	1 in TIW	0.11	0.33	0.70	0.80	0.86	0.85	0.65
None	3 in TIW	0.46	0.99	0.99	0.99	0.99	0.99	0.95
$\frac{1}{4}$ in pegboard	1 in FW	0.08	0.32	0.99	0.76	0.34	0.12	0.60
$\frac{1}{4}$ in pegboard	1 in TIW	0.08	0.41	0.99	0.82	0.26	0.32	0.60
Perforated Metal (24 ga, 13% open)	2 in FW	0.18	0.73	0.99	0.99	0.97	0.93	0.95
	4 in Soundblox	0.19	0.83	0.41	0.38	0.42	0.40	0.50
Spray-on— $\frac{1}{4}$ in thick		0.04	0.04	0.20	0.39	0.60	0.81	0.30
Spray-on— $\frac{1}{2}$ in thick		0.26	0.51	0.98	0.99	0.95	0.86	0.85

* $\frac{1}{4}$ in pegboard = perforated holes 1 in oc

**FW = Owens-Corning Fiberglass Wool

TIW = Thermal Insulating Wool

***NRC = Noise reduction coefficient = average of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz absorption coefficients to the nearest 0.05 Hz

enough to affect the room constant appreciably. This absorption increases with frequency, and it varies markedly with humidity and temperature. The absorption at normal room temperatures is a maximum at relative humidities in the range of 10%–30%.

Another item that affects the absorption properties of a material is the method of mounting. For a porous-type absorber, the space between it and the wall will increase the absorption as the space is increased.

If the absorption coefficients of the materials in the room are not known, the room constant can be determined from measurements of the reverberation time of the room. The reverberation time is the time for the sound-pressure level in a room to deteriorate by 60 dB or $\frac{1}{1000}$ of its original value. The value of R is given by Eq 19.

$$R = 0.16 (V/T)$$

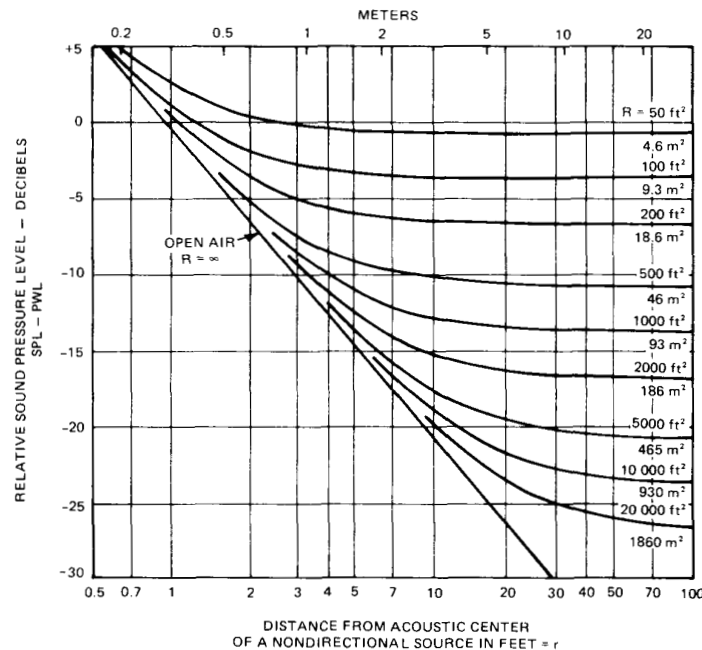
where

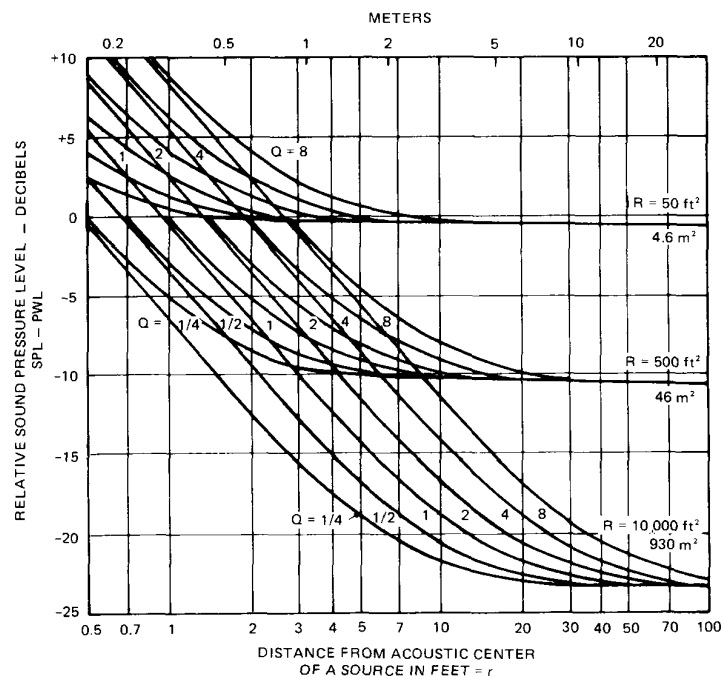
V = volume of the test room, m^3

T = reverberation time of the test room, s

The relation given in Eq 16 can be shown graphically in Fig 9 for the non-

Fig 9
Sound-Pressure Level (SPL) Relative to the Power Level (PWL)
for a Nondirectional Source for Different Values of the Room
Constant R , as a Function of the Distance from the Source





NOTE: The relation is shown for three different values of the room constant R , and for the six different values of the directivity factor Q .

Fig 10
Sound-Pressure Level (SPL) Relative to the Power Level (PWL)
for a Directional Source as a Function of the Distance
from the Source

directional source and in Fig 10 for the directions having the labeled values of directivity factor.

2.4.5 Reverberant Field. The graphs of Figs 9 and 10 show that close to the source the sound-pressure level tends to vary with the distance from the source as it does under free-field conditions ($R = \infty$). But far from the source the sound-pressure level becomes independent of the directivity of, and the distance to, the source. This region is called the reverberant field. Here, the level is determined by the acoustic power radiated by the source and the acoustic characteristics of the room. The region through which the transition between the free field and the reverberant field gradient occurs is determined by the directivity factor and the effective room absorption.

In terms of Eq 16 in the reverberant field, far from the source, r is large and therefore the directivity term can be neglected; Eq 16 becomes, for such a field

$$\text{SPL} = \text{PWL} + 10 \log \frac{4}{R} \quad \text{dB} \quad (\text{Eq 19})$$

Solving for the power level

$$\text{PWL} = \text{SPL} + 10 \log R - 6 \quad (\text{Eq 20})$$

Equations 19 and 20 are useful in calculating the sound-power level of a single source based on sound-pressure level measurements taken in a reverberant room.

2.4.6 Actual Room Behavior. In a highly reverberant room, the behavior on the average is similar to that shown in Figs 9 and 10. Most other rooms have characteristics that, on the average, fall between the reverberant behavior and the free-field sound-pressure level decrease of 6 dB for each doubling of the distance.

The calculations from the simple formula tend to over-estimate the level at a considerable distance from the source. Much more complicated formulas can yield values in closer agreement but are tedious unless they are programmed on a computer. The simple formula is useful for a preliminary estimate of the expected behavior, particularly if the absorption is small and if no one room dimension is markedly different from the others.

2.4.7 Reverberation Measurements. See Section 4.

2.5 Sound Propagation Outdoors. Sound waves travel from source to receiver outdoors through an atmosphere that is in constant motion. Turbulence, temperature and wind gradients, viscous and molecular absorption, and reflection from the earth's surface all affect the amplitude and create fluctuations in the sound received. The longer the transmission path through the atmosphere, the less certain the average amplitude and the greater the fluctuations in the sound received.

In addition to the effect of hemispherical divergence (see Eq 9), the excess attenuation owing to environmental and other conditions may include the following topics given in 2.5.1 through 2.5.5.

NOTE: Frequently it may be difficult to obtain the information needed to determine these excess attenuation effects. In such cases, it is always conservative practice not to include such effects.

2.5.1 Air Absorption. Air absorption is caused when energy is extracted from a sound wave by rotational and vibrational relaxation of the oxygen molecules in the air. The vapor content of the air determines the time constant of the vibration relaxation, which is more important than rotational relaxation. In addition, the *molecular absorption* depends, in a major way, on temperature. See Fig 11.

2.5.2 Fog, Rain, or Snow. There is evidence that absorption due to such particulate matter in the atmosphere is negligible. The subjective impressions that one occasionally has of such effects can generally be explained by other atmospheric properties which accompany the occurrence of precipitation. For

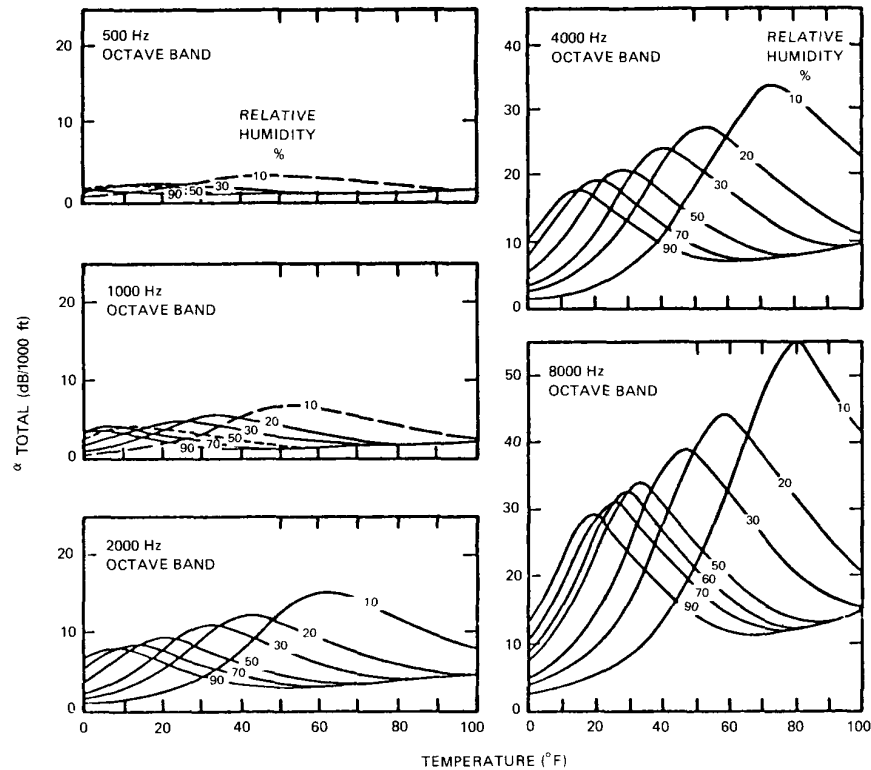
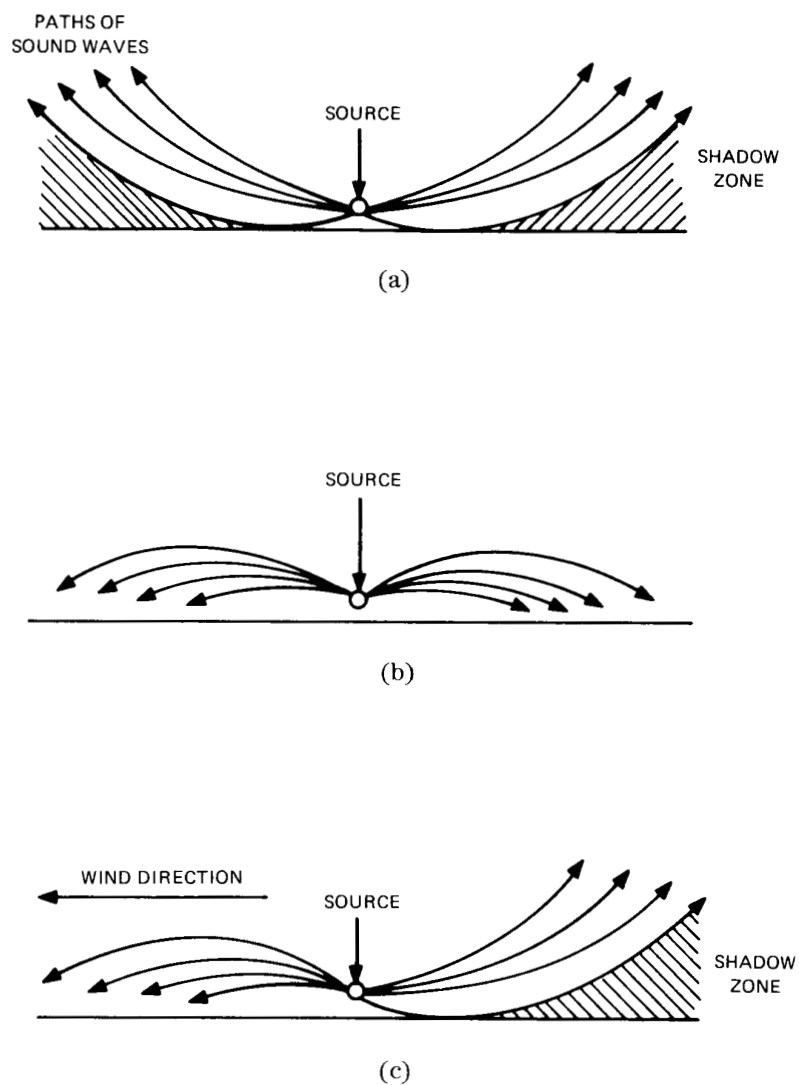


Fig 11
Atmospheric Absorption Coefficients for Octave Bands of Noise
for Different Temperatures and Humidities

example, temperature and wind gradients during light precipitation tend to be small so that sound *carries* farther outdoors than on a sunny day. Temperature inversions cause sound to travel farther than when isotropic conditions are present.

2.5.3 Barriers. Nonporous walls of sufficient mass (at least 20 kg/m²), if interposed between source and receiver, can result in appreciable noise reduction, because sound can reach the receiver only by diffraction around the boundaries of the obstacle. Barrier effects may be caused by either natural elevations (earth berm) or man-made obstacles (buildings).

2.5.4 Foliage. There have been large differences reported in the literature regarding excess attenuation due to foliage. Generally, any consideration of this excess attenuation is neglected unless the sound-wave path is through a significant distance of foliage (a minimum of 100 ft). In addition, there is wide variation depending on the nature and density of the vegetation.

**Fig 12**

(a) Influence of Negative Temperature Gradient (Cooler Air Above) on Bending of Sound Waves Upward (b) Influence of Positive Temperature Gradient (cooler air below) on Bending of Sound Waves Downward (c) Influence of Wind Direction on Bending of Sound Waves, Assuming Typical Wind Speed Increase with Height Above the Ground

2.5.5 Atmospheric Inhomogeneities. The speed of sound in air increases with the square root of the absolute temperature. When the atmosphere is in motion, the speed of sound is the vector sum of its speed in still air and the wind speed. The temperature and the wind in the atmosphere near the ground are almost never uniform. This atmospheric nonuniformity produces gradients of the speed of sound, and thus refraction of sound-wave paths. Near the ground, this refraction can have a major effect on the apparent attenuation of sound propagated through the atmosphere.

A simplifying assumption is a horizontally stratified atmosphere in which temperature and wind speed vary only with height above the ground. During the daytime, temperature normally decreases with height (lapse), so that sound waves from a source near the ground are refracted upwards. In the absence of wind, an *acoustic shadow* forms around the source [see Fig 12(a)] in which sound from the source is attenuated. Marked attenuations are observed at receiving points well into the shadow zone—it is just as if a solid barrier had been built around the source.

At night a temperature increase with height (inversion) is common near the ground and our *barrier* disappears as in Fig 12(b). Under severe inversions, increases of 5 dB – 15 dB can occur at distances of 1 mi from the source.

Near the ground, wind speed almost always increases with height. Because the speed of sound is the vector sum of its speed in still air and the wind vector, a shadow zone can form upwind of the source, but is suppressed downwind [See Fig 12(c)].

The combined effects of wind and temperature are usually such as to create acoustic shadows upwind of a source, but not downwind. Only under rare circumstances will a temperature lapse be sufficient to overpower wind effects and create a shadow surrounding a source. It is less rare, but still uncommon for a surface inversion to be sufficiently strong to entirely overcome an upwind shadow.

To determine the amount of excess attenuation due to wind and temperature, it is necessary to obtain somewhat detailed meteorological data in the area of interest. Such data may not be available and may require special study.

Environmental impact requirements for new plant construction frequently require the erection of meteorological towers to monitor various air quality parameters. Such an installation is an ideal source for the data required in computing excess attenuation factors. Depending upon the data available, various simplifying assumptions may have to be applied to existing procedures for determining the excess attenuation effects.

3. Laws and Regulations

3.1 Introduction Environmental noise problems can include a wide variety of noise sources and noise environments. One of the first steps in the evaluation of such problems is to determine compliance with existing laws. This section provides a summary of the laws as they exist today and which are significant to power-plant design. Representative state and local regulations are examined.

3.2 Federal Laws

3.2.1 Occupational Noise Exposure Regulations of OSHA. Recognizing the harmful effects excessive noise can have on the sense of hearing, the federal government has adopted regulations for limiting occupational noise exposure. Permissible noise exposures are defined based upon an 8 h workday and exposure to steady sound levels of 90 dB(A) and higher (see [16]). When the noise exposure consists of a combination of exposures at different levels and for different durations, a method to calculate a cumulative exposure is also presented. The regulation further requires that when employee exposure exceeds permissible limits, feasible administrative or engineering controls should be utilized to reduce exposure within permissible limits. If such controls are unsuccessful, personal protective equipment should be provided for, and used by, employees to reduce exposure to permissible limits. A hearing conservation program is required whenever noise exposure equals or exceeds an 8 h time weighted average sound level of 85 dB measured on the A-scale slow response.

3.2.2 29 CFR Bulletin 334, Guidelines to the Department of Labor's Occupational Noise Standards [17]. This bulletin explains the terms used in federal occupational noise regulations and what is expected of an employer to comply with regulations, and describes certain instruments, equipment, and procedures which will be acceptable as a basis for judging compliance. These guidelines help overcome some of the confusion in interpreting the Occupational Noise Regulations of OSHA. They emphasize that the use of personal protective equipment is considered by the Department of Labor to be an interim measure while engineering and administrative controls are developed. In addition, the characteristics of a continuing effective hearing conservation program are described.

3.2.3 Noise-Control Act of 1972. This act gives the Environmental Protection Agency responsibility to establish national noise standards for products that have been identified as major sources of noise. These include construction equipment, transportation equipment, motors and engines, and electrical and electronic equipment. Some noise-emission standards for railroads, trucks, and construction equipment have been promulgated under this act.

3.2.4 Regulatory Guide. NUREG 4.2, Nuclear Regulatory Guide for Preparation of Environmental Reports for Nuclear Plants [10] describes procedures and criteria for use in the preparation of an environmental report for a nuclear power plant prior to the issuance of a construction permit or an operating license. For information on audible noise see [10], Section 3.9, p 4.2–14,

ch 3, par 2; Section 4.1, p 4.2–15, ch 4, par 2; and Table 3, p 4.2–55, 4.2.1 and 4.3.1. These sections require an examination of the local population and an identification of the impact on their environment due to noise.

3.2.5 Department of Housing and Urban Development Environmental Criteria and Standards [15]. This department provides environmental standards, criteria, and guidelines for determining project acceptability and for necessary mitigating measures to ensure suitable noise environments. See [15].

3.2.6 Environmental Protection Agency [18]. Guidelines to rate the noise in various receiving areas are provided by the Public Health and Welfare Criteria for Noise. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety is also provided.

3.3 Representative State and Local Regulations

3.3.1 State of Illinois [13]. In 1973, the Illinois Pollution Control Board adopted rules and regulations pertaining to audible noise under [13], Ch 8, Noise Regulations. Permissible octave-band noise levels at the boundary lines of property are specified according to land use. In some cases, daytime and nighttime levels are specified. Also included are regulations for impulsive sound and for so-called prominent discrete tones. A-scale sound levels corresponding to the octave-band pressure levels range from 45 dB to 70 dB depending upon source land use and adjacent land use. It is interesting to note that for some cases the State Code is more restrictive than the City of Chicago ordinance. See 3.4.2.

3.3.2 State of New York [12]. In 1973, the State of New York adopted Rules of Procedure regarding certification for Major Steam Electric Generating Noise, [12], Part 75. These rules basically require

- (1) Measurement and documentation of ambient noise levels around the site
- (2) Estimates of the effects of site construction and plant operation on ambient noise levels with particular attention to areas of adjacent land use
- (3) An evaluation of the impact of site construction on ambient noise levels
- (4) An evaluation of the effects of plant operation and maintenance on ambient sound levels

The format of the information to meet these requirements will include tabulated data, graphic data, and overlays of the area showing ambient and projected sound-level contours.

3.4 Local Ordinances

3.4.1 City Noise Ordinances. The magazine, *Sound and Vibration*, [14] periodically updates a listing of municipal noise regulations covering various categories from emission sources to land use.

3.4.2 Chicago Noise Ordinance [11]. The most publicized municipal ordinance is probably the Chicago ordinance. For over 20 years, this ordinance specified permissible octave-band pressure levels at the boundary lines of zoned districts. In 1971, a new ordinance was passed and included noise-emission limits for motor vehicles, construction equipment, recreational vehicles, and other noise producing devices. A condensed summary of the regulations has been prepared by the Department of Environmental Control, City of Chicago.

3.5 Summary. For the construction and operation of power generating stations, there are two types of noise regulations with which the designer should become familiar

(1) In-plant or occupational noise regulations to prevent noise-induced hearing loss

(2) Out-plant or community regulations to limit the effects of site noise on the noise environs of the surrounding community

Occupational noise regulations specify limits of exposure to A-weighted sound levels, require reduction of noise exposure by engineering controls (reduce level) or administrative controls (reduce exposure time), and allow provision and use of hearing protection devices. Community regulations limit noise emissions from a building or site, specify C-weighted/A-weighted or octave-band levels, and can include provisions for various types of noise such as impulse, tonal, and steady. The trend in community regulations is toward more restrictive levels and more detailed measurements. In addition to the specification of permissible levels at the plant boundaries, some provisions are made to examine the existing ambient levels, to determine the statistical distribution of these levels with frequency of occurrence, and to predict the effects of plant operation on ambient environmental noise. Conformance with these regulations does not guarantee freedom from complaints, especially where noise sources exhibit strong tonal characteristics. The first step in developing noise-control procedures for a power station should be an examination of applicable noise regulations.

